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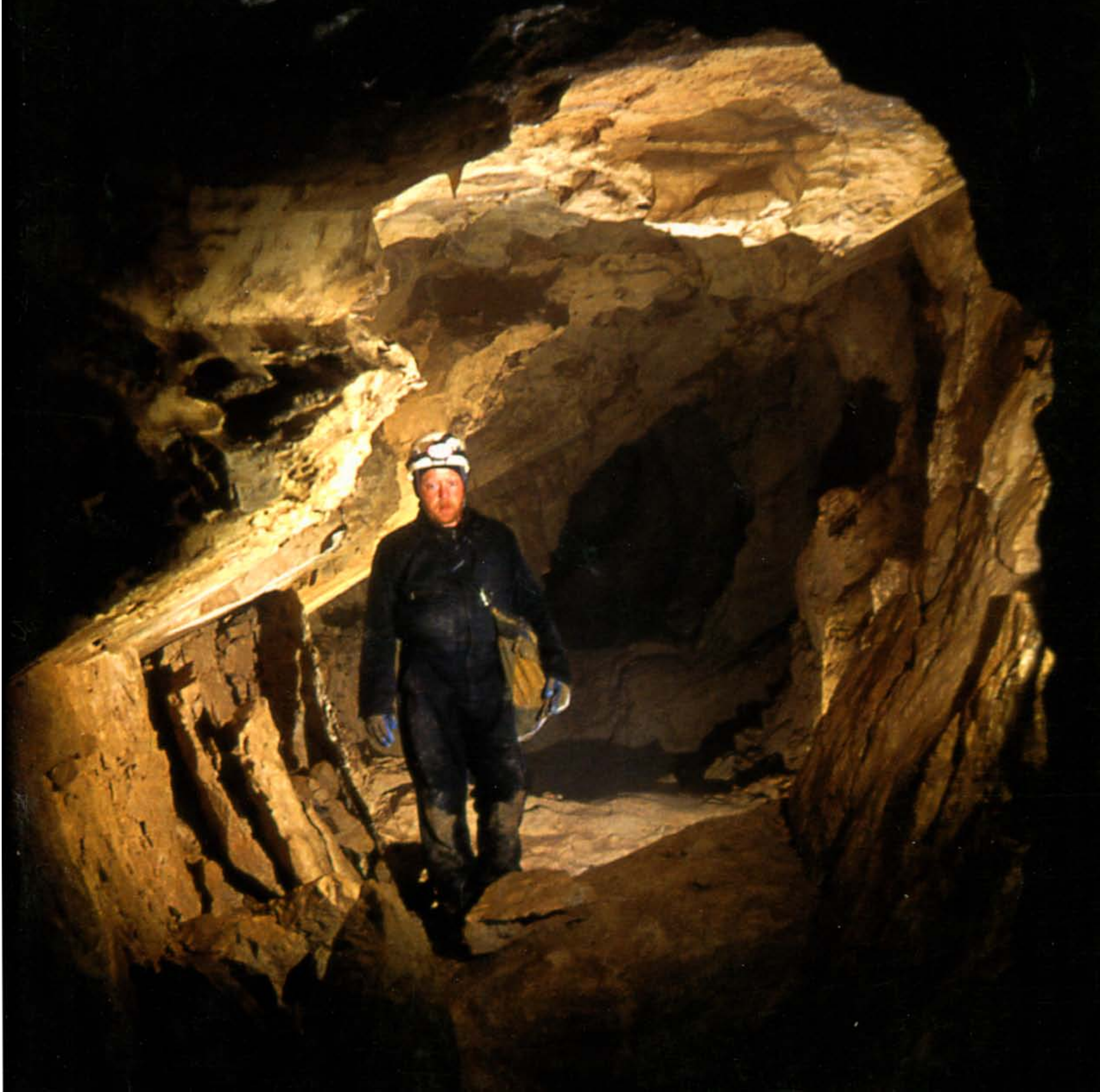

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Front cover: Thrust fault in Poia Lake Care Montana, see article by H. Bodenhamer beginning on page 326.

Z. Mohammadi and E. Raeisi – Hydrogeological uncertainties in delineation of leakage at karst dam sites, the Zagros Region, Iran. *Journal of Cave and Karst Studies,* v. 69, no. 3, p. 305–317.

HYDROGEOLOGICAL UNCERTAINTIES IN DELINEATION OF LEAKAGE AT KARST DAM SITES, THE ZAGROS REGION, IRAN

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Abstract: Leakage from dam reservoirs has been reported in different karst regions of the world. Water leakage occurs through the karst features directly or indirectly. The estimation of leakage locations, path(s), and quantity are subject to error due to uncertainties in the non-homogenous nature of a karst formation, method of study, and limited investigation due to time and cost factors. The conventional approaches for study on the karst development are local boring at the dam site and geological mapping. In this paper, uncertainties associated with conventional hydrogeological approaches are addressed from both qualitative and quantitative points of view. No major solution cavities were observed in boreholes and galleries of some dam sites in the Zagros Region, Iran, but huge karst conduits were discovered during the drilling of a diversion tunnel. This inconsistency is due to the point character of boreholes and the inherent non-homogeneity of karst. The results of dye tracing tests in boreholes may be significantly affected by location of the injection and sampling points, as tests executed at the Saymareh and Tangab Dam sites in the Zagros Region, Iran show. The quantitative uncertainty of leakage is analyzed for diffuse and conduit flow systems for cases with and without any grout curtain, under the combined effect of input uncertainties at the Tangab Dam site, southern Iran. Assuming a diffuse flow system, the mean leakage at 95% confidence interval for both strategies is estimated at less than 5% of the mean annual discharge of the river. Accordingly, the dam can be constructed without the necessity of a grout curtain. However, assuming a conduit flow system, the results reveal a significant uncertainty. A small diameter conduit can convey significant amounts of water under high reservoir pressure heads. The leakage of a 4 m diameter conduit (cross section area of 12.5 m^2) is 163 times more than the leakage of 0.5 m diameter conduit (cross sectional area of 0.2 m^2) while the cross sectional area ratio is 60. The uncertainty may be decreased if a detailed study is carried out on the stratigraphic and tectonic settings, karst hydrogeology, geomorphology, speleogenesis, and by performing several dye tracing tests, especially outside the proposed grout curtain area.

Introduction

Leakage from dam sites has been reported in numerous dams in karst areas. Solution activity forms conduits of unpredictable dimensions and geometry whose permeability is often measured in centimeters or meters per second. In most cases, the leakage occurs during the first filling and reservoirs may fail to fill despite an extensive investigation program and sealing treatment. Milanović (1997) reported the maximum leakage from reservoirs in different karst areas of the world. The main causes of leakage at karst dam sites are the non-homogeneous nature of the karst formations, inadequate data, limited investigation due to time and cost limitations, and unreliable models. The high permeability zones are local, representing a small percentage of the total karst area. The risk component may be unavoidable in spite of very detailed and complex investigation programs, including all available methods. It is not realistic to plan complete elimination of risk in karst areas. Therefore uncertainty analysis is a useful technique in assessment of dam safety issues due to leakage.

Yen and Tung (1993) and Tung (1996) classified the uncertainties into natural, model, parameter, data, and operational ones. Natural uncertainty is associated with the inherent randomness of natural processes. Model uncertainty reflects the inability of the model to accurately represent the system's true physical behavior. Models ranging from simple empirical equations to sophisticated computer simulations are used. Parameter uncertainties result from the inability to quantify accurately the model inputs and parameters. Data uncertainty includes measurement errors, non-homogeneity of data, and an inadequate representation of the data sample due to time and cost limitations. Operational uncertainties include those

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associated with construction, manufacture, deterioration, maintenance, and human factors.

The task of uncertainty analysis is to determine the uncertainty of the system output as a function of uncertainties in the model and the system inputs (Tung, 1996). Furthermore, it offers the designer useful insights regarding the contribution of each stochastic variable to the overall uncertainty of the system outputs. Such knowledge is essential to identify the important parameters to which more attention should be given to have a better assessment of their values, and accordingly, to reduce the overall uncertainty of the system outputs. In general, uncertainty analysis provides an estimate of the uncertainty distribution for selected output, according to the inputs.

The most complete and ideal description of uncertainties is the probability density function of the quantity subject to uncertainty. However in most practical problems, such probability functions cannot be derived or found precisely. Accordingly, in this study, the discrete probability distribution (DPD) is used instead of continuous probability distribution. Another measure of uncertainty is the reliability domain, such as the confidence interval. A confidence interval is a numerical interval with a specific probabilistic confidence. Several techniques can be applied to conduct uncertainty analyses. Each technique has different levels of mathematical complexity and data requirements.

Uncertainty analysis has been used extensively in dam safety risk assessments (Bowles et al., 1998; 1999; 2003; Chauhan and Bowles, 2003). Assessing the uncertainty in the hydrogeological studies of karst dam sites has received less attention. An application of a probabilistic risk analysis to the problem of designing a water retention dike on karst terranes was presented by Steven and Bromwell (1989).

The objectives of this article are (i) qualitative analysis of uncertainties in conventional approaches for obtaining hydrological parameters which affect dam leakage estimation with examples of some karst dam sites in the Zagros region, Iran, and (ii) quantitative analysis of applying the diffuse and conduit flow systems for estimation of leakage at the Tangab Dam site, the Zagros region, Iran, by means of uncertainties of input parameters (e.g., permeability, hydraulic gradient, conduit cross section, and friction factor). The results provide recommendations for minimizing the leakage uncertainty.

REGIONAL SETTING

Iran is geologically a part of the Alpine-Himalayan orogenic belt. Five major structural zones, different in structural history and tectonic style, can be distinguished in Iran (Stocklin, 1968): a) The Zagros Range, b) The Sanandaj-Sirjan Range, c) Central Iran, d) East and South-East Iran, e) The Alborz and Kopet-Dagh Ranges. The Zagros Range is divided into the three structural zones of the Khozestan Plain, the Simply Folded Zone (SFZ) and the Thrust Zone (Stocklin, 1968). It is about 12 km thick and mainly made of limestone, marl, gypsum, sandstone and conglomerate. Since Miocene time, it has been folded into a series of huge anticlines and synclines. The SFZ passes northeastward into a narrow zone of thrusting bounded on the northeast by the Main Zagros Thrust Line. A wide variety of lithologies including crushed limestone, radiolarite, and ultra basic and metamorphic rocks have been intensively thrust-faulted in this zone. The width of the thrust zone varies from 10 to 70 km and makes up the highest elevations in the Zagros. Karstic carbonate formations cover about 11% of Iran's land area. The total area of karstified carbonate rocks in Iran is about 185,000 km^2; 55.2% of this in the Zagros (Raeisi and Kowsar, 1997).

Most of the outcropping carbonate rocks are of Cretaceous and Tertiary age. The most important karst features in the Zagros Range are karren, grikes, springs, and, to a lesser extent, caves and dolines. Most of the springs are permanent, and a high percentage of the spring discharges are baseflow. The Zagros Folded Zone is characterized by a repetition of long and regular anticlinal and synclinal folds. The anticlines are normally mountain ridges of limestone, and the synclines are valleys and plains. Most of the karst formations in the Zagros Folded Zone are sandwiched between two impermeable formations, forming broad highland independent aquifers (Raeisi, 2004; Raeisi and Laumanns, 2003).

The general direction of ground-water flow is mostly toward the local base of erosion, parallel to the strike. Karst water discharges as springs or flows into the adjacent alluvium aquifer where a direct connection exists between the alluvium and the karst formation. Several dams are under study in karst areas of the Zagros region, especially in the SFZ. Leakage of water has been reported in several karst dams. Designs of grout curtains are mainly based on the geological maps of the dam sites and borehole data. The complexity of karst aquifers and the problem of leakage after dam construction in the Zagros region imply that an uncertainty analysis is a necessity at the design stage.

QUALITATIVE ANALYSIS OF LEAKAGE

The qualitative uncertainty is mainly a response to conventional methods of study in the non-homogeneous karst formation. The main characteristics of karst aquifers are the existence of irregular networks of pores, fissures, fractures, and conduits of various sizes and forms. Such structures with significant physical and geometrical heterogeneity cause complex hydraulic conditions and spatial and temporal variability of hydraulic parameters (Denic-Jukic and Jukic, 2003). Controls in the development of karstic aquifers were discussed by Ford and Williams (1989).

Karst development, especially in the main conduit, is controlled by numerous factors such as geological and tectonic settings, base of erosion, thickness, lithology, precipitation, temperature, and CO_2 pressure. These factors are not the same in different karst regions, such that the location and geometry of the main karst conduits differ even within short distances. Local borings (boreholes, galleries and tunnels) and geological mapping at the dam site are the conventional approaches for study of the karst development, consequently affecting the decision about zone(s) and path(s) of leakage and finally estimation of leakage value by applying a model. Qualitative uncertainties associated with boreholes, geological mapping and model are discussed as follows.

Uncertainties Associated with Borings

Exploration boreholes present a unique technique for evaluation of deeper positions of karst terranes, but they provide information which, in many cases, represents only the area in the vicinity of boreholes. The probability of cavity discovery in a borehole network with 50 by 50 m spacing is 1/2500. Experience is replete with cases of the drill hole that just missed a major cave or similar feature (Merritt, 1995). Some of the case studies include:

- Salman Farsi Dam (Iran): No major solutional cavity was observed along 400 m of one of the galleries, but at its end, a cavity with approximate dimension of 150 × 50 × 40 m was discovered.
- Tangab Dam (Iran): No major karst conduits were discovered in any of the boreholes and galleries, while a huge shaft was discovered during drilling of the diversion tunnel.
- Maroon Dam (Iran): No conduit was discovered along the galleries and boreholes. However, a 3 m opening was discovered in the diversion tunnel. This conduit leaked about 4 $m^3 s^{-1}$ at the first filling before the grout curtain was completed.
- Kohrang III Tunnel (Iran): In one of the adit tunnels, the sediment in a conduit was washed by high pressure water with 800 L s^{-1} discharge from the adit tunnel inlet. The karst conduits were observed frequently in the adit tunnel; the apertures of active karst conduits range from a few centimeters to more than one meter. The velocity of some water jets exceeds 10 m s^{-1} (Sadr and Baradaran, 2001).

Furthermore, water-table measurements and various hydrologic tests (e.g., Lugeon and dye tracing) were carried out in the boreholes. The results of these studies may have high uncertainty due to nonhomogeneity of karst and borehole characters such as number, depth, location, and arrangement.

Lugeon Test Uncertainty

Measurement of permeability by the Lugeon test is a common application in boreholes. Many problems arise in deriving the permeability from the Lugeon test due to the anisotropy and nonhomogenity of karstified formations because such tests are limited to narrow zones around the boreholes. Uncertainties may exist in the measured permeabilities as follow:

(a) Water must be injected into the isolated section separated by rubber packer. The packer is mechanically, hydraulically, or pneumatically expanded and pressed against the borehole wall. Leakage of injected water around the packer may cause great error in the measured permeability value.

(b) Very often the test at a 5 m section produces unrealistic results because the permeability is an average of the 5 m section. A high permeability zone may be located within a small portion of the 5 m section. The test section may be reduced to 1 m in such a situation to increase the reliability of measurements (Milanović, 2000).

(c) Low permeability at the deepest sections of a borehole cannot be considered as base of karstification, because heterogeneity is a natural characteristic of a karst aquifer.

(d) Borehole construction is limited to the area near the dam body or to the proposed grout curtain area. The critical leakage zones may be located outside the proposed grout curtain area. For example, the permeability of the last boreholes in the right and left embankments in Kowsar Dam site, the Zagros region of Iran, and at the end of most boreholes are quite high. This implies that leakage zones may be situated outside the proposed grout curtain.

Isopotential Uncertainty

Isopotential maps can be prepared by contouring water levels in piezometers. Karst aquifers contain both diffuse and conduit components. The route of major conduit systems is marked by well-defined ground-water troughs (White, 1988). The water-table surface in topologically or structurally complex areas may be quite irregular. The unique feature of a karst aquifer is the rapid response of the conduit system compared with that of a diffuse system. Large dimensions of karst conduits, their good interconnections, high water level gradients, and the high permeability of surface zones enable rapid filling and emptying of karst drains.

A high precipitation rate may fill the conduit system, causing water level rise by tens of meters in a few hours. The ground-water trough fills up, bringing water level in a conduit system to the level of the diffuse water table, or mounds the water above it (White, 1988). It can be concluded that the water table configuration depends on the distance of boreholes to a major drain (conduit), capacity of the drain, and the time of measurement. The probability of a borehole tapping the major conduits is low, because the conduit systems occupy a low percentage of a karst aquifer. Therefore, the water-table configuration (isopotential map) mainly presents the flow in a diffuse system.

DYE TRACING UNCERTAINTY

Although the dye-tracer test is one of the most powerful techniques to determine karst development, it is a point-to-point connection and it is dependent on the location of injection and sampling points (or boreholes). Therefore, major karst conduits may be missed. Estimation of ground-water flow velocity is one of the main goals of tracer tests. Although the equation for estimation of velocity is very simple, extensive uncertainties may exist in the results of dye-tracing tests, as explained below.

Injection Point

In general, the injection point must be connected to a conduit system. Dye injection into a diffuse system may create serious uncertainties in velocity. The injected dye may flow in a diffuse system for a long time and then drain into a conduit. Consequently, the average velocity is calculated between the injection point and the sampling point. The share of travel time through the diffuse system may be significant in the total travel time such that the average velocity reduces to values typical of diffuse flow. An obvious example is the Saymareh Dam, the Zagros region, west of Iran.

An injected borehole with a depth of 254 m was constructed in the northern flank of the Ravandi Anticline. The lithology of the HM28 borehole mainly consists of Asmari karstic limestone from 48 m to the bottom of the borehole. Fifteen kilograms of Rhodamine B (Basic Violet 10) were injected into the deep HM28 borehole. The karst system around the HM28 borehole is diffuse type. Thus, no dye was detected in the sampling points. The following justify the storage of dye around the HM28:

- Calculations showed that the dye could be stored in the vicinity of the HM28 borehole with a minimum concentration of 2759 ppb (Asadpour, 2001).
- The permeability of the HM28 borehole under the water table was less than 10 Lugeon and no conduits were observed in the lithological column of the HM28 borehole below the water table.
- The Gachsaran Formation (consisting of impermeable layers) outcrops in the vicinity of the HM28 borehole, preventing the infiltration of rainwater into the Asmari Limestone and consequently karst is undeveloped.

Sampling Points

The injected dye flows directly or indirectly into a conduit. The dye concentration is higher and travel time is lower in the main conduit compared to the nearby diffuse system. If the boreholes are connected to the diffuse system, the dye may not be detected or the calculated velocity may be in the range of diffuse flow. The connection of boreholes to the diffuse system and the small number of boreholes increase the uncertainty in the calculated velocity. Boreholes (sampling points) are mainly drilled for the geotechnical purposes.

For instance, at the Tangab Dam site, the Zagros region, southern Iran, all the boreholes were located within the diffuse system. The dye concentration in a borehole 50 m away from the injection point and other nearby boreholes were very low with insignificant dye concentration, while the injected dye was detected at high concentration after 5 days in some of the downstream springs about 5 kilometers away from the injection point. It can be concluded that none of the boreholes intersected the conduit transporting the dye. The detected dye in the boreholes was due to dispersion. The calculated velocity in the boreholes is not representative of the conduit system and is subject to uncertainty.

Dye Dilution

The concentration of injected dye may be reduced by the absorption of dye on the contact surface of limestone with the ground water, the decay of dye in darkness, and dilution with ground water. The dye may dilute significantly when it emerges into a big river. It may be absorbed or diluted to such a low level that it cannot be detected by a spectrofluorophotometer. Dye dilution to an undetectable level creates great uncertainty in the results. It implies a false result of no connection between injection and sampling points. The uncertainty can be reduced by increasing the amount of injected dye. For example, ten kilograms of uranine were injected in a borehole on the right abutment of Sazbon Dam site, the Zagros region, Iran (Aghdam, 2004). The dye was not detected in the big river 100 m away from the injection point. It was only detected at very low concentration in three boreholes on the left abutment. The dye may not be detectable in the river and other boreholes in the left abutment, creating uncertainties in the results. The uncertainty can be alleviated with further dye tracing in the left and right abutments.

UNCERTAINTIES ASSOCIATED WITH GEOLOGICAL MAPPING

Although geological mapping is one of the primary techniques to determine the most probable leakage zone in a dam site, it is not capable of predicting conduit locations and probable leakage zones because the karst conduits are small in size and they cannot be identified precisely based on geological maps. The general direction of flow is mainly controlled by bedding-plane partings, concentration and patterns of joints and faults, relief, base of erosion and pattern of folding. There are numerous pathways providing alternative routes for ground-water flow. At the initial stage of karst development, an optimum hydraulic path with least resistance to flow, shortest and steepest route is enlarged out of the large number of all possible alternative routes. Once a conduit is developed, it acts like a drain, and the growth of alternative paths is suppressed while conversely, the conduit aperture is enlarged by continued dissolution.

It is a common theory in Iran that the fault is the only general direction of flow. However, faults may have positive, negative, and neutral effect on ground-water flow and conduit enlargement (Kastning, 1977). Faults often operate hydrologically like major joints. Where large vertical faults are present in a karst area, it is common to find sinkholes and larger landforms aligned along them or close to them, but the situation is variable and less predictable with respect to solution caves. It is comparatively rare to find an entire system of conduits that is controlled primarily by faults or contained within them (Ford and Williams, 1989). Because they are initially mostly widely opened, faults attract migrating solutions during and after deep tectonism. Parts of faults become sealed by the secondary calcite so that, although substantial voids remain elsewhere, they can not be connected to permit ground-water flow along, up, or down the entire fault plane.

Many fault planes are highly impermeable to ground-water flow. Faults are sometimes important in introducing blocks of other lithologies that may act as a barrier to water movement. This may arise from normal or reverse faulting of non-karst rocks or may involve fault plane guided intrusions of igneous material (Ford and Williams, 1989). These impose an impervious curtain across an aquifer, considerably interrupting ground-water flow and aquifer development. Further, the other karst development parameters such as local relief and base of erosion normally exert a greater influence on the direction in which ground-water flows, because hydraulic gradient is strongly influenced by them. It is local relief that determines the lowest points at which ground-water outflow can take place (Ford and Williams, 1989). It can be concluded that the mapping of faults is not enough to determine the direction of ground-water flow and further hydrogeological studies are needed to determine the role of faults on the general direction of flow.

Quantitative Analysis of Leakage

The quantitative uncertainty analysis requires a significant amount of data as input. Data collection for input variables and parameters is extremely expensive and time consuming, particularly in complex non-homogenous karst dam sites.

Various analytic and computational techniques were applied for examining the effect of uncertain input within a model. The effect of changes in inputs on model predictions (i. e., sensitivity analysis), the uncertainty in the model outputs induced by the uncertainties in its inputs, and the comparative importance of input uncertainties in terms of their relative contributions to uncertainty in the output may be considered in uncertainty analysis (Morgan and Henrion, 1990). A drawback of sensitivity analysis is that it ignores the degree of uncertainty in each input. An input that has a small sensitivity but a large uncertainty may be just as important as an input with a large sensitivity but smaller uncertainty. Gaussian approximation is the simplest approach that considers both sensitivity and uncertainty consequently the variance of the output is estimated as the sum of squares of the contributions from each input (Morgan and Henrion, 1990).

However, Gaussian approximation is a local approach in that it considers the behavior of the input function only in the vicinity of the mean or median. Therefore, we need to use a global approach that explicitly evaluates the function (distribution) of each input. Use of discrete probability distribution (DPD) to approximate the uncertainty in output is widely used in decision analysis. It is usual to approximate continuous distribution by discrete distributions with three or five values. Conventionally, the middle value is chosen equal to the median and the other points are chosen roughly to minimize the total area between the continuous cumulative distribution and the stepwise cumulative function representing the discrete distribution (Morgan and Henrion, 1990).

The first step of the DPD approach is to determine the five points of discrete distribution, as illustrated in Fig. 1. The DPD for each input consists of five pairs; each pair is a value and corresponding probability. We then obtain a corresponding distribution for a × b (Fig. 1), taking the cross products of the values and of the probabilities, obtaining a DPD with 5 × 5 = 25 value-probability pairs. In the second step, the DPD for a × b is condensed; that is, the twenty-five-point distribution is approximated by a five-point distribution. Thus, when using the result to obtain the cross product for a × b × c (Fig. 1), the resulting DPD has only twenty-five points, rather than 5 × 25 = 125 points.

The quantitative analysis of uncertainty associated with estimation of leakage is studied for two simple one-dimensional flow conditions including diffuse and conduit at the Tangab Dam site by using DPD method. A karst aquifer is classified as having diffuse, conduit, or mixed flow regimes (White and Schmidt, 1966, Shuster and White, 1971, Atkinson, 1977). In a diffuse system, laminar flow occurs through interconnected fissures less than 1 cm in diameter. The flow is turbulent in a conduit system; sizes ranging from 1 cm to more than 1 m. Models ranging from simple empirical equations to sophisticated computer simulations (e.g., Howard and Groves, 1995; Dreybrodt et al., 2002; Kaufmann, 2003; Romanov et al., 2003; Bauer et al., 2003; Liedl et al., 2003) are used. The Darcy equation simulates a diffuse flow system

$$Q = kiA \tag{1}$$

where, Q is discharge, k is permeability, A is total cross

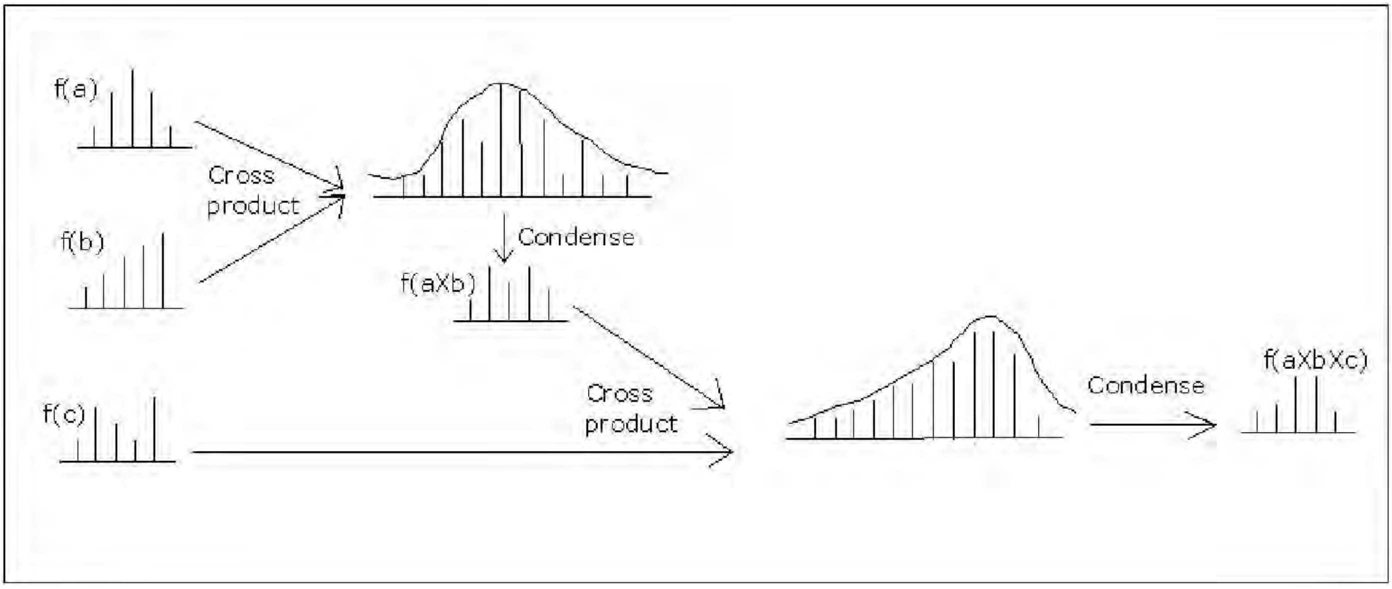

Figure 1. Schematic diagram of the DPD method.

sectional area, and i is hydraulic gradient. The Darcy-Weisbach equation is applicable in a conduit flow system

$$Q = \left[\frac{2dgA^2}{f}\right]^{1/2} [i]^{1/2} \tag{2}$$

where, d is diameter of the conduit, A is the conduit cross section area, g is gravity, and f is friction factor. Most karst aquifers contain both diffuse and conduit flow regimes. It is a very difficult task to determine the percentage of diffuse and conduit flow and the cross section of the conduit. Therefore, great uncertainties exist in model selection.

Case Study

The Tangab Dam is currently under construction in the northern flank of the Podenow karstic anticline, at the entrance of a gorge on the Firoozabad River, about 80 km southeast of Shiraz, the Zagros region, southern Iran (Fig.2). The dam is designed as a rock-fill embankment with clay core (Fig. 3). The technical data are presented in Table 1. The catchment area of the Firozabad River at the dam site is approximately 1356 km^2, and its mean annual flow is 3.8 m^3 s^{-1}. A geological map of the dam site is shown in Figure 2.

The main geological formations consist of Pabdeh-Gurpi (Paleocene-Oligocene), Asmari (Oligocene-Miocene), Transition Zone and Razak (Lower Miocene). The Pabdeh-Gurpi Formation is not exposed at the surface near the dam site nor in the area of the reservoir, but it constitutes a hydrogeologically important aquiclude beneath the Asmari Limestone. The Asmari Limestone forms the walls of the dam site gorge. The core of the Podonow Anticline is composed of the Asmari Formation limestone which is sandwiched between the two impermeable formations that include the Pabdeh-Gourpi (marl, shale and marly limestone) and Razak Formations (silty marl to silty limestone with interbedded layers of gypsum) (Karimi et al., 2005). The thickness of the Asmari Formation in the study area is about 400 m and its contact with Razak Formation is transitional. The thickness of the Transition Zone varies from zero to 300 m, and it is composed of alternating layers of marl, marly limestone and limestone (Karimi et al., 2005).

The hydrogeological setting of karstic springs near the dam site was extensively studied by Karimi (1998) and Karimi et al. (2005). The Asmari Formation constitutes the bedrock at the selected site. The beds dip very gently upstream. Fractures and joints are widely spaced and moderately opened. A minor fault passes to the left of the dam site. No faults were detected in the foundation area of the dam.

The reservoir will be in direct contact with the karstic Asmari Formation in both abutments (Fig. 2). The contact area is 600 m by 200 m in the left abutment and 200 m by 200 m in the right abutment. The geological conditions for construction of the grout curtain also appear favorable. Large voids were not detected (although a few karst features are likely). Therefore, it is expected that adequate seepage control can be obtained by taking the curtain into the marly limestone at depth (about 150 m) and extending it 120 to 150 m laterally into the abutments. The dimensions of designed grout curtain are presented in Figure 4.

No solution cavities or major karst conduits were observed in boreholes or galleries. However, two caves

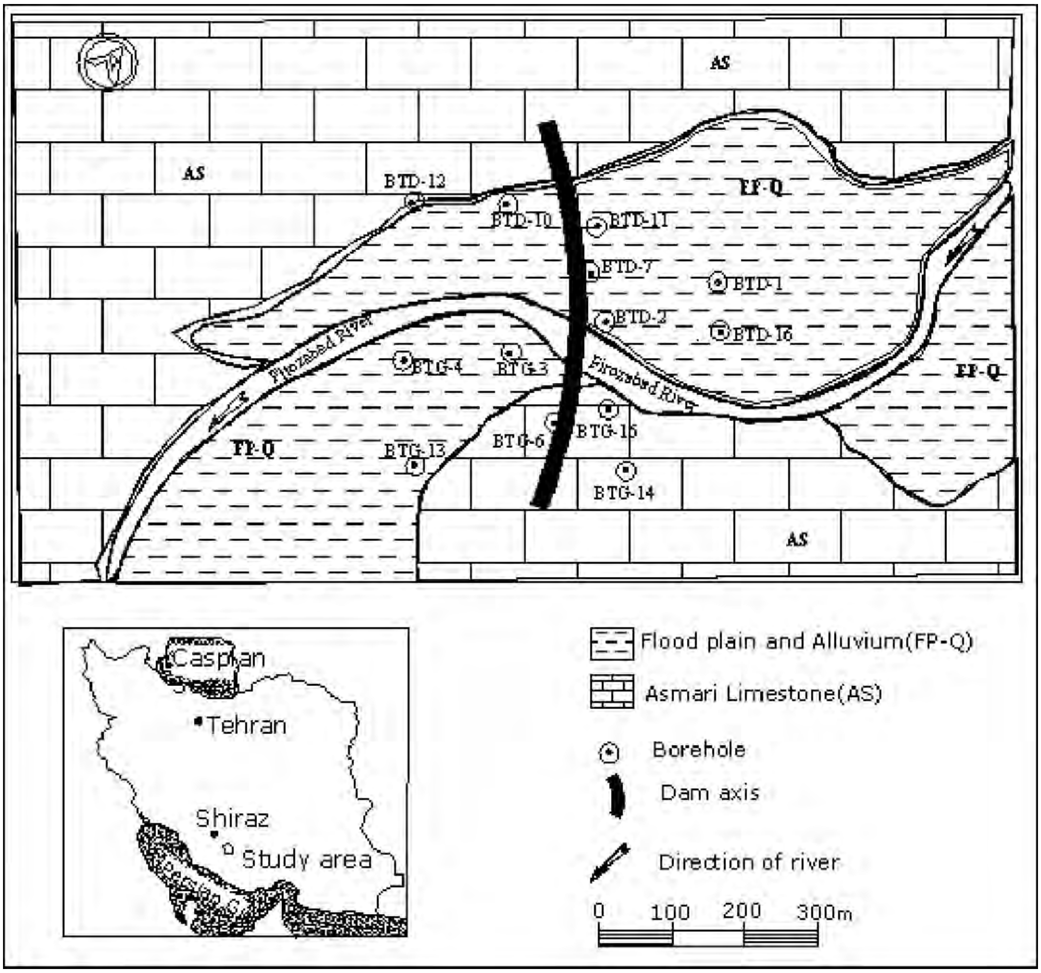

Figure 2. Location of the Tangab Dam and geologic map of the study area.

have formed along joints on the northern flank, 500 m and 100 m from the inlet of the valley. A 30 m deep shaft of 3 m diameter was discovered during tunnel excavation at the dam site. Injected dye tracers from boreholes of the right and left embankment were detected in the downstream springs.

The first dye tracing test was carried out by Asadi (1998) on the right bank. This study proved the hydrogeological connection between the dam site and the main springs of Tangab gorge. Evaluated average flow velocities are from 21 to 200 mh^{-1} (Asadi, 1998).

The second tracing test was executed by Talaie (1999). This test concludes that the main passage of water flow is from the reservoir through the left abutment of the dam site in the direction of the river. None of these studies reveal conduit flow from the right to the left bank of the dam, but there could be a conduit flow connection from the left bank of the dam to the springs downstream of the dam axis (Talaie, 1999). Therefore, despite a dominant diffuse-flow system close to the dam site based on boreholes and galleries observations, discovered caves and shaft and tracing tests results reveal the possibility of a conduit-flow system. The quantitative analysis of uncertainty associated with estimation of leakage is conducted for two simple one-dimensional flow conditions, including diffuse and conduit, in the following sections.

Diffuse Flow System

Assuming a one-dimensional diffuse-flow system, water leakage is estimated using the Darcy equation (Equation 1). Uncertainty associated with leakage is analyzed for two scenarios of dam construction: with and without any grout curtains. The input parameters in this analysis are permeability, hydraulic gradient, and cross-sectional area (k, i and A in Equation 1).

In the first scenario (construction of the dam without grout curtain), probable leakage is calculated using the Darcy equation by applying the DPD method to produce all cross combinations of permeability, hydraulic gradient and cross-sectional area. Permeability was measured in 13 boreholes (Fig. 2) by the Lugeon method. The Lugeon test was done during drilling operation in sections of 5 m in depth in all boreholes. A total of 261 Lugeon tests were performed in these boreholes. Permeability ranges from 1

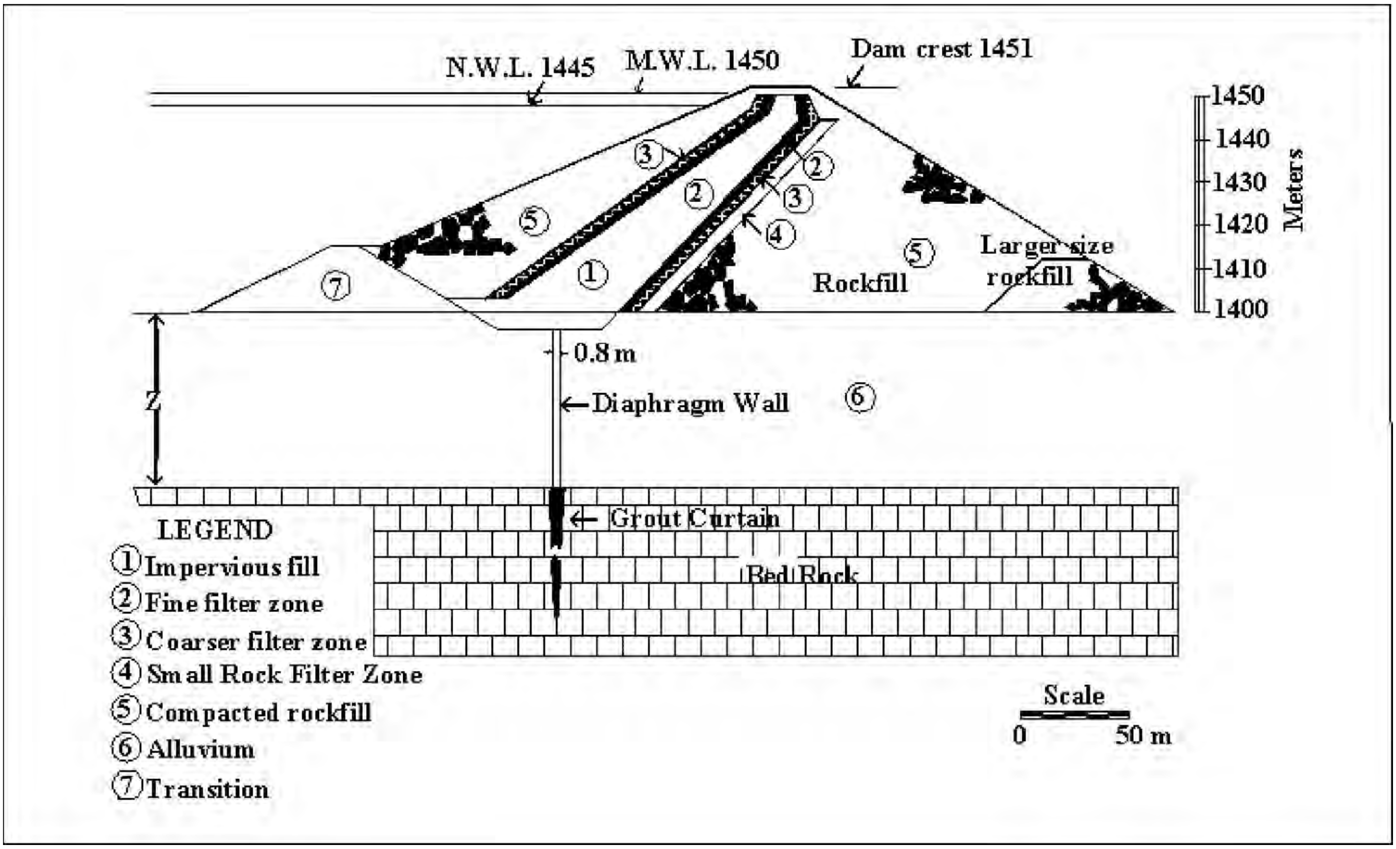

Figure 3. Typical cross section of the Tangab Dam and foundation.

to more than 100 Lugeon units. About 48% of permeability values are less than 5 Lugeon units and 17% are more than 50 Lugeon units.

Water levels were observed to range from 1370 to 1374 m above Mean Sea Level (MSL) close to the dam axis. The hydraulic gradient before construction at Tangab Dam site was around 0.001 using isopotential maps (Nadri, 1999). Both banks are recharged by the river based on the isopotential maps. After construction of Tangab Dam, normal water level at the reservoir will be 1445 m above MSL, and maximum water head difference between upstream and downstream from dam axis (at a distance about 110 m) will be about 75 m. Consequently, maximum hydraulic gradient will be about 0.6. Random data for hydraulic gradient were generated between the lower limit (0.001 before dam construction) and the upper limit (0.6 after dam construction without grout curtain).

The reservoir will be in contact with Asmari Limestone beyond the designed grout curtain (Fig. 4) at both abutments and depth. Assuming normal water level in

Table 1. Technical characteristics of the Tangab Dam.

Purpose	Flood Control and Irrigation
Type	Rock-fill embankment with clay core
Embankment volume	1.4 million m^3
Crest length	270 m
Crest width	10 m
Crest elevation	1452.5 m above MSL
Height from foundation	55 m
Height from river bed	51 m
Maximum water level	1451 m above MSL
Normal water level	1447 m above MSL
Reservoir volume at maximum water level	130 km^2
Reservoir volume at normal water level	10 km^2

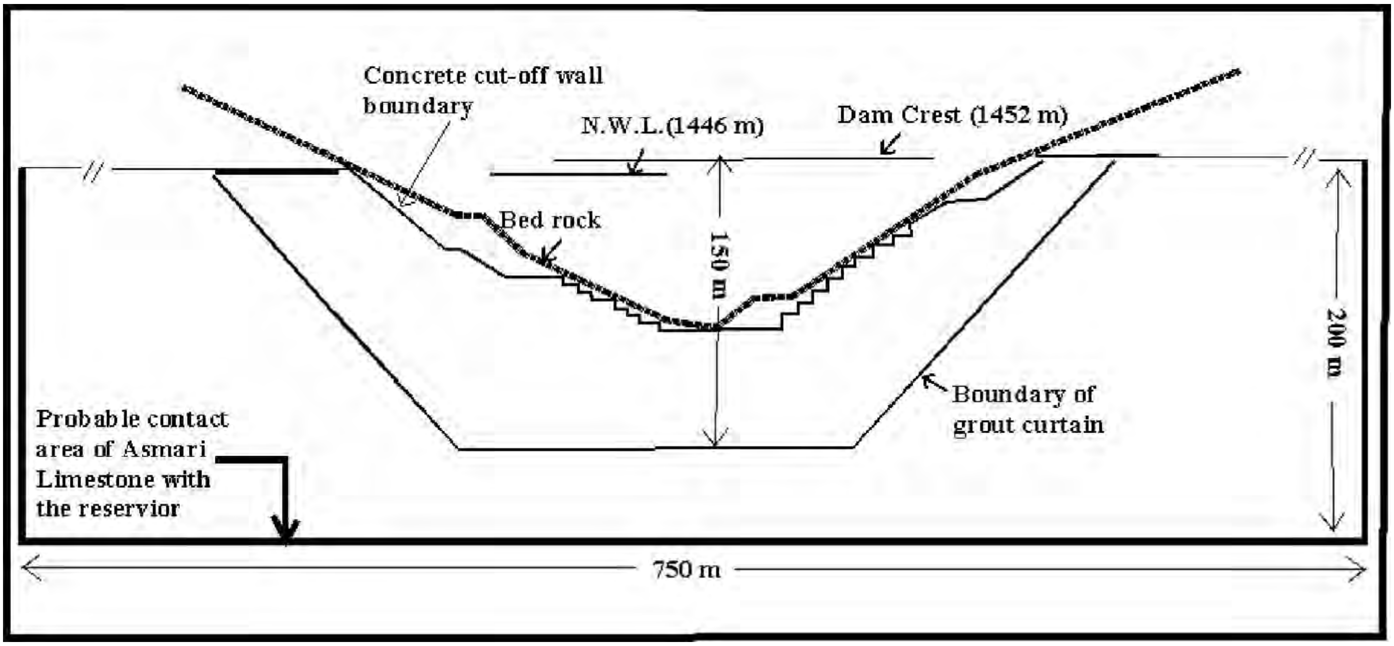

Figure 4. Dimension of grout curtain at the Tangab Dam and probable cross sectional area of leakage.

the reservoir, the probable cross section of leakage along the dam axis is estimated to be 750 m length (at both abutments) and 200 m depth according to outcrop of Asmari limestone at abutments of the dam site. The cross section area of the Tangab gorge (35 m high × 200 m wide) along the dam axis should be subtracted from this area (Fig. 4).

The probability distribution of estimated leakage is lognormal. Statistical parameters are presented in Table 2. The mean and maximum leakage rates are about 0.2 and 1.5 $m^3\ s^{-1}$, respectively. The maximum value of leakage was calculated using the maximum values of permeability and hydraulic gradient. The maximum permeability is 22 times more than the average, and 90% of the permeability data are less than the maximum value. Therefore, maximum leakage is not a true representation of the diffuse leakage flow. The mean leakage at 95% confidence interval (0.19 ± 0.05 $m^3\ s^{-1}$) can be considered as the most reliable leakage value.

The second scenario is the construction of the Tangab Dam with 270 m grout curtains in the right and left abutments (Fig. 4). Permeability data are identical to the first scenario. However after construction of the dam with designed grout curtain, the hydraulic gradient will be decreased to 0.1 because the length of leakage flow between upstream and downstream from the dam axis will be increased due to construction of the grout curtain. Therefore, hydraulic gradient ranges from 0.001 (before dam construction) to 0.1 (after construction of dam with grout curtain).

The probable cross sectional dimension of leakage is the assumed total contact area of the reservoir with the Asmari limestone at both abutments and depth minus the areas that will be blocked by construction of the grout curtain (Fig. 4). The statistical parameters of the uncertainty analysis are presented in Table 3.

The mean probable leakage is estimated equal to 0.2 ± 0.005 $m^3\ s^{-1}$. The mean probable leakage in the second

Table 2. Statistical parameters of leakage uncertainty without grout curtains at diffuse flow system (First strategy: $i = 0.001$–0.6).

Statistical Parameters	Permeability ($m\ s^{-1}$)	Hydraulic gradient (dimen.)	Probable leakage ($m^3\ s^{-1}$)
Minimum	1.70×10^{-7}	0.001	4.86×10^{-5}
Mean	4.10×10^{-6}	0.296	0.19
Maximum	8.90×10^{-5}	0.6	1.51
Variance	5.05×10^{-11}	0.044	0.51
Skewness	1.4	−0.054	2.51
Conf. Interval (95%)	1.00×10^{-6}	0.041	0.048
Coeff. of Variation	1.6	0.709	2

Table 3. Statistical parameters of leakage uncertainty with grout curtains at diffuse flow system (Second strategy: $i = 0.001$–0.6).

Statistical Parameters	Permeability (m s^{-1})	Hydraulic gradient (dimen.)	Probable leakage (m^3 s^{-1})
Minimum	1.70×10^{-7}	0.001	3.16×10^{-5}
Mean	4.10×10^{-6}	4.90×10^{-2}	0.02
Maximum	8.90×10^{-5}	0.01	0.16
Variance	5.05×10^{-11}	1.16×10^{-3}	1.74×10^{-3}
Skewness	1.46	0.02	2.54
Conf. Interval (95%)	1.00×10^{-6}	6.66×10^{-3}	5.17×10^{-3}
Coeff. of Variation	1.57	0.69	2.03

strategy reduces to less than 88% of the value estimated in the first strategy. This emphasizes the effectiveness of a grout curtain in a diffuse flow system. However, both strategies in diffuse flow system imply that the amount of leakage in the Tangab Dam site is not significant (less than 5% of mean annual discharge of Firozabad River), and that the dam may be constructed without the necessity of grout curtains, assuming diffuse flow.

Conduit Flow System

In spite of absence of solution cavities and major conduits in boreholes, two caves and shafts at the left embankment of the Tangab Dam, and the results of dye-tracing tests reveal that a conduit system exists at the study area. The probable leakage in a one-dimensional conduit flow system is estimated using the Darcy-Weisbach equation (Equation 2) for a single conduit in two scenarios of dam construction: with and without a grout curtain. The input parameters are hydraulic gradient, diameter of conduit, and friction factor (i, d, and f in Equation 2).

In the first scenario, hydraulic gradient ranges from 0.001 before, to 0.6 after, construction of the dam without a grout curtain. The lower limit of the conduit cross section is assumed to be the threshold of the turbulent flow, which occurs around the conduit having 0.5 cm diameter for commonly observed hydraulic gradient (White, 1988). The upper limit of the conduit cross section is very difficult to determine in a complex karst system. The cross section of the caves in the left abutment of the Tangab Dam ranges from a series of small openings in the end of the caves to more than 12 m^2. The smallest cross section along the flow path from inlet to outlet controls the leakage. The uncertainty is analyzed under four single upper limits of conduit diameters equal to 0.5, 1, 2, and 4 m. The lower and upper limits of friction factor are assumed to be 0.01 and 0.1 (Ford and Williams, 1989).

The probability distribution of generated random data of hydraulic gradient, friction factor and conduit diameter is evaluated to be normal (Table 4). The Darcy Weisbach equation (Equation 2) is used to calculate the probable leakage by means of DPD method for all the combinations of the input parameters.

The statistical parameters of the leakage probability distribution function in the first strategy are presented in Table 4. The mean of probable leakage at 95% confidence interval is about 0.8 ± 0.1, 4.67 ± 0.64, 19 ± 2.7 and 131 ± 17 m^3 s^{-1} for a single cross section with diameter of 0.5, 1, 2, and 4 m, respectively. All values of leakage are more than 10% of mean annual discharge of Firoozabad River.

Leakage is strongly dependent on the conduit cross sectional area. The leakage of a 4 m diameter conduit (cross section area of 12.5 m^2) is 163 times more than the leakage of 0.5 m diameter conduit (cross sectional area of 0.2 m^2) while the cross sectional area ratio is 60. This implies that the uncertainty increases with the increase of conduit dimension. It can be concluded that information regarding the dimension and number of major conduit systems can decrease leakage uncertainty.

In the second scenario (construction of dam with grout curtain), all the input parameters are identical to the first scenario except hydraulic gradient that ranges from 0.001 before to 0.1 after construction of dam, respectively. The statistical parameters of probable leakage are presented in Table 5. The mean probable leakage at 95% confidence interval is about 0.33 ± 0.04, 1.94 ± 0.25, 8 ± 1.1 and 54.6 ± 7 m^3 s^{-1} for a single cross section with diameter of 0.5, 1, 2, and 4 m, respectively.

The mean leakage decreases to less than 50% of the mean leakage obtained when the dam is constructed without grout curtains. The effectiveness of grout curtains depends on the lack of major conduits outside the grout curtain area. Detailed studies on stratigraphic and tectonic settings, karst hydrogeology, geomorphology, speleogenesis, and several dye tracings outside the proposed grout curtain area can determine the karst development and existence of possible conduits in this region, and help to reduce leakage uncertainty (Mohammadi et al., 2007).

CONCLUSIONS

Leakage from dam sites has been reported in numerous dams in karst areas. The estimation of leakage (i.e., location, path and quantity) can have errors due to uncertainties in the non-homogenous nature of a karst

Table 4. Statistical parameters of leakage uncertainty without grout curtains at conduit flow system (First strategy $i = 0.001$–0.6) for maximum conduit diameters of 0.5, 1, 2, and 4 m.

Statistical parameters	Hydraulic gradient	Friction factor	Conduit diameter alternatives				Probable leakage ($m\ s^{-1}$)			
			D_1[a]	D_2[b]	D_3[c]	D_4[d]	D_1[a]	D_2[b]	D_3[c]	D_4[d]
Minimum	0.001	0.01	0.005	0.005	0.005	0.005	0.0045	0.0045	0.0045	0.0045
Mean	0.296	0.057	0.252	0.48	0.99	2.01	0.8	4.67	19	131
Maximum	0.6	0.1	0.5	1	2	4	3.04	16.7	74	472
Variance	0.044	7.9×10^{-4}	0.031	0.12	0.49	2.1	0.76	26.3	481	20,138
Skewness	−0.054	−0.07	−0.06	−0.09	−0.1	−0.3	1.2	0.6	0.9	1
Conf. Interval (95%)	0.041	5.5×10^{-3}	0.034	0.047	0.13	0.28	0.1	0.64	2.7	17
Coef. of Variation	0.709	0.49	0.6	0.69	0.8	0.9	1.1	1.9	2.4	3.2

[a] D_1 = Conduit diameter ranges from 0.005 to 0.5 m.
[b] D_2 = Conduit diameter ranges from 0.005 to 1.0 m.
[c] D_3 = Conduit diameter ranges from 0.005 to 2.0 m.
[d] D_4 = Conduit diameter ranges from 0.005 to 4.0 m.

formation and conventional methods of study (boring and geological mapping). An uncertainty analysis requires a significant amount of data as input. Data collection is expensive and time consuming, particularly in complex non-homogenous karst dam sites. Therefore, in the case of limited data, a qualitative uncertainty analysis can be applied.

All obtained information about karst development based on the measurements and tests in the boreholes may contain uncertainty. Karst development is a heterogeneous process making the detection of critical leakage zones difficult. Boreholes are representative of only a small fraction of karst-aquifer area, and the chances of missing large caves are high. The probability of a borehole tapping major conduits is also low, because the conduit systems occupy a low percentage of a karst aquifer. Therefore, the flow in a diffuse system is mainly indicated by water-table configuration (isopotential map), and conduit flow is not apparent. Dye tracing is a point-to-point process, and it is dependent on the location of the injection and sampling points. Therefore, major karst conduits may be missed. The dye may dilute significantly to the extent that it cannot be detected at the sampling points. Furthermore, karst conduits are small in size and they cannot be located precisely based on geological maps. Karst aquifers contain both diffuse and conduit flow regimes. It is a very difficult task to determine the percentage of diffuse and conduit flow and the cross section of the conduit. Therefore, great uncertainty is inherent in model selection.

In this study, quantitative uncertainty analysis was carried out on one-dimensional diffuse and conduit flow systems for two different strategies of construction of the

Table 5. Statistical parameters of leakage uncertainty without grout curtains at conduit flow system (Second strategy $i = 0.001$–0.1) for maximum conduit diameters of 0.5, 1, 2, and 4 m.

Statistical Parameters	Hydraulic gradient	Friction factor	Conduit diameter alternatives				Probable leakage ($m\ s^{-1}$)			
			D_1[a]	D_2[b]	D_3[c]	D_4[d]	D_1[a]	D_2[b]	D_3[c]	D_4[d]
Minimum	0.001	0.01	0.005	0.005	0.005	0.005	0.0044	0.0044	0.0044	0.0044
Mean	4.90×10^{-2}	0.057	0.252	0.48	0.99	2.01	0.33	1.94	8	54.6
Maximum	0.01	0.1	0.5	1	2	4	1.24	6.85	30.2	193
Variance	1.16×10^{-3}	7.9×10^{-4}	0.031	0.12	0.49	2.1	0.12	4.1	76.5	3184
Skewness	0.02	−0.07	−0.06	−0.09	−0.1	−0.03	1.2	1	1.3	1
Conf. Interval (95%)	6.66×10^{-3}	5.5×10^{-3}	0.034	0.047	0.13	0.28	0.04	0.25	1.1	6.9
Coef. of Variation	0.69	0.49	0.6	0.69	0.8	0.9	1	1.3	1.8	2.3

[a] D_1 = Conduit diameter ranges from 0.005 to 0.5 m.
[b] D_2 = Conduit diameter ranges from 0.005 to 1.0 m.
[c] D_3 = Conduit diameter ranges from 0.005 to 2.0 m.
[d] D_4 = Conduit diameter ranges from 0.005 to 4.0 m.

Tangab Dam, the Zagros region, Iran, with and without any grout curtains. The input parameters are the probability distribution function of the measured permeability, cross-sectional area (with and without grout curtain), generated data of hydraulic gradient (lower and upper limits correspond to before and after dam construction, respectively), conduit diameter (ranging upward from turbulent flow threshold and observed caves and shafts at the Tangab Dam site), and friction factor.

The mean of probable leakage in diffuse flow system is not significant (less than 10% of the mean annual discharge of river), with or without grout curtains. The mean probable leakage could reduce to less than 88% and 50% in a diffuse flow and conduit flow system, respectively, due to construction of a grout curtain. Leakage uncertainty arises mainly from the conduit flow especially outside the grout curtain area. Conduits might develop at the normal water surface. Leakage is significantly dependent on the conduit diameter. Determination of conduit flow outside the grout curtain is the most important approach for decreasing leakage uncertainty. An extensive and detailed investigation on stratigraphic and tectonic settings, karst hydrogeology, geomorphology, speologenesis, and several dye tracings outside the proposed grout curtain area may succeed in locating the possible conduits in this region, and thus reducing the leakage uncertainty.

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J. G. Palacios-Vargas and J. C. S. Benito – A new genus and three new species of Neanuridae (Collembola) from North America. *Journal of Cave and Karst Studies,* v. 69, no. 3, p. 318–325.

A NEW GENUS AND THREE NEW SPECIES OF NEANURIDAE (COLLEMBOLA) FROM NORTH AMERICA

José G. Palacios-Vargas[1] and José Carlos Simón Benito[2]

Abstract: *Speleonura* n. g. (Neanurinae) and the type species *S. kenchristianseni* n. sp., are described and illustrated from Porter's Cave, Bath County, Virginia. The new genus is characterized by the lack of eyes and the presence of well developed tubercles on the head and body, it is similar to *Paleonura* but the shape and disposition of the tubercles differentiate the new genus from others Neanurinae. The other two species described are *Paleonura petebellingeri* n. sp. (Neanurinae) from Skyline Caverns, Warren County, Virginia, similar to *Paleonura anops* (Christiansen & Bellinger, 1980) but they differ in the chaetotaxy on abdominal segments, and *Morulina stevehopkini* n. sp. (Morulininae) from litter of Mitchell County, North Carolina, which is easy to distinguish from other members of the genus because of its strong hypertrichosis.

Introduction

During our recent studies on the Neanuridae from Mexico and Central America (Palacios-Vargas and Simón Benito, in press; Simón Benito and Palacios-Vargas, in press) we received specimens from Virginia and North Carolina that were in the collection of Dr. Kenneth A. Christiansen. The specimens were remounted and study revealed the presence of a new genus and three new species that were not included in the work of Christiansen and Bellinger (1980). In this contribution, we describe these new American taxa. Used herein is the chaetotaxy system of Deharveng and Weiner (1984), as modified in Palacios-Vargas and Simón Benito (in press).

Genus and Species Descriptions

New genus

Speleonura

The genus is characterized by the lack of eyes and the presence of well developed tubercles on the head and body. The head antennal and ocular tubercles are well developed and subdivided. Abdominal segment V with dorso-internal tubercles coalesce. These characters differentiate the new genus from the others in the family. The structure of the antennae shows that the new genus is a member of the subfamily Neanurinae. The type species is *Speleonura kenchristianseni* new species.

Discussion

The new genus shares the lack of eyes with some species of several other genera, such as *Chirolavia* Deharveng, 1991, *Galanura* Smolis, 2000, *Coecoloba* Yosii, 1956, *Nepalanura* Yosii, 1966 and *Echinanura* Carpenter, 1935. It also seems very similar to *Paleonura* sharing the presence of eight sensilla of similar size on antennal segment IV. However, the shape and disposition of the tubercles on the body differentiate the new genus from other Neanuridae.

New species

Speleonura kenchristianseni

Length 550 µm. Color under slide white. Cuticular granulation strong. Tubercles well developed on head and body; on thoracic segment I dorso-internal and dorso-lateral undeveloped, on thoracic segment II and III dorso-lateral undeveloped. Each tubercle subdivided into 2 to 5 small bosses each with strong granulation. Body setae consisting of thick macrosetae with acuminate tip, thin microsetae, in addition to sensorial setae (Fig. 1e, 1f).

Antennal segment I with seven setae, antennal segment II with 11 setae. Antennal segment III sensorial organ with two globular sensilla in a cuticular fold, and two guard sensilla. Ventral sensilla of guard straight, one microsensillum ventro-external. Antennal segment IV with eight similar sensilla (Fig. 1b).

Eyes absent. Mandibles with three teeth (Fig. 1c), maxillae styliform (Fig. 1c). Antennofrontal tubercle subdivided into six subtubercles; setae C and E not on tubercle. Ocular tubercles well developed, each with about six subtubercles, and three setae. Tubercles dorso-internal and dorso-external well developed, dorso-internal with 1 seta and the dorso external 3 setae (Fig.1a).

Coxae I-III with 3, 5 and 6 setae on fore leg, middle leg and hind leg, respectively; trochanters with 6,6,5 setae; femora with 12,12,11 setae. Tibiotarsi I, II and III without tenent hairs; with 19, 19, and 18 setae, respectively. Unguis untoothed. No empodial appendage. Thoracic and abdominal chaetotaxy as in Figs. 1e and 1f. The total dorsal chaetotaxy is shown in Table 1.

Ventral tube with 3 + 3 setae subequal in size. Furcula vestigial with 5 setae and 6 microsetae (Fig. 1g). Female

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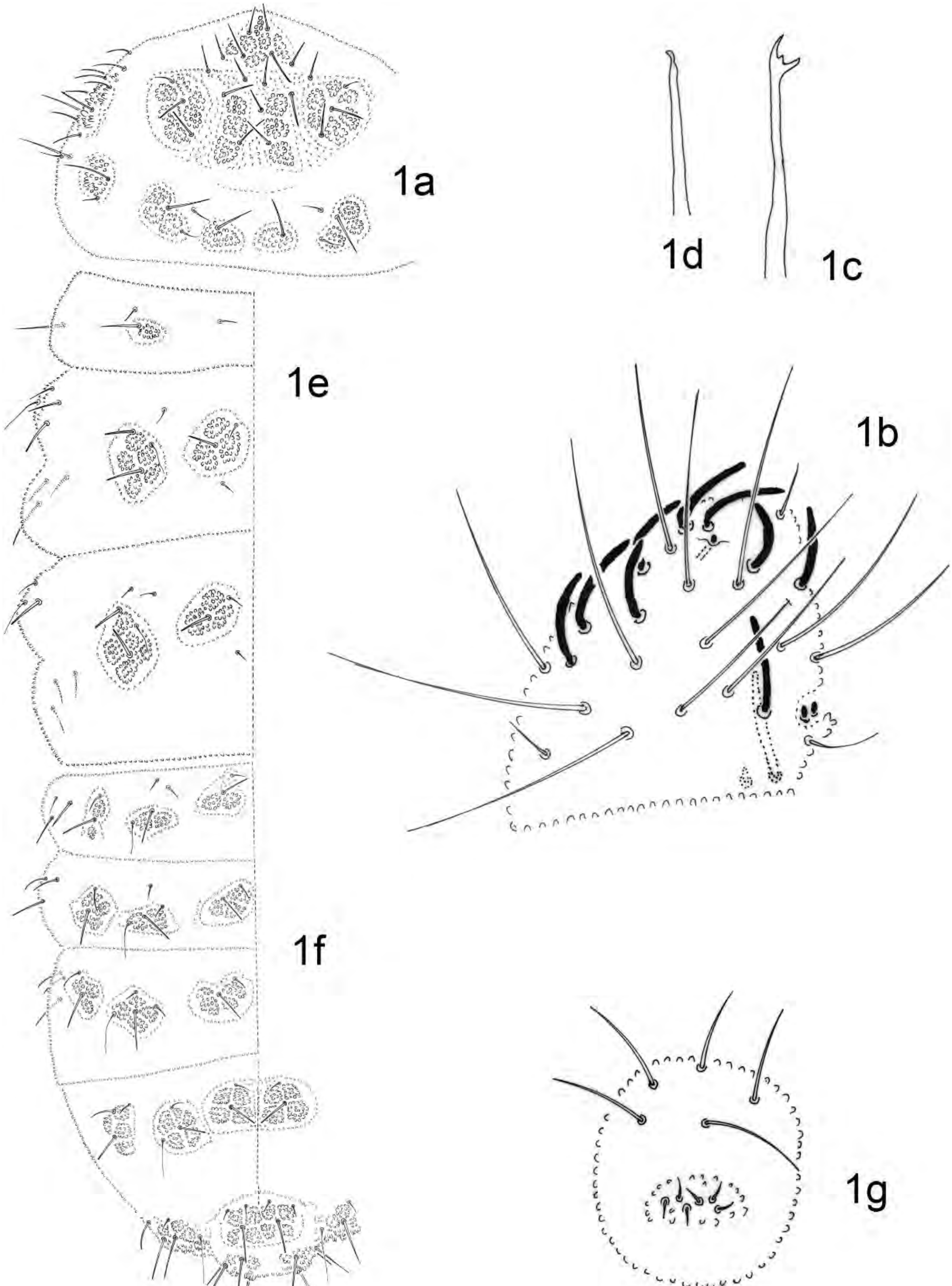

Figure 1. ***Speleonura kenchristianseni*** **n.sp. 1a, dorsal chaetotaxy of head; 1b, dorsal chaetotaxy of Ant. III and IV; 1c, mandible; 1d, maxilla; 1e, thoracic chaetotaxy; 1f, abdominal chaetotaxy; 1g, furcal vestige.**

Table 1. Total dorsal chaetotaxy of *Speleonura kenchristianseni* n. sp.

Head setae group	Tubercles	Number of setae	Kind of setae	Setae
Cl	1	3	M, M	FGD
Af	1	5	M	AB,OCE
Oc	2	3	m, M, M	Oca, Ocm, Ocp
Di	2	1	M	Di1
De	2	3	M, m, m	De1, De2, Di2
DL + L + Sc	2	13-14	M, m; 3M, 3m;2M, 3m	
Total amount	10	29		

Thorax	Di	De	DL	L
I	m	M, m	M	…
II	M, 2m	2M,m+s	2M,m+s+ms	M,2m
III	M, 2m	2M,2m+s	2M,2m+s ?	M,2m
Abdomen				
I	M,m	M,2m+s	M,m	2M,m
II	M,m	M,2m+s	M,m	M,2m
III	M,m	M,2m+s	M,m	2M,2m
IV	M,m	M,m+s	2M,m	7m
V	M, 2m	3M,m+s		
VI	5M, 2m			

Abbreviations: Af (antennofrontal), Cl (clypeal), De (dorso external), Di (dorso internal), DL (dorso lateral), L (lateral), M, macroseta; m, microseta; Oc (ocular), Sc (Subocular), Oca (Ocular seta anterior), Ocm (Ocular seta median), Ocp (Ocular seta posterior), s (sensorial seta).

genital opening with 2 + 2 pregenital, 20 circumgenital, and 2 eugenital setae.

Discussion

The new species has some similarities with species of the Nearctic *Paleonura*, in the general shape of the body, kinds of body setae, and number of setae on the vestigial furcul tubercle. However, the presence of well developed tubercles clearly separates it from *Paleonura* spp. This specimen was previously identified as a *Neanura* sp., but *Neanura* has three eyes per side and the dorso-internal tubercles are separate on abdominal segment IV.

Etymology. This species is named for Dr. Kenneth A. Christiansen, Grinnell College, Iowa, for his contribution to the study of Collembola.

Material. Porter's Cave, Bath County, Virginia, David Hubbard Col., holotype female. Slide 7874 in the Christiansen collection, at Grinnell College, Grinnell, Iowa.

New species

Paleonura petebellingeri

Length (n = 3) 825 µm (range 570 – 1050 µm). Color white under slide. Granulations very fine, except for small areas around some setae. Cuticular granulation stronger in dorso-internal region of abdominal segment V. Tubercles poorly developed, apparent only on posterior abdominal segments (Fig. 2f). Body setae consisting of thick macrosetae with thick tip, and thin microsetae, besides the sensorial setae (Fig. 2a).

Antennal segment I with seven setae, antennal segment II with 11 setae. Antennal segment III sensorial organ with two globular sensilla in a cuticular fold, and two guard sensilla. Ventral guard sensillum almost straight, one microsensillum ventro-external. Antennal segment IV with eight similar sensilla, except for S1, which is smaller than the others (Fig. 2b).

Eyes absent. Mandibles with three teeth (Fig. 2c), maxillae styliform (Fig. 2d). No head tubercles developed. Ocular area with three setae, one microseta and two macrosetae. Head chaetotaxy in Fig. 2e.

Coxae I-III with 3, 5 and 6 setae; trochanters with 5,5,5 setae; femora with 12,11,10 setae. Tibiotarsi I, II and III without tenent hairs, with 18, 18, and 17 setae respectively. No empodial appendage. Thoracic and abdominal chaetotaxy in Figures 2a and 2f. The total chaetotaxy is shown in Table 2.

Ventral tube with 4 + 4 setae. Furcula vestigial with 5 setae and 6 microsetae (Fig. 2g). Female genital opening with 3 + 3 or 4 + 4 pregenital setae, 13-10 circumgenital setae and 2 eugenital setae. Each anal tubercle with 12 macrosetae and 2 microsetae.

Discussion

We place this new species in the genus *Paleonura* because of the lack of blue pigment and eyes, the presence of dorso-internal setae on abdominal segment V, and the clear separation of dorso-internal and dorso-external

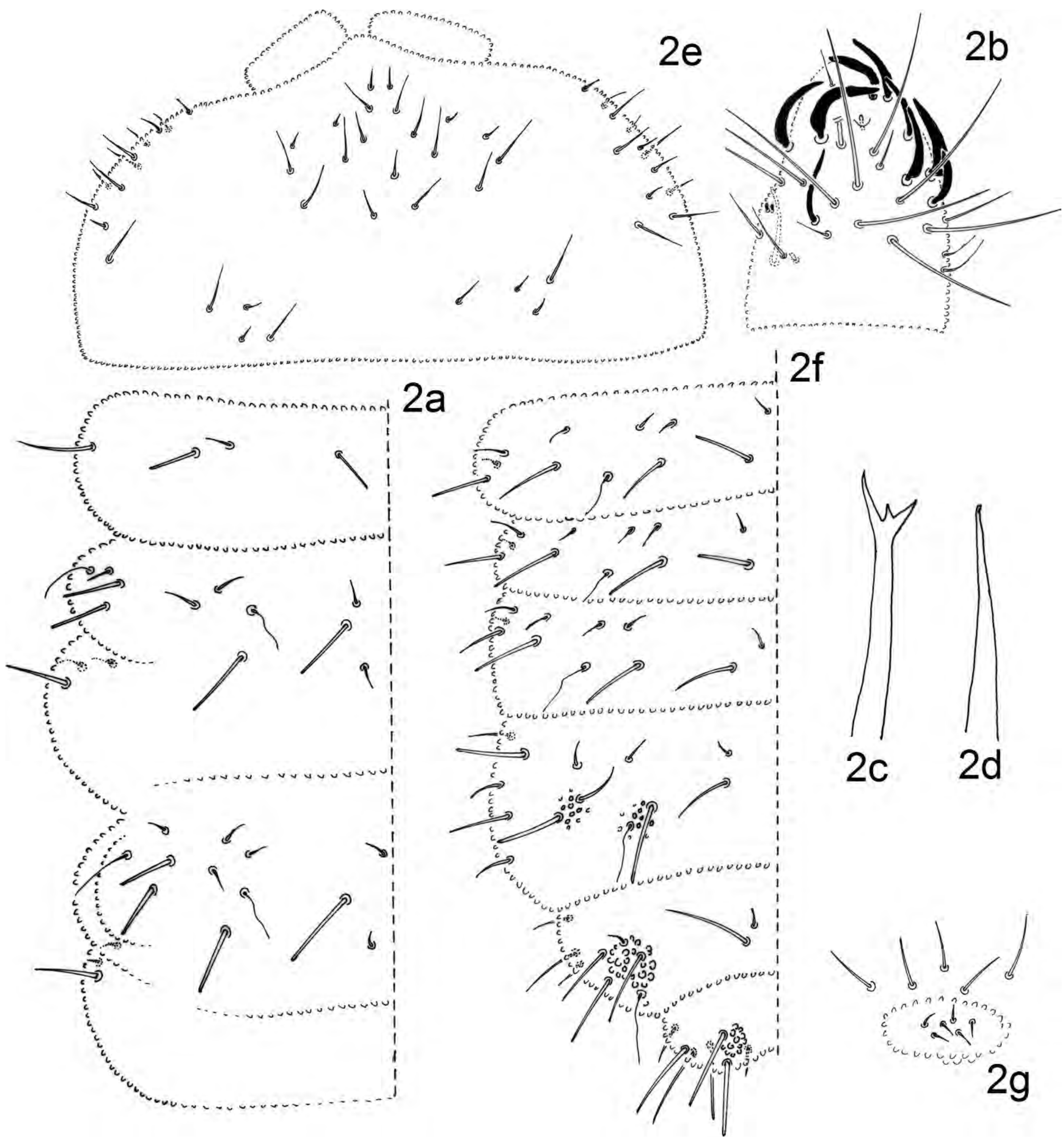

Figure 2. *Paleonura petebellingeri* n. sp. 2a, thoracic chaetotaxy; 2b, dorsal chaetotaxy of Ant. III and IV; 2c, mandible; 2d, maxilla; 2e, head chaetotaxy; 2f, abdominal chaetotaxy; 2g, furcal vestige.

tubercles. It appears more closely related to *Paleonura anops* (Christiansen and Bellinger, 1980). Both species lack eyes and have a vestigial furcula represented only by 3 + 3 microsetae. However on *P. petebellingeri* the sensillum 1 on antennal segment IV is smaller than the others. Another difference between the species is the chaetotaxy on abdominal segments; in *P. petebellingeri* the dorso-internal tubercle of abdominal segment V, has one macroseta and one microseta, while *P. anops* has one macroseta and two microsetae. In *P. petebellingeri* tubercle dorso-external has three macrosetae and one microseta, but *P. anops* has two macrosetae and three microsetae.

Table 2. Total dorsal chaetotaxy of *Paleonura petebellingeri* n. sp.

Head setae group	Tubercles	Setae number	Kind of setae	Setae
Cl	···	2	M, m	FG
Af	···	4 + 1	3M, m	ABCD, 0
Oc	···	3	M, M, M	Oca, Ocm, Ocp
Di	···	1	M	Di1
De	···	3	M, m, m	De1, Dde2, Di2
DL + L + Sc	···	13	2M, 2m; 3M, 6m	
Total amount		27		

Thorax	Di	De	DL	L
I	M	M, m	M	···
II	M, 2m	M,2m+s	2M,m+s+ms	M,2m
III	M, 2m	M,3m+s	2M,m+s	M,2m
Abdomen				
I	M,m	M,2m+s	M,m	M,2m
II	M,m	M,2m+s	M,m	M,2m
III	M,m	M,2m+s	M,m	M,2m
IV	M,m	M,m+s	2M,m	2M, 2m
V	M, m	3M,m+s	M,2m	
VI	7 (5M, 2m)			

Abbreviations: Af (antennofrontal), Cl (clypeal), De (dorso external), Di (dorso internal), DL (dorso lateral), L (lateral), M, macroseta; m, microseta; Oc (ocular), Sc (Subocular), Oca (Ocular seta anterior), Ocm (Ocular seta median), Ocp (Ocular seta posterior), s (sensorial seta).

Variation. Some cases of asymmetries were observed on abdominal segment II: dorso-lateral with one seta present and one microseta missing, lateral with only one microseta instead of two. Abdominal segment I dorso-lateral of one specimen has one macroseta, instead of one macroseta and one microseta.

Etymology. This species is named in memory of Dr. Peter F. Bellinger, for his contributions on the Collembola.

Material. Skyline Caverns, Warren County, Virginia, January 22, 1995, David Hubbard Col., Holotype female (slide 7806) and two paratype females (slides 7806 and 7792) from the Christiansen collection at Grinnell College, Grinnell, Iowa. In cave soil. 7806 specimens collected on 3-16-1995; 7792 collected on 1-22-1995.

New species

Morulina stevehopkini

Length (n = 2) 2.2 mm. Color black, ventral side dark gray. Eyes very dark. Habitus convex, typical of the genus. Tubercles very well developed, forming rather semispherical structures with granulation and reticulations. Macrosetae with blunt tip and fine serrations, microsetae thin, smooth, and sensorial setae, difficult to distinguish (Fig. 3a).

Antennal segment I with 24 setae and few reticulations (Fig. 3b), antennal segment II with 26 setae. Antennal segment III with 24 setae; only two guard setae of the sensorial organ observed (Fig. 3c). Antennal segment IV with about 65 very small dorsal setae and poorly defined bilobulate apical bulb, without differentiated sensilla (Fig. 3b). Labrum with 4/4,5,4 smooth setae of different sizes (Fig. 3d). Mouth cone long, labium with10 pairs of setae (Fig. 3e), labial organ absent. Maxilla with four reduced lamellae (Fig. 3f), mandible with three subequal apical teeth and one basal paired tooth (Fig. 3g).

Eyes 5 + 5 black (Fig. 3h), ocular tubercle with 6-7 ocular setae, three of them longer and thicker than the others. Postantenal organ moruliform with about 50 tubercles, slightly wider than the most proximal eye (Fig. 3h).

Coxae I-III with 2,9,? setae; trochanters with 6,8,8 setae; femora with 15, 15, 15 setae. Tibiotarsi I, II and III with 19, 19, and 18 setae respectively, two longest ventral setae longer hooked apically (Fig. 3i). Unguis with strong basal tooth. No empodial appendage.

Hypertrichosis strong dorsally and ventrally. Number of tubercles from thorax to abdomen IV are: 3,4,4/4,4,4,3. (Figs. 3a, 4a, 4b, 4c and Table 3).Tubercles with some microsetae. Ventral tube with 9 pairs of setae. Anal tubercle with about 35 setae (Fig. 4d). Vestigial furcula with 7 setae and 2 dens without mucro, each with one seta (Fig. 4e). Pregenital setae very abundant, about 75 (Fig. 4e). Female and male genital setae very small, more than 50.

Discussion

Morulina stevehopkini is easy to distinguish from other members of the genus because of the strong hypertrichosis it has. It shares with *M. gigantea* the presence of only one seta on each dens, but *M. stevehopkini* has a bigger postantenal organ, more ocular setae 6-7 (versus 3). The redescription of

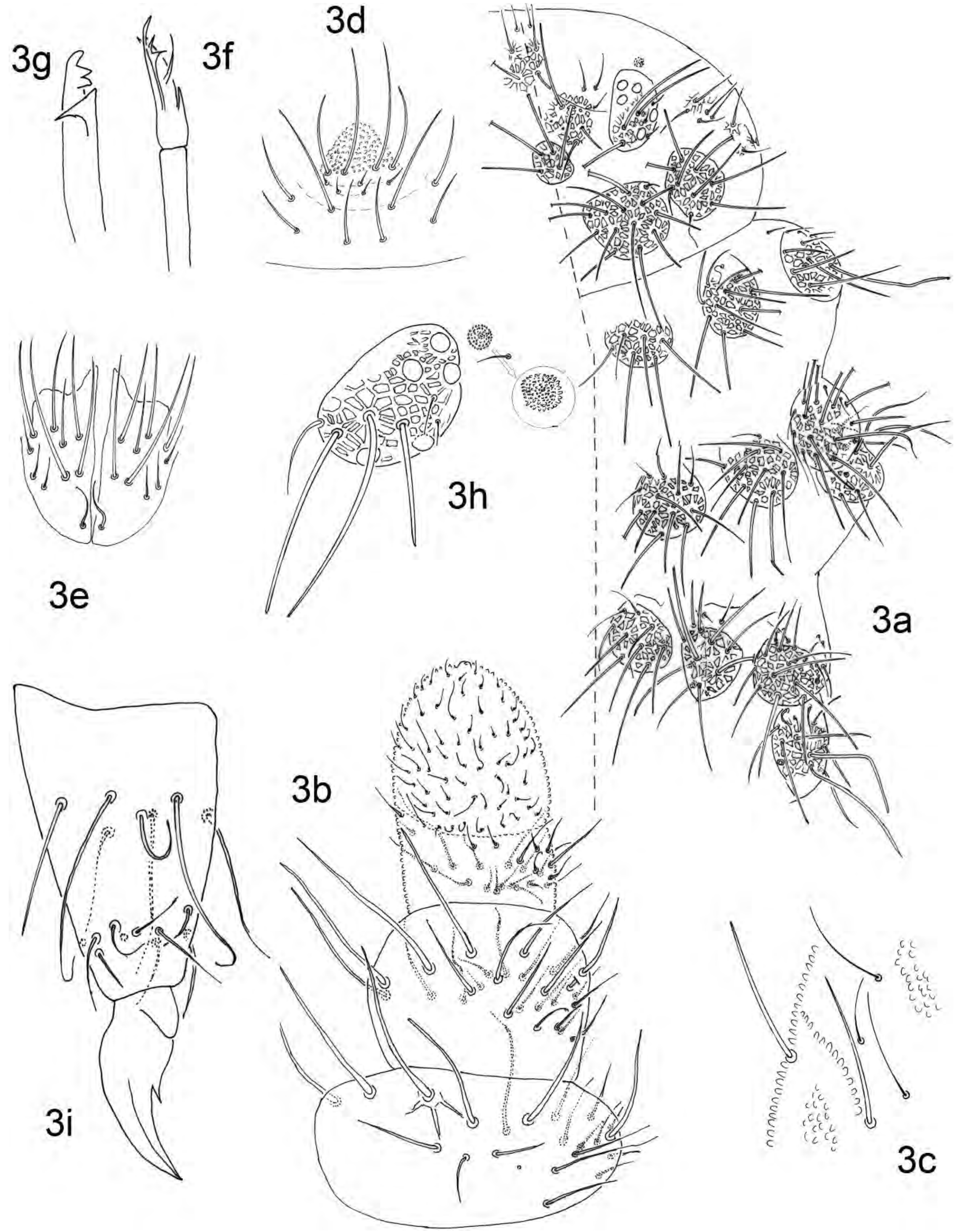

Figure 3. ***Morulina stevehopkini*** **n. sp. 3a, cephalic and thoracic chaetotaxy; 3b, Ant. from I to IV, dorsal view; 3c, sensorial organ of Ant. III; 3d, labrum; 3e, labium; 3f, maxillae; 3g, mandible; 3h, ocular tubercle with magnification of postantenal organ; 3i, tibiotarsus III.**

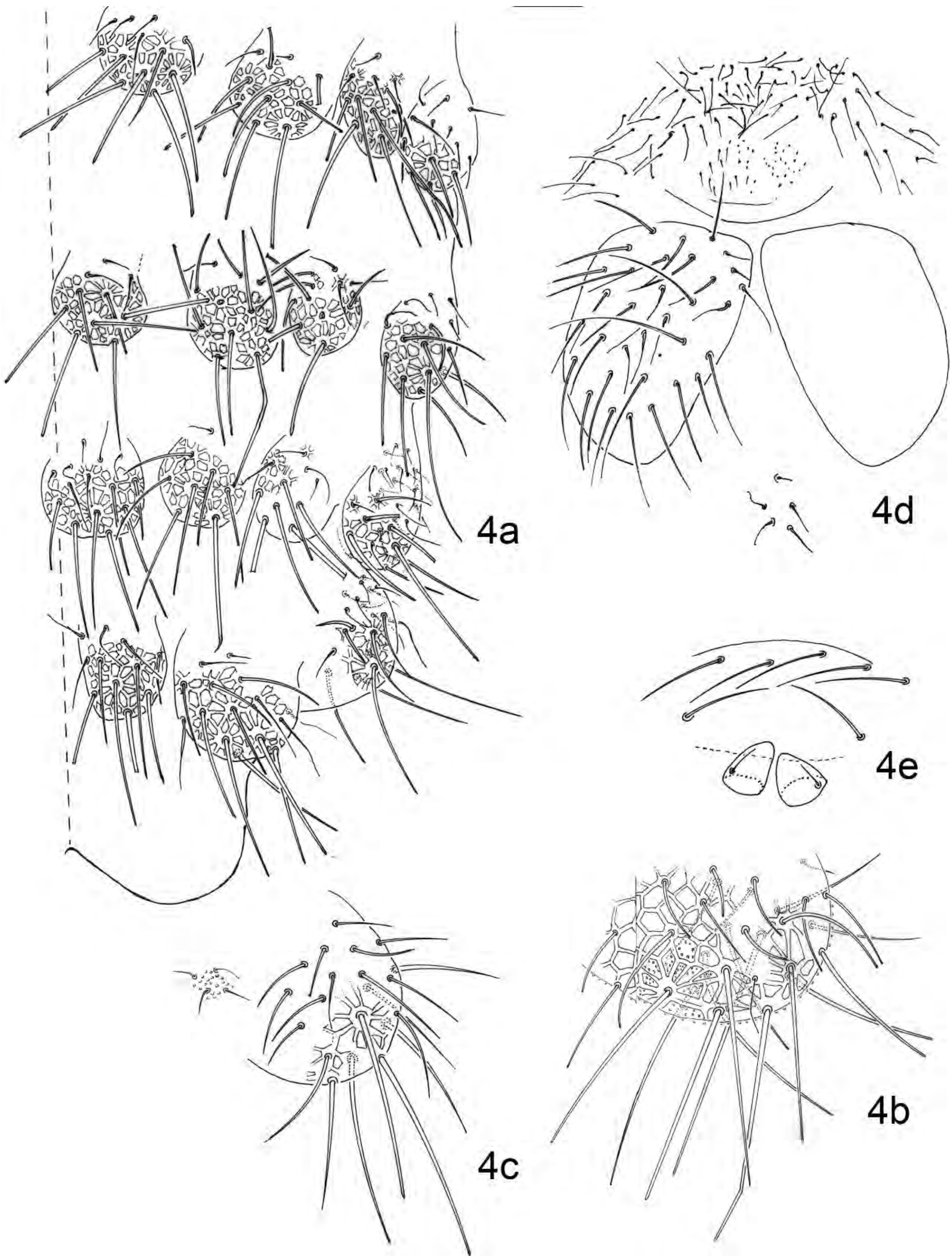

Figure 4. ***Morulina stevehopkini*** **n. sp. 4a, chaetotaxy of Abd. I to IV; 4b, tubercle of Abd. V; 4c, tubercle of Abd. VI, ventral view; 4d, anal tubercle and genital region; 4e, furcal vestige.**

Table 3. Total dorsal chaetotaxy of *Morulina stevehopkini* n. sp.

Head setae group	Tubercles	Setae number	Kind of setae	Setae
Cl	1	5	M	CDEFG
Af	3	4	M	AB
Oc	1	6	M, m	Oca, Ocm, Ocp
Di	1	13-15	M	
De	1	8-9	M	
DL + L + Sc	···	3 + 6	M, m	
Total amount		45 – 48		

Thorax	Di	De	DL	L
I	6-9	11-12	9-11	-
II	11-12	10-12	17-18	5-6
III	9-12	11-13	17-19	11-12
Abdomen				
I	12	9-12	9-11	9-12
II	10-14	11-13	8-11	13-14
III	14-15	8-11	10	13-21
IV	9-11	13-15	18	
V	23-27			
VI	15-20			

Abbreviations: Af (antennofrontal), Cl (clypeal), De (dorso external), Di (dorso internal), DL (dorso lateral), L (lateral), M, macroseta; m, microseta; Oc (ocular), Sc (Subocular), Oca (Ocular seta anterior), Ocm (Ocular seta median), Ocp (Ocular seta posterior).

M. gigantea by Fjellberg (1985) and *M. callowayia* by Yosii (1958) allows comparison with the new species *M. stevehopkini*. Most important differences are chaetotaxy of dorso-internal tubercle on the thoracic segment I (3-5, 12, 6-9 setae respectively) and the chaetotaxy of fused tubercles dorso-internal + dorso-external of abdominal segment V (13-16, 14, 23-27 setae respectively).

Etymology. Species named in memory of Dr. Stephen P. Hopkin, recently deceased, for his contribution to the biology of springtails (Collembola).

Material. Leaf litter, Bakersville, Mitchell County, North Carolina, August 24, 1981. K A. Christiansen Col., Holotype male (slide 7613), paratypes, one male (7613) and three females (7623) North Carolina Slide 7623 from Christiansen's collection at Grinnell College, Iowa, USA.

Acknowledgements

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PREGLACIAL DEVELOPMENT OF CAVES AT STRUCTURAL DUPLEXES ON THE LEWIS THRUST, GLACIER NATIONAL PARK, MONTANA

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Abstract: Two significant caves in Glacier National Park are developed in Middle Proterozoic carbonate rocks. One lies within two large-scale duplex structures resting on the Lewis Thrust. The other is in the hinterland region of one of the duplexes. Both of the caves are aligned along bedding planes, joints, and faults. Poia Lake Cave has large segments that, in part, are aligned along low-angle thrust faults. Both Poia Lake Cave and Zoo Cave have uptrending, dead-end passages developed above the main passage along near-vertical normal faults. In Poia Lake Cave, three small maze sections also lie above the main passage. My previous speleogenic model involving a semi-confined aquifer, with mixing zones along faults and fracture zones now seems unlikely because the strata would be unable to simultaneously confine the aquifer and allow descending water to mix along fracture zones and faults. A second model involving a deep-looping system, while more feasible, also seems unlikely due to the short flow length of postulated cave passages. Recent studies suggest cave development occurred under confined aquifer conditions whereby long-traveled deep water ascends from an artesian aquifer near the Lewis Thrust. The aquifer developed after the hinterland region of the Lewis Thrust was uplifted during the Laramide Orogeny. It remained active until the system was disrupted by late Pleistocene glacial erosion. Since the original phreatic development of the caves, they have been subjected to some collapse, vadose entrenchment, and deposition of clastic sediment including rounded cobbles and glacial varves.

Introduction

The origin of alpine caves in previously glaciated areas has classically been attributed to increased run-off from melting glaciers, higher precipitation during interglacial periods, or events in the Holocene (Hill et al., 1976; Warwick, 1976; Campbell, 1975). More recently, glaciers have been postulated to inhibit cave development (Audra, 2004), and many caves in alpine settings have origins that predate glaciation. Some alpine caves began as deep-phreatic looping systems that probably developed soon after uplift (Worthington, 2005). Others began as middle Tertiary artesian systems (Audra et al., 2003; Bodenhamer, 2006), and some began in semi-confined aquifers beneath impermeable strata that were partly removed prior to glaciation (Fernandez-Gilbert et al., 2000). Following initial development, many alpine caves were modified or enlarged by phreatic and vadose systems associated with warmer late Tertiary climates and Pleistocene interglacials (Audra, 2000). Large parts of some alpine caves have been removed during downcutting or have been filled during glacial advances (Audra, 2000; Ford et al., 1983; Schroeder and Ford, 1983).

Alpine caves in Glacier National Park were first studied by Campbell (1975, 1978b). Campbell mapped four caves in the park. He also identified stratigraphic and structural controls within Poia Lake Cave and proposed a model of speleogenesis in which the cave was formed entirely by vadose water during the Pleistocene (Campbell, 1975). Beginning in the fall of 2004 and ending in the summer of 2005, I supervised a cave mapping and monitoring project in Glacier National Park (BHS-OLEC, 2005). Part of this project included a preliminary geologic map of Poia Lake Cave and a history of development that began in the Pliocene as a semi-confined phreatic aquifer (Bodenhamer, 2006). In addition, the spatial orientation of Zoo Cave and other nearby caves were investigated and an inclusive model for their speleogenesis developed. The completed study provided geologic maps and descriptions of Poia Lake Cave and Zoo Cave and two competing models for the origin of both caves. One model involves downward flowing water in an unconfined phreatic aquifer, and the other involves upwelling water from a long-flowed artesian aquifer.

Setting

The caves discussed in this article are on the eastern edge of the Lewis Range in Glacier National Park, Montana (Fig. 1). The highest peak in the Lewis Range reaches an altitude of about 3200 m, and the plains just to the east of the caves are at about 1700 m. The Lewis Range is topographically rugged as a result of several episodes of glacial erosion, the earliest of which dates into the late Pliocene (Karlstrom, 1991). The crest of the Lewis Range

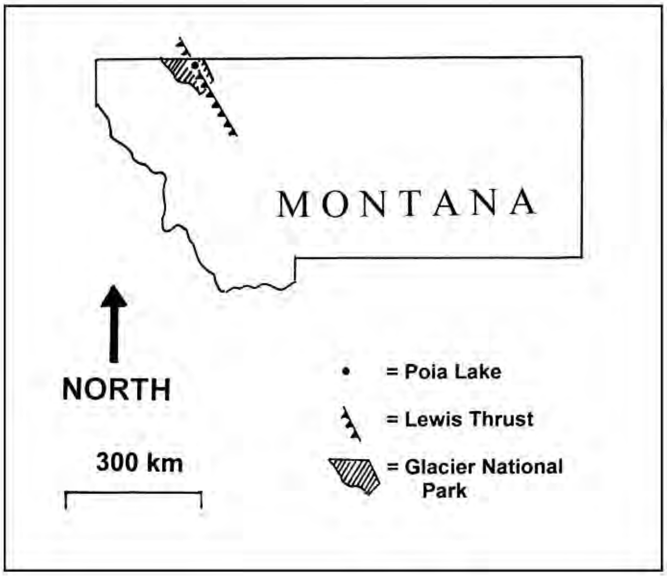

Figure 1. Location map of study area.

follows the eastern limb of the Akamina Syncline which sits atop the Lewis Thrust. The axis of the Akamina Syncline and the strike of the Lewis Thrust trend N40°W (Whipple, 1992). At its widest, the Akamina Syncline spans nearly 25 km. The trace of the Lewis Thrust follows the eastern front of the Lewis Range for nearly 100 km and is estimated to have a displacement on the order of 100 km (Price and Montjoy, 1970). Above the Lewis Thrust, the Lewis Range is composed of Middle Proterozoic sedimentary and metasedimentary rock, which attain a thickness of more than 9000 m. As viewed from the east of Glacier National Park, the Lewis Thrust has driven massive Middle Proterozoic carbonates over Cretaceous shale and sandstone. Alt and Hyndman (1999) consider the Lewis Thrust one of the most spectacular examples of an overthrust fault in the world because of its excellent exposures in cliff faces on the south end and east side of the Lewis Range.

Two structural duplexes sit atop the Lewis Thrust in the vicinity of the caves. Structural duplexes are systems of faults in which two low angle faults bound a packet of rocks that are cut by a series of diagonal thrust faults. The structurally higher fault is called the roof thrust and the structurally lower thrust is called the floor thrust. Diagonal thrusts are called core thrusts and rock packets bounded by faults; in this case, the roof, floor, and core thrusts are called horses (Boyer and Elliot, 1982). A labeled diagram of a structural duplex is given in Figure 2. The two structural duplexes in the vicinity of the caves are named the Swift Current Duplex and the Yellow Mountain Duplex; the roof thrusts are named after the duplexes (Jardine, 1985). The Lewis Thrust is the floor thrust for both duplexes. Poia Lake Cave is in the hinterland region of the Yellow Mountain Duplex and may be within a smaller subsidiary duplex (Bodenhamer, 2006), and

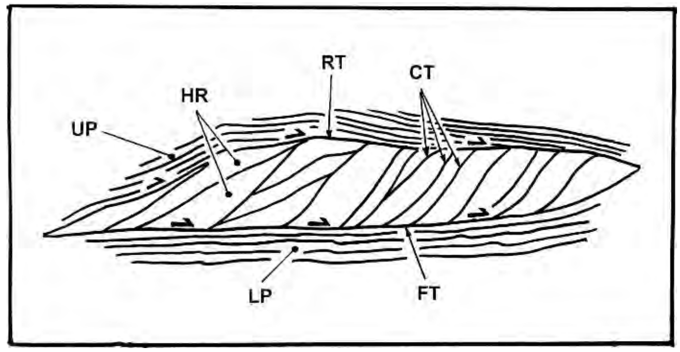

Figure 2. Diagram of a structural duplex. UP=Upper plate. RT=Roof thrust. HR=Horses. CT=Core thrust. FT=Floor thrust. LP=Lower plate (after Jardine, 1985; Bodenhamer, 2006).

Zoo Cave is within a horse of the Swift Current Duplex. Figure 3 shows the position of Zoo Cave and Poia Lake Cave in relation to the Swift Current and Yellow Mountain Duplexes. This profile view is nearly perpendicular to the strike of the roof and floor thrusts and consequently only shows a few core thrusts.

Both caves are developed in the lowermost carbonate rocks of the Middle Proterozoic Belt Series. These carbonates are commonly referred to as dolomite and limestone, but some researchers have suggested they would better be described as carbonaceous siltstones or dolomitic siltstones, because they contain less than 50% carbonate (Smith and Barnes, 1966). The high silicate content of these rocks has resulted in some depositional features that are not typically seen in carbonates. These include cross bedding and ripple marks, which can been seen at a few locations in the bedrock of the walls and floors of the caves (BHS-OLEC, 2005). Other bedrock features found within the caves include chert lenses, stromatolites, stylolites, and thin gypsum beds (Campbell, 1975; Bodenhamer, 2006). Poia Lake Cave is thought to be in the middle member of the Altyn Formation (Campbell, 1975; Bodenhamer, 2006) and Zoo Cave is thought to be in the middle member of the Waterton Formation (BHS-OLEC, 2005). A surficial geologic map with an overlay of Poia Lake Cave and other cave entrances in the area is shown in Figure 4.

Poia Lake Cave

The entrance to Poia Lake Cave is at an altitude of about 1860 m on the south-facing side of a steep-sided glacial valley about 140 m above Poia Lake. A spring issues about 30 m below the entrance. This spring drains a stream that runs through the lower part of the cave. Estimated discharge at the spring ranges from 0.15 $m^3\ s^{-1}$ in the late winter to 2.3 $m^3\ s^{-1}$ in the early spring (BHS-OLEC, 2005). Poia Lake Cave is the longest cave in the study area with slightly over 1650 m of passage. The main passage of the cave ascends from the entrance toward the

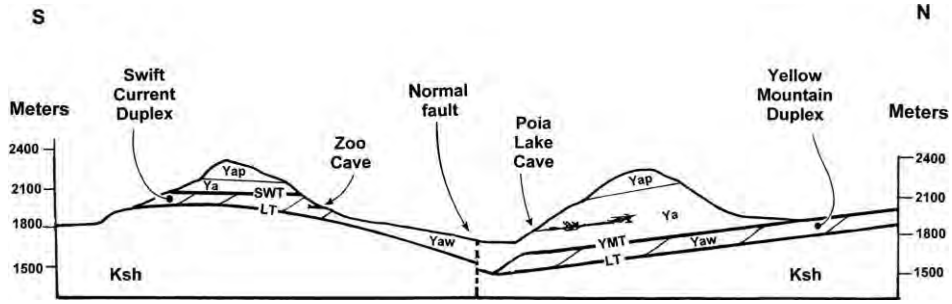

Figure 3. Structural profile along a line from Zoo Cave to Poia Lake Cave (looking west). LT = Lewis Thrust. SWT = Swift Current Thrust. YMT = Yellow Mountain Thrust. Yaw = Middle Proterozoic Altyn and Waterton Formations, undifferentiated. Ya= Middle Proterozoic Altyn Formation. Yap = Middle Proterozoic Appekunny Formation. Ksh = Cretaceous shale and sandstone.

north at a slope of about 12°. This slope approximates the local dip of the Altyn Formation. The entrance is the lowest point of the cave, and the highest is in a small maze above the known terminus of the cave, 112 m above the entrance. At three places in the cave, passages are developed in multiple tiers. In general the lowest tier is an active stream passage, the middle and upper tiers are dry walkways, crawlways, and rooms, and connecting the tiers in a few places are small, multilevel mazes.

Passages in Poia Lake Cave can be divided into six morphogenic types that correlate with variations in guiding fractures and lithology (Fig. 5). Guiding fractures include

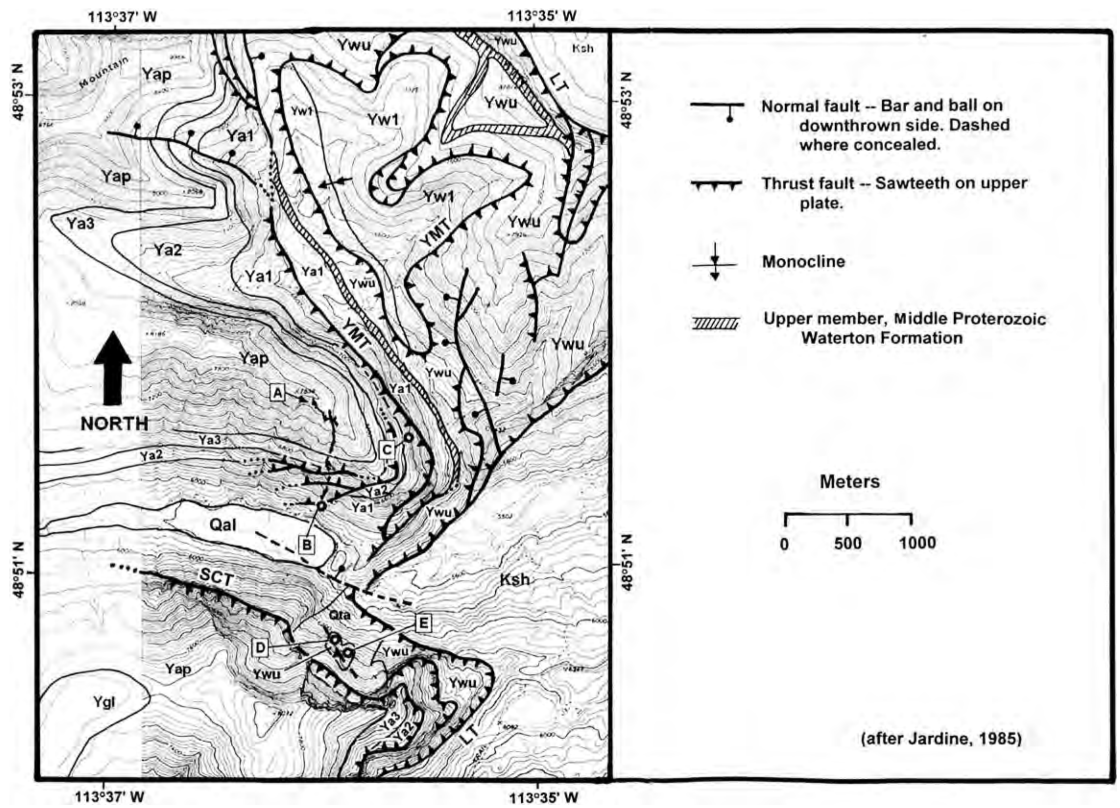

Figure 4. Geologic map of surface above caves near Poia Lake. A = Poia lake Cave passage. B = entrance to Poia Lake Cave. C = Entrance to Dancing Goat Cave. D = Entrance to Jens Cave. E = Entrance to Zoo Cave. LT = Lewis Thrust. SWT = Swift Current Thrust. YMT = Yellow Mountain Thrust. Yw1 = lower member of Middle Proterozoic Waterton Fortmation, Ywu = Middle Proterozoic Waterton Formation undifferentiated, Ya1 = lower member of Middle Proterozoic Altyn Formation, Ya2 = middle member of Middle Proterozoic Altyn Formation, Ya3 = upper member of Middle Proterozoic Altyn Formation, Yap = Middle Proterozoic Appekunny Formation, Ygl = Middle Proterozoic Grinell Formation. Ksh = Cretaceous shale. Qal = Quaternary alluvium, Qta = Quaternary landslide.

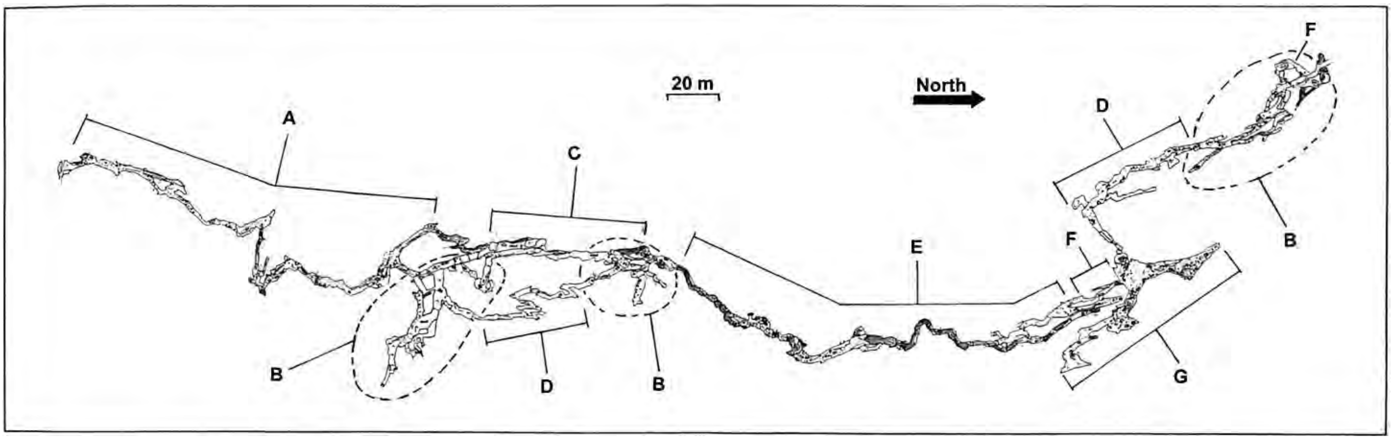

Figure 5. Morphogenic passage types, Poia Lake Cave. A=Abandoned vadose and modified phreatic passages near entrance, B=Multilevel phreatic mazes, C=Midlevel phreatic passages with vadose modifications above lower-tier stream passages, D=Upper-tier phreatic passages, Lower-tier stream passage, F=vertically developed phreatic passages, G=Middle-tier rooms and walkway (Bodenhamer, 2006).

bedding planes, joints, thrust faults, and normal faults. While remapping the cave geology, five thrust faults, six normal faults, and numerous vertical joints were identified (Figs. 6–10). Displacement on thrust faults mapped in the cave is estimated to be on the order of 10 to 100 m, and measured normal fault displacement ranges from 8 cm to 1.5 m (Bodenhamer, 2006). Described differences in the bedrock lithology of the cave walls are referred to by three letter abbreviations (Fig. 7). These abbreviations are roughly equivalent to Roman-numeral subunits, used in my previous study (Bodenhamer, 2006). Lithologic units in Poia Lake Cave are believed to be conformable, but in many places unit contacts are disrupted by thrust faults or covered by clay. Lithologic unit abbreviations and descriptions are provided in Table 1.

Zoo Cave

The entrance to Zoo Cave is south of the entrance to Poia Lake Cave on the opposing wall of the Kennedy Creek Valley at an altitude of about 1970 m (Fig. 3). The entrance is at the base of a small cliff surrounded by talus slopes associated with undermining and mass wasting of horses near the foreland of the Swift Current Duplex (Fig. 11). The cave has slightly over 300 m of passage, all part of a small mostly filled-in multilevel phreatic maze. More than half of the floor surface in the cave is covered with thick deposits of wood rat droppings, in some places as much as 1 m deep. Where not covered by droppings, clay or breakdown mask the floor surface.

Nearly all passages in Zoo Cave are elliptical walkways developed along bedding planes, steeply dipping joints, normal faults, and thrust faults. Three normal faults (labeled NFa to NFb) and one thrust fault intersect passages in Zoo Cave (Figs. 12–13). Normal faults are believed to be the result of torsional forces that developed in horses during formation of the Swift Current Duplex (Jardine, 1985). The thrust fault is the lower core thrust of the horse that contains the cave. Lithologic units in the cave are described in Table 2. In comparison with Poia Lake Cave, variations in lithology and structure within Zoo Cave are more dramatic, but differences in the character of cave passages are more subtle. Passages within Zoo Cave consist of 1) vertically oriented elliptical walkways, 2) horizontal walkways with high rounded and domed ceilings, 3) high slanting domes, 4) a low rounded walkway, and 5) a low crawlway (Figs. 12–13).

Speleogenetic Models

Previous work on the geology of Poia Lake Cave proposed a speleogenetic model in which upper-tier passages developed in a semi-confined aquifer between inflow and outflow zones that were established as overlying strata were removed by downcutting (Bodenhamer, 2006). Palmer (2003) described the development of early conduits in caves that would have preceded the development of an upper tier and favored directing all of the inflowing waters toward a single resurgence. In Poia Lake Cave, it was speculated that the inflow zone was along normal faults in the overlying Appekunny Formation, or directly into the Altyn Formation, and the resurgence was in the upper Altyn Formation. It was also speculated that multilevel mazes were the result of mixing zones attributed to the semi-permeable nature of the thrust faults. Lastly, middle-tier phreatic passages developed as inflow and outflow zones were lowered by further downcutting. Additional work on the geology of Zoo Cave identified several problems with the initial speleogenic model for the origin of Poia Lake Cave. The most important of these problems are explained below.

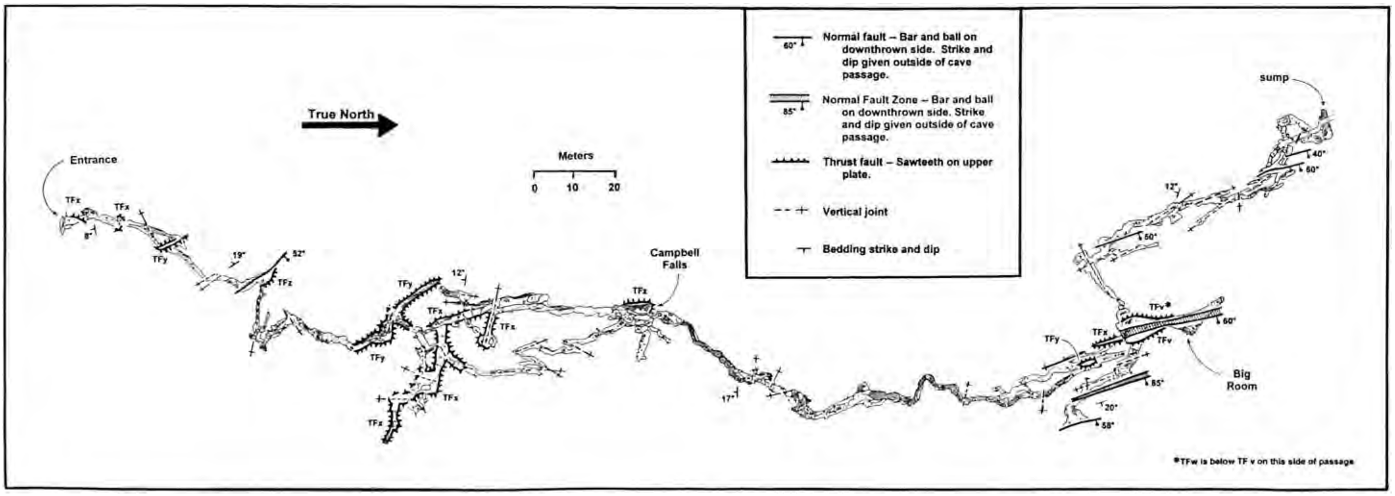

Figure 6. Structural map of Poia Lake Cave. Thrust Faults (TFv to TFz) are labeled to correlate with geologic profile in Figure 7 and Figure 8. Thrust faults extend sheet-like through the area of the cave. They are mapped where they crop out on cave walls (modified from Bodenhamer, 2006).

Lack of Upstream Branching Passage

If the upper tier of Poia Lake Cave had developed as a result of multiple inflow zones directed toward a single favored resurgence cave, the passages would probably branch upstream. Instead the cave is relatively linear with no major branches. Passages possibly branched in a headward part of the cave that is inaccessible or has been removed by erosion, but the deeply incised canyon to the east of the cave suggests that an inflow zone should have existed there, and passages in the known cave should branch toward this potential inflow zone.

Steeply Sloping Phreatic Passage

Most phreatic passages in the cave slope over long distances at an angle of about 12° following bedding. This relatively steep slope is unlikely to have developed below a piezometric surface in a highly fissured karst, as the lower parts of the cave would have formed over 100 m below the piezometric surface. Development of phreatic caves at great depths below an unconfined piezometric surface is well documented (Worthington, 2005), but the earlier model suggested a resurgent zone much lower than the piezometric surface (Bodenhamer, 2006). This suggests that the surface, like the upper-tier passage, also sloped steeply. This situation may have been possible if the upper tier passage developed as a drawdown vadose cave (Ford, 2000). Drawdown vadose caves initiate phreatically under an upwardly convex piezometric surface that is high near the inflow, but bends downward and slopes steeply near the resurgence. After phreatic passage development, a drawdown vadose cave evolves into vadose passages that lower the piezometric surface. If the upper-tier passage in Poia Lake Cave had developed as a drawdown vadose model, subsequent lowering of the piezometric surface would have

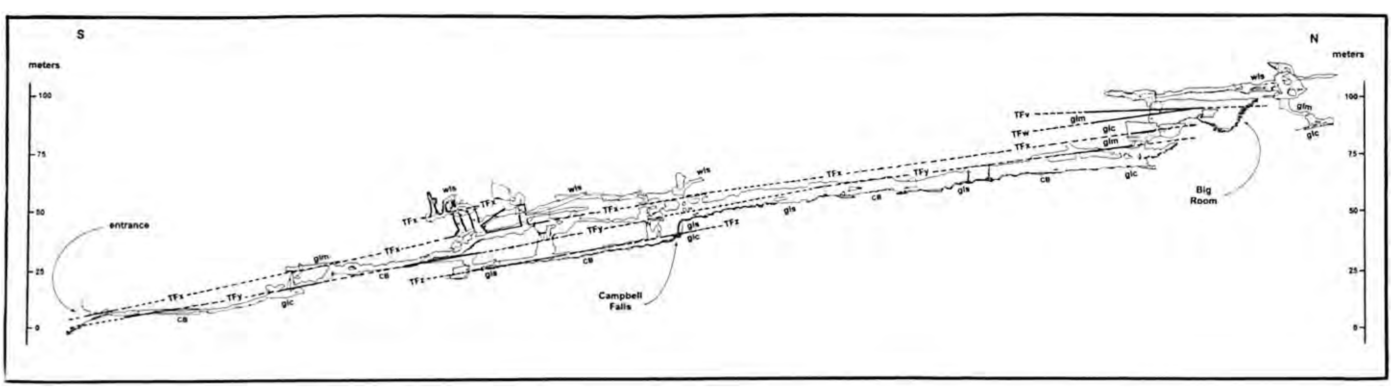

Figure 7. Geologic profile of Poia Lake Cave looking along strike of bedding. Thrust faults are dotted where inferred. Stratigraphic unit abbreviations: gls = medium gray thin bedded limestone with sand layers. glc = light gray limestone with dark chert lenses. glm = light gray massive limestone, wls= tan, white stylolitic limestone, CB= rounded cobble deposits (Bodenhamer, 2006).

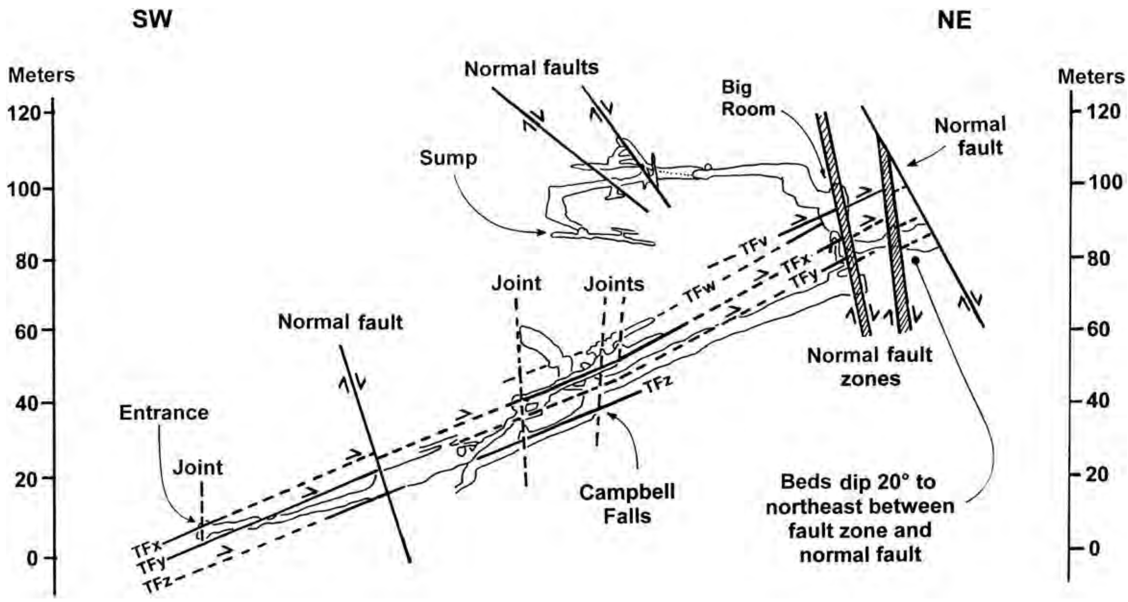

Figure 8. Structural Profile looking along the strike of thrust faults in Poia Lake Cave. Thrust Faults (TFv to TFz) are labeled to correlate with structural map in Figure 6 and geologic profile in Figure 7.

precluded development of middle-tier and other phreatic passages. Furthermore upper-tier passages would have probably been entrenched by vadose water during the drawdown phase.

Figure 9. Thrust Fault X in upper-level passage in Poia Lake Cave. Fault cuts diagonally across center of photo.

Development of Multilevel Mazes at Mixing Zones

Passages in multilevel mazes are larger in cross section than nearby upper-tier passages. This assumes a more aggressive corrosion chemistry was at work in the formation of the mazes. The original model of down-flowing phreatic water suggested that phreatic water was able to mix with descending waters, except where they met in the vicinity of mazes. Because the mazes are developed along or near faults, it was thought that the faults acted to separate flows in some places while at others they permitted mixing (Bodenhamer, 2006). One problem with this notion is that fracturing is so prevalent throughout the strata it is unlikely that either thrust faults or normal faults could inhibit ground-water flow over any sizeable area. Furthermore, throughout phreatic parts of the cave, faults clearly are followed by conduits, and nowhere do they seem to have perched descending water.

Failure to Recognize Gypsum Beds

My previous study of Poia Lake Cave, did not recognize thin gypsum beds within the light gray silty limestone unit (glc). The gypsum beds are obscured by secondary calcite deposits in the first few hundred meters of the cave but are more obvious in less accessible upper-tier passages above the Big Room. Gypsum beds contributed greatly to the solubility of nearby dolomite layers. Ground water flowing through layers of gypsum and into adjacent layers of calcite and dolomite can result in a slight increase in precipitation of calcite, but a 150% increase in the dissolution of gypsum and a 500% increase in the dissolution of dolomite (Palmer, 2000). Recent identification of local gypsum layers means that initial cave

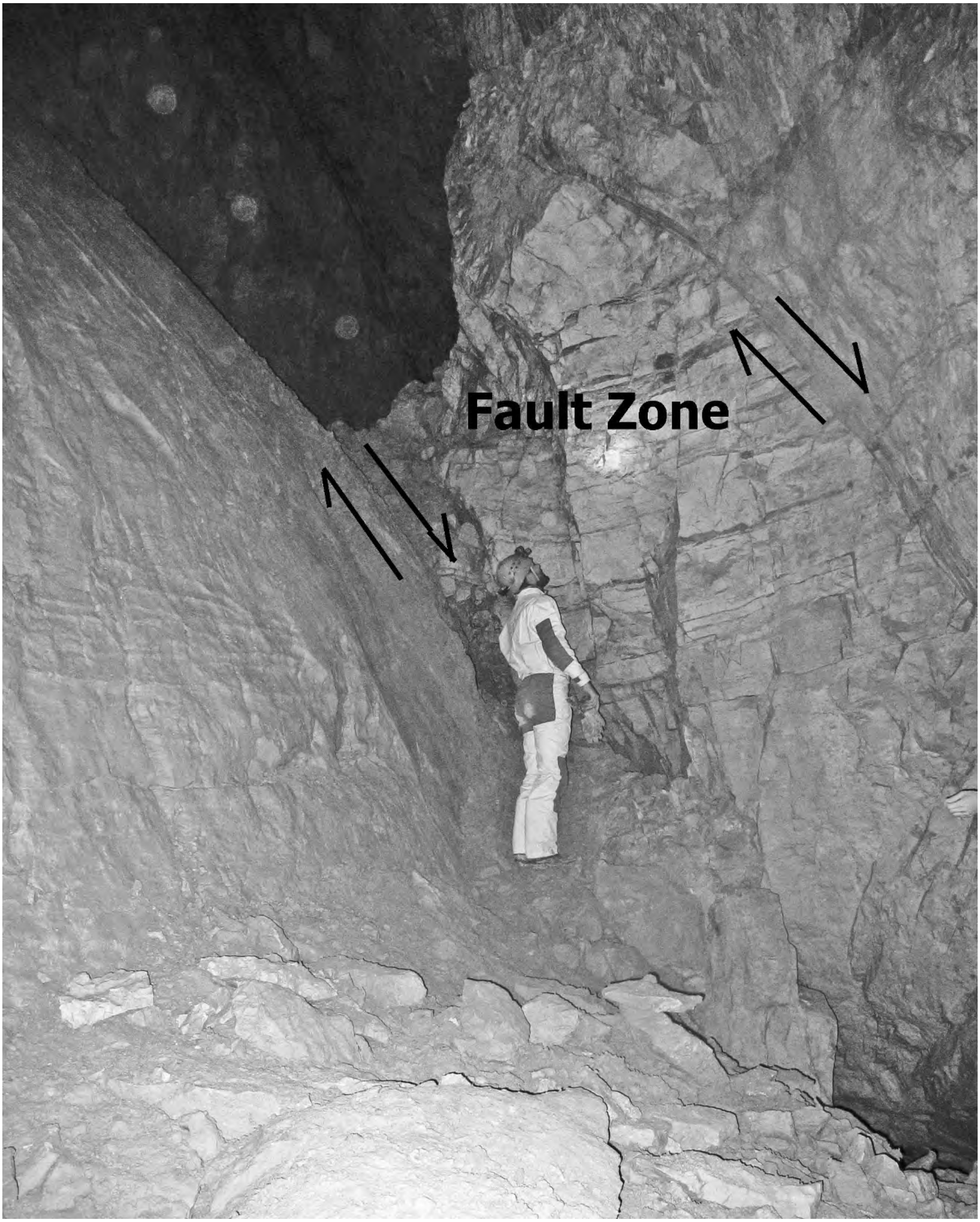

Figure 10. Normal fault zone in the Big Room of Poia Lake Cave. West side of fault zone runs diagonally from upper left corner of photo to near caver's feet. East side runs parallel to west side about 2 m to the right of caver's head.

Table 1. Description of lithologic units in Poia Lake Cave that are believed to be conformable as shown.

Abbreviation	Description
wls	Chalky-textured, tan-white, stylolitic limestone (or dolomite). Stylolites are about 0.5 m apart with 3 mm cubic hematite crystals concentrated where stylolitic sutures intersect cave walls.
glm	Light-gray massive limestone with discontinuous chert lenses.
glc	Light-gray silty dolomite with numerous dark chert lenses and a few gypsum beds about 3 cm thick. In places the dolomite is tinted dirty orange. Stromatolites are recognized in a few places.
gls	Light-gray silty dolomite with interbedded medium grained sand layers and a few dark chert lenses. Sand layers are less than 4 cm thick with 2 to 20 cm of interbedded sand-free dolomite. Ripple marks are observable at some places where sand layers are exposed on the floor.

development was probably along a few dolomitic units adjacent to or near gypsum beds.

Deep-Looping Phreatic Model

According to this scenario, early conduits develop along a deeply circulating flow path that initiated on a gently sloping phreatic surface. The flow paths follow partings (or other fractures) to considerable depth, then loop upward in phreatic lifts that follow intersecting fractures (Ford, 2000). Deep flow paths in looping systems are favored over shallower ones, even though they are longer, because increasing temperature at depth decreases viscosity and allows deep-flowing water to travel through the aquifer more quickly than it would along a shorter shallow path. Looping caves can consist of one or many loops, and the depth and frequency of loops is a function of flow-path length, stratal dip, and fracture anisotropy (Worthington, 2005). Poia Lake Cave and the other nearby caves may have originated as parts of a deep-looping system.

In the case of Poia Lake Cave, the deep-looping system could have initiated beneath a piezometric surface that was about 100 m higher than the present entrance. Inflowing water to the north of the cave could have descended along faults or other fractures that cut through the overlying

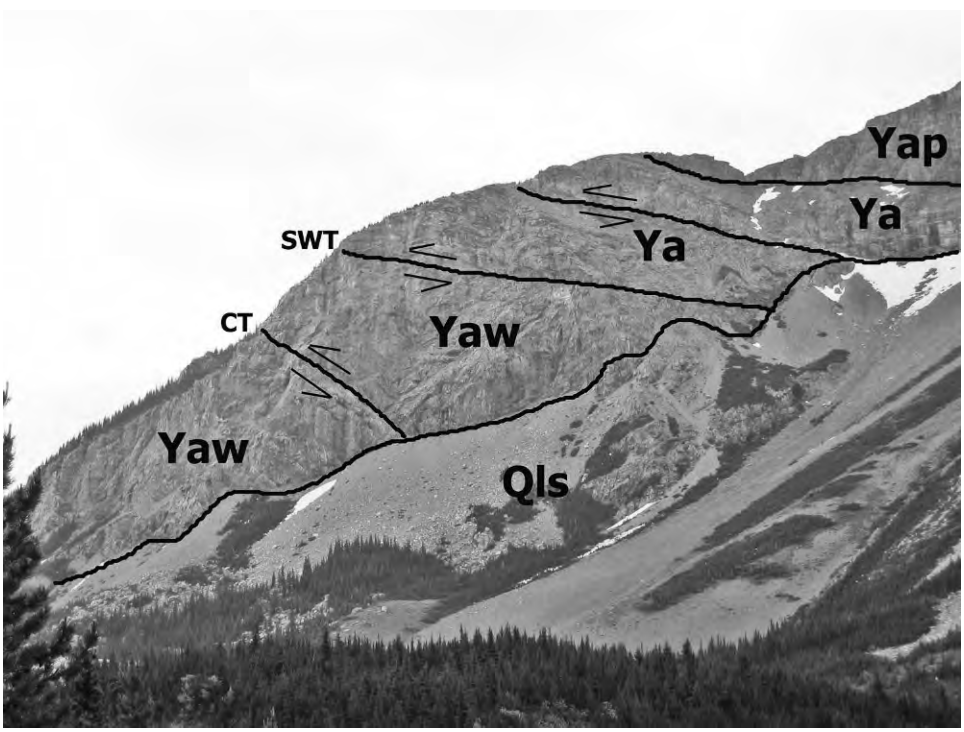

Figure 11. Southeast view of Swift Current Duplex. Zoo Cave is out of photo to the left about 200 meters. Core thrusts splay off the Lewis Thrust, which is the floor thrust of the duplex, and connect with the Swift Current Thrust, which is the roof thrust. Talus field in lower middle of photo is a landslide resulting from undermining of core thrusts in duplex. CT = core thrust. SWT = Swift Current Thrust. Ya = Middle Proterozoic Altyn Formation. Yaw = Middle Proterozoic Altyn and Waterton Formation undifferentiated. Yap = Middle Proterozoic Appekunny Formation. Qls = Landslide.

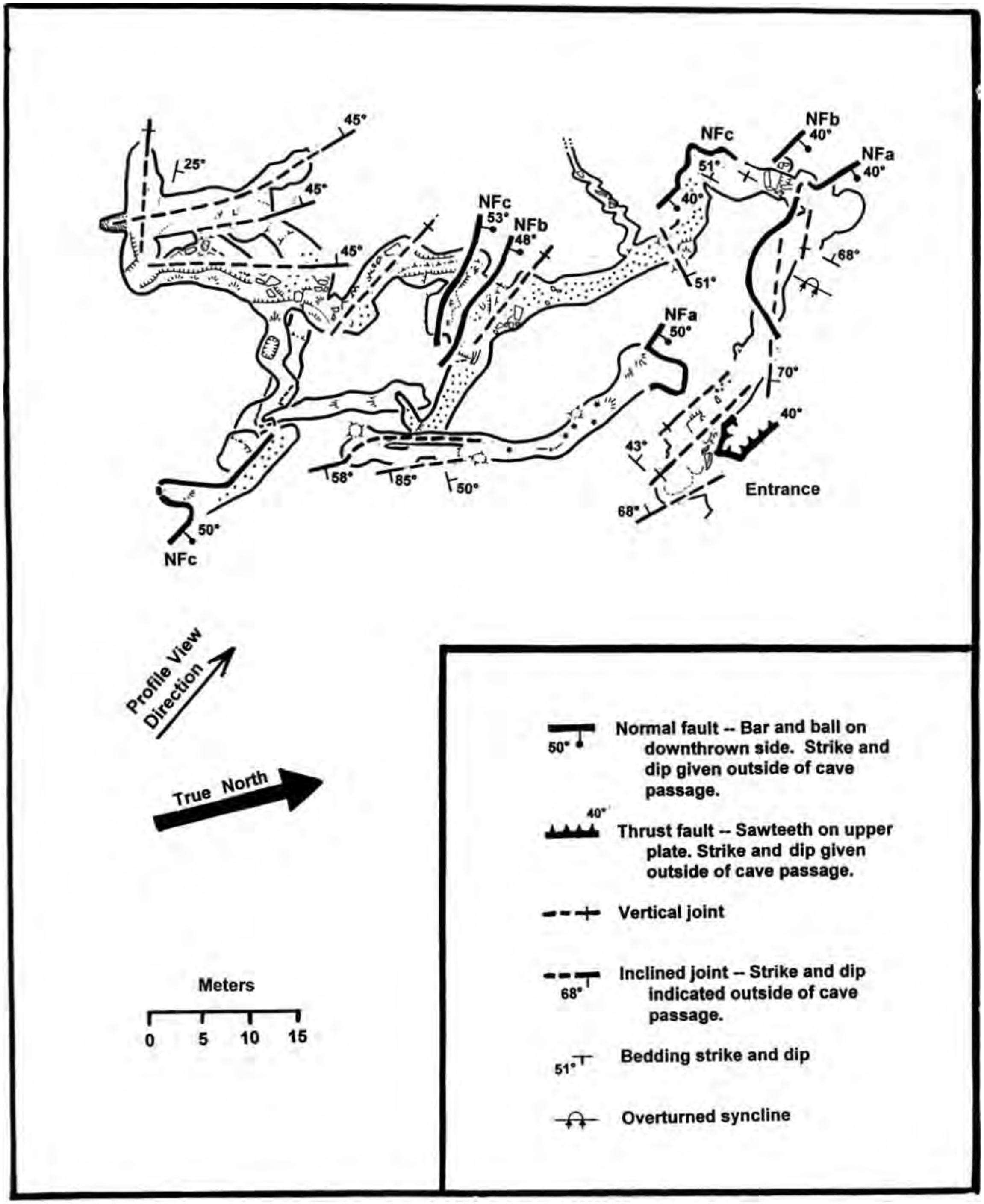

Figure 12. Structural map of Zoo Cave. Normal faults (NF) are labeled to correlate with geologic profile in Figure 14.

shaly Appekunny and into the calcareous Altyn Formation. The top of the piezometric surface was probably near or above the contact between the two. Below the piezometric surface, water flowed slowly southward following stratal dip, vertical joints, and thrust faults. A geologic profile diagramming a deep-looping system that could have been responsible for a phreatic origin of the caves is given in Figure 14. Early conduits near gypsum beds might have been favored, resulting in rapid enlargement in adjacent dolomite layers. Over time, a few large looping conduits might have developed, the largest of which is represented by the upper-tier passages, which were connected during this phase of development. The downstream end of the higher upper-tier passage and the upstream end of the lower upper-tier seem to be clay choked, indicating that they might have been connected

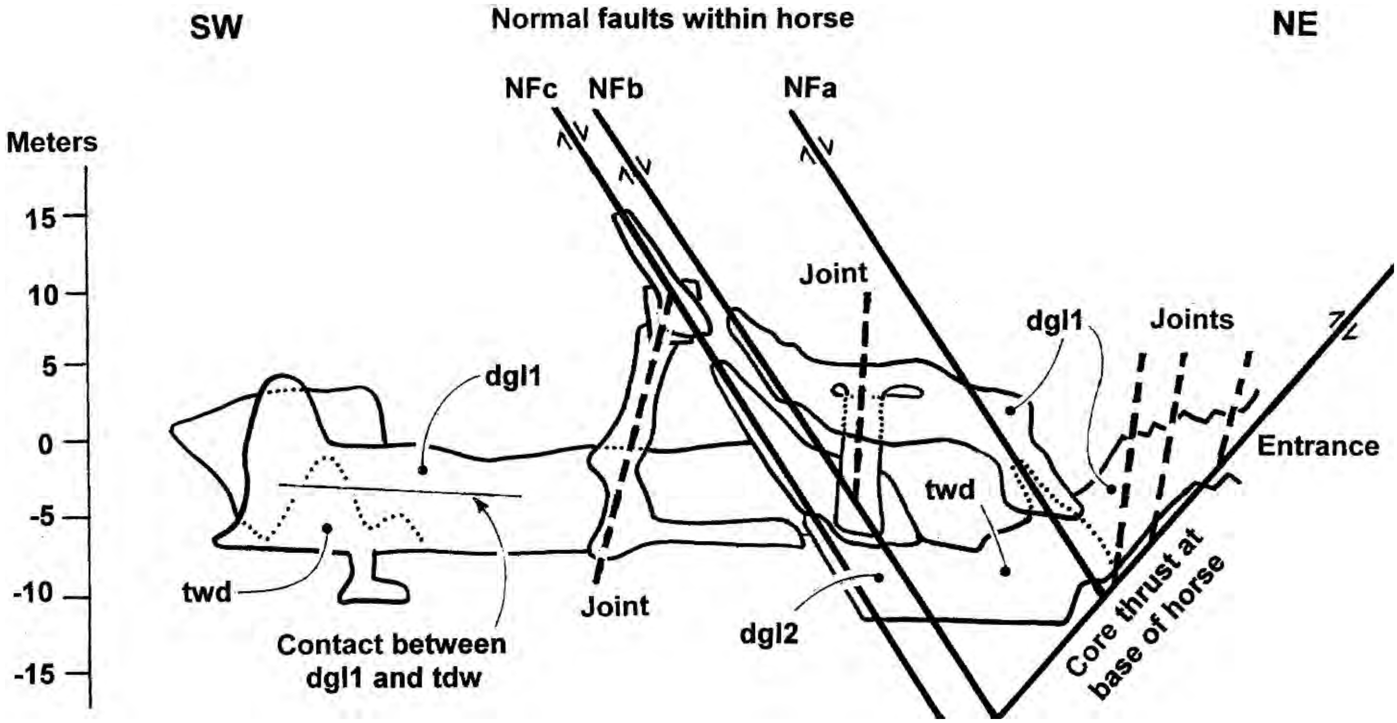

Figure 13. Geologic profile looking along the strike of normal faults in Zoo Cave. The cave lies between the Lewis Thrust and Swift Current Thrust in a structural horse that connects between the two major structures. Stratigraphic unit abbreviations: dgl1 = dark gray thin bedded limestone, dgl2 = dark gray limestone with numerous gypsum veins, tdw = tan to white chalky, massively bedded dolomite.

during development but have since been filled in by clay. If the two sections of upper-tier passage were once connected, they could have delivered water to some point south of, and probably lower than, the present entrance. Here water might have looped upward in a phreatic lift that has since been removed by erosion. Placing a connection between these two upper-tier passages makes a deep-looping model seem viable. However, there are other difficulties to consider.

Connections Between Lower-Tier Phreatic Passages

Lower-tier phreatic passages could have developed as downcutting dropped the piezometric surface, which caused lower tiers to develop as a new loop at a lower level (Worthington, 1991). However, establishing a flow path between lower phreatic tiers is more difficult than one between the two sections of clay-choked upper-tier passages. There are no clay choked middle-tier passages that would likely connect, and the lower-tier passages are almost entirely modified by vadose entrenchment.

Development of Multilevel Mazes in Poia Lake Cave

Multilevel mazes in Poia Lake Cave are challenging to explain as part of a deep-looping origin. Cave maze patterns are categorized into four general forms, each of which is associated with particular types of recharge and porosity. The four patterns are spongework, anastomotic, network, and ramiform (Palmer, 2000). Based on morphology, the multilevel mazes in Poia Lake Cave are either network or ramiform. Network mazes in plan view look like interconnecting, rather linear passages, and ramiform mazes look more irregular and curvilinear. Network mazes can be formed by diffuse downward percolating water or by upwelling water, whereas rami-

Table 2. Description of lithologic units in Zoo Cave with less certain stratigraphic relations. Unit dgl1 overlies unit twd, but the relationship of dgl2 to the other units is difficult to determine because of displacement along normal faults.

Abbreviation	Description
dgl2	Dark gray thin bedded limestone. Limestone is folded and tilted near entrance.
dgl1	Dark gray brecciated limestone. Gypsum infills breccia to give unit a mottled appearance.
twd	Tan-white massive dolomite. In some places the dolomite is chalky.

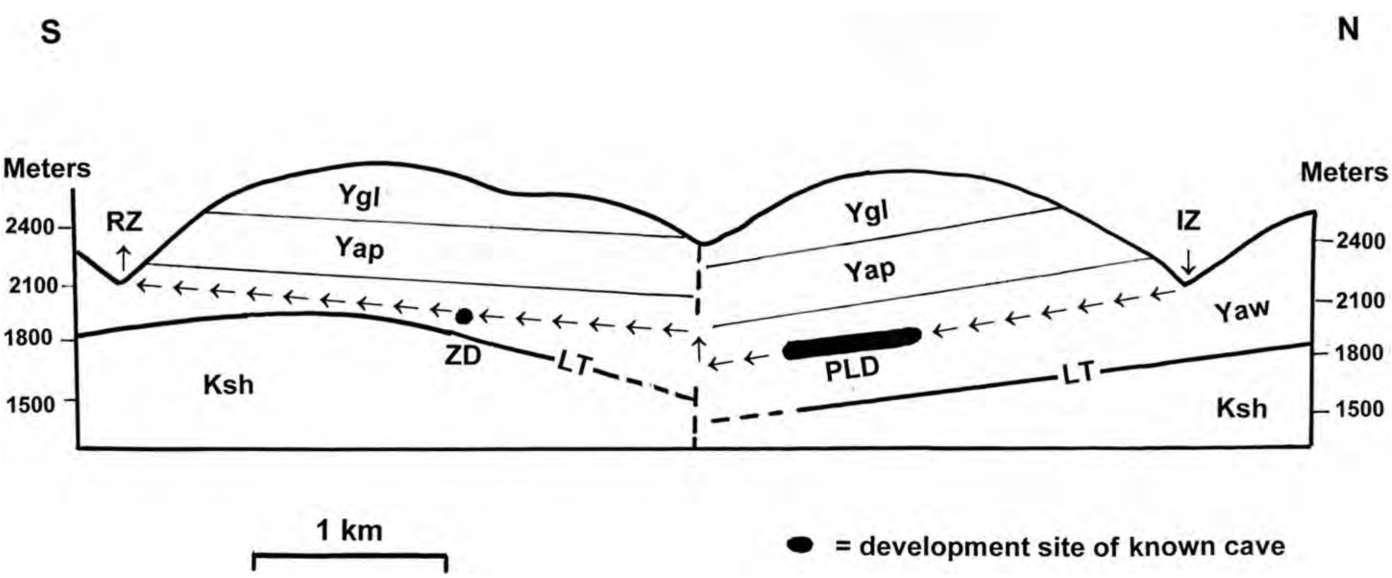

Figure 14. Deep-looping model that could have developed after the contact between the Altyn Formation and Appekunny Formation was breached by downcutting (late Pliocene?). Lines of arrows represent possible deep-looping groundwater flow path. LT=Lewis Thrust, Yaw=Altyn and Waterton Formations undifferentiated, Yap=Appekunny Formation, Ygl=Grinnell Formation, Ksh=Cretaceous shale and sandstone. ZD=Site of development for Zoo Cave, PLD=Site of development of Poia Lake Cave, IZ=Insurgent zone, RZ=Resurgent Zone. Roof thrusts, core thrusts and piezometric surface are omitted for clarity. The location of roof and core thrusts relative to the Lewis Thrust can be seen in Figure 2. The piezometric surface would have trended from the insurgent zone to the resurgent zone.

form mazes are thought only to be formed by upwelling water. Diffuse recharge resulting in the development of network mazes has been attributed to recharge through a porous caprock or by mixing at depth in a porous soluble rock. None of the strata overlying or containing the caves is notably porous. This indicates that the multilevel mazes, whether classified as network or rami-form, developed as a result of upwelling water. Because each multilevel maze is higher than adjacent upper-tier passages, the mazes possibly developed by water that ascended from the developing upper-tier passage in the same way it would in a phreatic lift. Instead of reaching another descending passage, the water returned to the upper-tier passage along a circulating path that eventually developed into a multilevel maze. The notion of multilevel mazes developing in circulating paths above developing upper-tier passages is feasible, but seems contrary to the development of the deep-looping system that initiated because the deep-looping path was more efficient than a shallower one.

Development of Middle-tier Rooms

The middle-tier rooms and connecting passage are much larger in cross section than nearby upper- and middle-tier passages. The larger size may be attributable to upwelling water following short circulating paths similar to those discussed in the preceding section. During development of the middle tiers water could have ascended along fault zones that intersect these tiers. Further enlargement of the Big Room could be attributable to stoping at fault zones caused by undermining of vadose waters that invaded the cave much later (see section on postphreatic modifications). However, the notion of initial enlargement of the middle-tier rooms by water circulating above developing middle-tier passages suffers from the same problem of inefficiency as discussed in the preceding section.

Length of Flow Path in Poia Lake Cave

In order for a deep-looping system to develop, a distance of at least 3300 m is needed between inflow and outflow points because the lower viscosity at depth does not compensate for the longer flow path (Worthington, 2005). The suspected inflow for Poia Lake Cave is about 3200 m north of the entrance. An outflow zone may have existed at least 100 m or more to the south of the current entrance, which might be far enough away to have established the critical length. However, downcutting of 30 m is required to drop the piezometric surface below the upper tier. Considering the 12° dip of the Altyn and overlying Appekunny Formations, maintaining critical length for development of lower phreatic tiers is difficult to explain.

Length of Flow Path in Relation to Zoo Cave

Zoo Cave is higher than Poia Lake Cave and directly in line with the major trend of Poia Lake Cave. Both caves were possibly connected before the valley between them was cut (Figs. 4 and 14). This would have required a phreatic lift just to the south of the present entrance to Poia Lake Cave that would have delivered water upward at least 100 m to the level of Zoo Cave. From there, the water could have flowed southward through Zoo Cave to a resurgence about 3500 m south of the present entrance to Poia Lake Cave. This scenario would have created a nice long flow path for a deep-looping system (Fig. 14). However, flow in the vicinity of Zoo Cave would be up dip, which is inconsistent with a conventional deep looping model. Furthermore, Zoo Cave is a maze cave, and explaining its development as part of a deep-looping system presents the same difficulty as discussed above in the section on the multilevel mazes in Poia Lake Cave.

Long-Flow Artesian Model

Poia Lake Cave might have originated as part of a long-flowed artesian system. Initially this model was not considered because it is difficult to imagine a flow path for an artesian system because strata in the vicinity of the cave dip toward the crest of the mountains. Classic artesian systems in the western United States, such as those in the Bighorn Mountains of Wyoming and the Little Belt Mountains of Montana, are established in strata that dip away from the mountains (Downey, 1984). However, unsolved difficulties with a deep-looping model, led to development of a long-flow artesian model, that accounts for the incongruent dip of strata in the vicinity of the caves.

The development of caves in artesian systems is attributed to the concept of transverse speleogenesis (Klimchouk, 2000). According to this theory, water traveling along a long-flow artesian path will encounter fractures and rise upward as a result of hydrostatic head. As the water rises up through the fractures, it moves through strata of differing permeability, and mixes with other long-traveled artesian waters, making the ensuing mix more corrosive. The name transverse speleogenesis implies the upward flow is typically transverse, or normal, to bedding. This type of spelogenesis has a few important characteristics as follows:

- Caves can develop at depths well below the water table so long as the site of development is lower than the hydrostatic head.
- Cave development is typically slower than development in unconfined settings, but because the site is deeply buried during artesian development, cave formation can span tens of millions of years.
- Cave patterns are typically guided by tectonic structures and are quite uniform in size and morphology within individual lithologic units.
- Cave patterns formed in artesian systems of differing lithology and structure are highly variable, including large rooms, mazes, and dead-end branches.
- Some linear sections of artesian caves give a false impression that they were formed by unconfined downward-moving water, but these sections are only following lateral discordances between lithologies.
- Clastic sediment in artesian caves is mostly fine silt or clay, and deposition is generally uniform and distributed evenly throughout most of the cave.

In the case of an artesian model for Poia Lake Cave, and the other caves in the area, an artesian system could have developed after the movement of the Lewis Thrust during the Laramide Orogeny (Late Cretaceous to early Tertiary). While the hinterland was elevated, strata dipped away from the mountain. Movement of the large slab of Middle Proterozoic rocks above the Lewis Thrust is believed to be driven by uplift at the hinterland of the thrust followed by gravity sliding away from the uplift. Water descending along fractures in the hinterland region eventually encountered strata near the Lewis Thrust and followed the dip of the strata. Variability in the lithology of strata near the Lewis Thrust set the stage for transverse speleogenesis as waters flowing through these rocks developed differing chemistries. As water flowed into the vicinity of the present-day caves, it ascended along fractures such as core thrusts in duplexes. When the ascending water flowed through gypsum layers and into dolomite, it became corrosive and gradually hollowed out the phreatic parts of the caves. A geologic profile diagramming a long-flow artesian model for Poia Lake Cave is presented in Figure 15.

Long-Flow Artesian Model Versus Deep-Looping Model

In a deep-looping model, water flows laterally between inflow and outflow points. If upper-tier phreatic passages constituted the first loop to form, they would need to be connected. However, in an artesian system, the two sections could develop independently at the same time, because the flow can transverse across strata. Furthermore, in an artesian system, lower tiers could have developed at the same time as upper tiers, and none of the tiers need to be connected.

In a deep-looping model, development of multilevel mazes and middle-tier rooms require flow that circulates from the developing loop, and this circulatory flow seems incongruent with the efficiency of a deep-looping system. Mazes and large rooms are typical in artesian systems. Their flow typically follows structures through various lithologies. Mazes can develop as water moves up through many closely spaced fissures that cross several layers, and large rooms can develop as water circulates in fracture zones within one layer.

In a deep-looping system, a critical flow length between an inflow and outflow must be maintained. This critical length may have been difficult to maintain when the piezometric surface dropped during cave development in

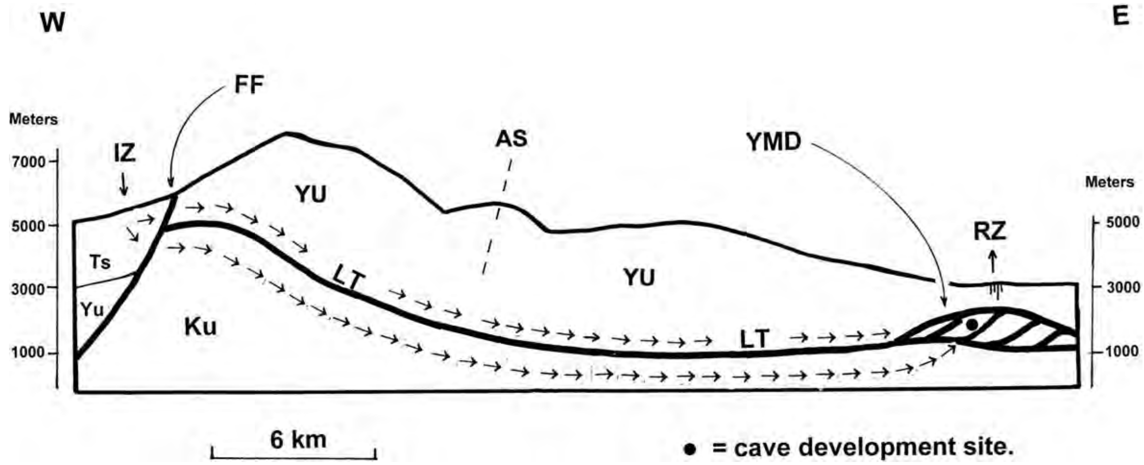

Figure 15. Long-flow artesian model that could have developed following uplift of the hinterland of the Lewis Thrust and development of insurgent and resurgent zones (Oligocene to Pliocene?). Line of arrows represents flow path of artesian water. LT=Lewis Thrust, FF=Flathead Fault, YMD=Yellow Mountain Duplex, AS=Axis of Akimina Syncline, YU=Undifferentiated Middle Proterozoic strata, Ku = Undifferentiated Cretaceous sedimentary rocks. Ts= Tertiary valley fill, IZ =Insurgent Zone, RZ =Resurgent zone.

Poia Lake Cave. In an artesian model, distance between insurgence and resurgence is tens of kilometers long, and caves develop in a deeply buried setting, far below the piezometric surface where they are not affected by downcutting for tens of millions of years.

LONG-FLOW ARTESIAN MODEL FITS CAVE FEATURES

Caves developed by artesian systems typically have dead-end lateral passages, because flow can be perpendicular to the bedding along vertical fissures. These deliver water upward across the bedding and not exclusively along it. This process explains dead-end passages in the multilevel mazes and upper tiers in Poia Lake and Zoo Cave.

When water ascends a vertical fissure during the development of an artesian cave, it may be more corrosive than when it first enters a bed. This causes the passage to narrow from bottom to top across a rock unit. This process might explain the cross sectional shape of the upper-tier passages nearest the entrance of Poia Lake Cave.

During the development of an artesian cave, if corrosive water ascending a vertical fissure enters a lithology that causes it to become less corrosive, the passage may terminate or narrow abruptly. This process could explain the open narrow fissures that extend upward out of dome-shaped rooms in the multilevel maze nearest the entrance of Poia Lake Cave.

Water moving out of a tight fracture into a solutionally enlarged fissure may create small eddies that can direct flow outward and down the walls. Eddies such as these might explain the mounding of clay deposits in the middle of the floors of the upper-tier passage nearest the entrance of Poia Lake Cave.

Springs that drain large regional karst aquifers are typically high in dissolved sulfate (Worthington, 1991). The long-flow artesian system proposed for Poia Lake Cave and the caves nearby was at least 35 km long from inflow to outflow. At this length, the water flowing through the aquifer likely would have gained sulfate, making the upwelling water more corrosive. This could account for the development of the caves in lithologies that are highly siliceous. It also might explain the presence of cubic hematite crystals concentrated at the intersection of cave passages and along sutures of stylolites. The hematite crystals may be residual from oxidation of pyrite induced by sulfate rich waters.

POSTPHREATIC MODIFICATIONS

Whether the caves described in this article originated in a deep-looping, long-flow artesian system, or some other as yet to be explained system, after phreatic development, the caves were modified by events associated with downcutting of surface streams and glaciers. Although all the caves were modified by these events, Poia Lake was the most affected. Poia Lake Cave is the only cave in the area that presently has an active stream flowing through it, and it may be the only cave in the area that was ever invaded by a surface stream. For this reason, most of this section focuses on features in Poia Lake Cave.

As downcutting incised valleys above the developing phreatic caves, the piezometric surface lowered, causing reduced velocity of water flowing through the cave, which in turn caused clay in suspension to be deposited. If the caves developed according to the deep-looping model, incision of valleys would have resulted in decreased flow velocities. Because flow velocities through the deep-looping system would not have been fast enough to transport clay in the late stages of development, clay was deposited as passages were progressively abandoned during valley incision. If the caves originated as part of a long-flow artesian system, flow velocities through the caves would have increased as piezometric lows directed and concentrated flows toward incised valleys, but, because the velocities were still relatively slow, clay deposition remained uniform throughout the cave (Klimchouk, 2000).

As phreatic passages were abandoned and drained, ceilings may have collapsed in some places as a result of loss of buoyant support (White and White, 2000). Collapse was more severe in passages and rooms developed in fracture zones. In the Big Room and nearby middle-tier rooms of Poia Lake Cave, clay was deposited on top of breakdown. In some places the clay is over 10 cm thick. These deposits may indicate that dewatering of phreatic passages occurred in distinct stages, or that other events flooded the cave after valley incision had lowered the piezometric surface.

As valley incision progressed, it eventually exhumed the middle-tier passage of Poia Lake Cave and allowed a surface stream to enter the cave. The stream left scallops on the lower parts of the walls and deposited silt, sand and rounded cobbles on the floor (Fig. 7).

The Big Room in Poia Lake Cave may have been partly undermined by vadose stream erosion. Collapse in the back part of this room is extensive and breakdown is deposited on top of previous clay-covered breakdown.

Sediment in the upper-tier passages above the Big Room could have been washed in by vadose water. These deposits are coarser than the clay that covers the floor of most phreatic passages elsewhere in the cave. Collapse of the Big Room temporarily blocked vadose water flow beneath the Big Room and diverted water through the upper-tier passage (Bodenhamer, 2006).

Clay laminations deposited on the floor of the middle-tier passages in Poia Lake Cave are probably varves derived from glacial outwash. However, the suspected varves are difficult to distinguish from other clay deposits in the cave making it difficult to determine if glacial melt waters flooded the cave.

Since the initial invasion of the middle-tier phreatic passages in Poia Lake Cave, the middle tier near the entrance has been abandoned by the cave stream. Coupled with this abandonment is the entrenchment of the lower-tier passage to a depth of over 7 m, development of Campbell Falls, and creation of another lower tier downstream from the falls that feed the spring below the entrance. From the time a surface stream first invaded Poia Lake Cave to the present, the level of the resurgence has dropped about 20 m.

Timing of Speleogenetic Phases

Poia Lake Cave and the caves nearby developed in two distinct speleogenetic phases. The first phase was phreatic and the second was vadose. Estimates of the timing of each phase are possible by relating the development to timed surface events and by considering the development of features within the cave relative to similar features on the surface and within other caves in the region.

Phreatic Phase (Oligocene to Pleistocene?)

The thick slab of Middle Proterozoic rock above the Lewis Thrust was emplaced during the Laramide Orogeny (74 to 59 Ma). Following emplacement, the slab and the Lewis Thrust were deformed due to isostatic rebound (Sears, 2001). An artesian system may have initiated at this time, if fracturing in the inflow and outflow zones penetrated through the Lewis Fault and into the underlying Cretaceous strata. However, it is more likely that an artesian system developed after movement of the Flathead Fault. The Flathead Fault is related to the slow subsidence of the hinterland of the Lewis Fault, which began in the Oligocene and ended in the Miocene (McMillan et al., 2006). At the beginning of subsidence, some strata in the hinterland dipped eastward and would have provided an ideal setting for establishment of a multistory artesian aquifer. As subsidence continued, strata were gradually rotated until it was dipping east as it does today. However, regardless of dip after its establishment, the artesian aquifer probably remained active as long as the recharge area was higher than the resurgence area, and the confining strata of the aquifer were not disrupted by downcutting of the surface. The earliest downcutting is believed to be in the Pliocene as discussed below.

Vadose Phase (Late Pleistocene)

Features within Poia Lake Cave suggest that phreatically developed parts of the cave were exhumed during the late Pleistocene as a result of rapid and alternating glacial and fluvial downcutting.

Vadose modification in middle tiers is minor compared to that in lower tiers. Furthermore, no vadose modifications occur in upper-tier and multilevel mazes. If valley incision had been a result of uninterrupted fluvial erosion, surface streams would have invaded the upper-tier and multilevel mazes as the valleys were cut. Also, the middle tier would be more entrenched. This suggests that the upper-tier passages were affected by a glacier that cut through the level of these passages and down to that of the middle-tier passages before fluvial erosion was resumed after the glacier retreated.

If the lamenated clay deposits in Poia Lake Cave are varves, they are relatively thin in comparison with similar deposits from other caves in the region. Varved clays in Castleguard Cave, which is at about the same altitude and approximately 350 km to the north, are over 2 m thick and represent several episodes of glaciation (Schroeder and Ford, 1983). Varved clays in Virgil Cave, which is also at about the same altitude, but 150 km to the south, are about 1 m thick (Rykwalder, 2007). The suspected varves in Poia

Lake Cave are only about 40 cm thick. If Poia Lake Cave had been exhumed early in the Pleistocene, and glacial flooding in the cave was similar to that in the other caves in the region, glacial meltwater would have flooded the cave several times, and varves would be thicker. The relatively thin depth of the suspected varves suggests that if glacial meltwaters entered Poia Lake Cave, it was not until late in the Pleistocene.

Paleoflow through Poia Lake Cave was similar to present day flow. Estimates of paleoflows can be derived from the dimensions of scallops and rounded cobbles in abandoned stream passages. A relationship for stream velocity as a function of scallop length is provided by Moore and Sullivan (1997). Scallop lengths in the modified phreatic passages near the entrance are up to 4 cm long, which yield a velocity of 0.5 to 1.5 m s^{-1}. Scallops cover only the lower part of cave walls in Poia Lake Cave; that cross sectional area of 0.75 m^2 multiplied by the estimated velocity gives an estimated flow volume of 1.5 to 2.3 m^3 s^{-1}.

A relationship for size of particles transported as a function of stream velocity was developed by Hjulstrom (1939). The largest cobbles in the abandoned stream passage measure 25 cm. Using the same cross sectional area, a flow of 0.375 to 1.1 m^3 s^{-1} can be estimated. Present-day flow through Poia Lake Cave ranges from 0.25 to 5 m^3 s^{-1}. The two estimates of paleoflow are close enough to present-day flows that it seems reasonable to assume that a surface stream invaded the cave during an interglacial of the late Pliestocene when flow rates where similar to those of today.

CONCLUSIONS

Speleogenic models for the evolution of alpine caves in previously glaciated areas should consider the possibility that the caves originated as deep phreatic systems that might have initiated after regional uplift. In lieu of absolute dating techniques, detailed mapping of guiding fractures, lithologic variations, and distributions of floor deposits all provide considerable insight toward developing a speleogenic model and timeline for events. In the case of Poia Lake and Zoo Caves, three models were considered, each with a different phreatic origin. The phreatic origin in the first model is attributed to development in a semi-confined, descending aquifer that was established during downcutting. This model does not adequately explain the steep dip of phreatic passages within Poia Lake Cave or the multilevel mazes in both Poia Lake and Zoo Cave. In the second model a deep looping system with phreatic lifts is considered. This model better explains the steeply dipping passages in Poia Lake Cave, but does not adequately explain mazes in both caves. Also, the flow path may be too short for the development of lower phreatic passages in Poia Lake Cave. The third model involves a long-flow artesian aquifer. This model accounts for steep passages,

Table 3. Comparisons of the phreatic origin of 3 speleogenic models of Poia Lake and Zoo Cave.

	Origin 1	Origin 2	Origin 3
Characteristic	Semi-confined down-flowing aquifer during downcutting	Deep looping with phreatic loops	Long-flow artesian aquifer
Length of flow	2.5 km	2.5 to 5.5 km	35 km
Timing of origin	Pliocene to Pleistocene	Pliocene to Pleistocene	Oligocene to Pliocene
Upper tier passages	Develops near surface of piezometric surface	Develops as loop below piezometric surface	Develops as upwelling water follows intersection of thrust faults, bedding planes and joints
Middle tier passages	Develops as piezometric surface drops	Develops as a second loop after piezometric surface drops	Develops simultaneously with upper tier passages along lower structures
Multilevel mazes	Develop at mixing zones where descending vadose water meets phreatic water	Develop in recirculating paths at quasi phreatic loops	Develop as upwelling waters rise through closely spaced joints and faults
Large rooms	Develop below fault zones by undermining of cave stream during vadose phase	Develop either in recirculating paths or by undermining of cave stream during vadose phase	Develop by circulating of upwelling waters in fault zones
Clay deposits	Deposited during dewatering and flooding	Deposited during dewatering and flooding	Deposited uniformly by upwelling waters

mazes, and is a better fit for other features in both caves, but requires an unconventional artesian flow path. Table 3 compares the phreatic origin of each model. After a phreatic origin each model recognizes that downcutting and other events modified both caves, but had the greatest effect on Poia Lake Cave, which was invaded by a surface stream. Postphreatic modifications include partial collapse, vadose entrenchment, and deposition of coarse clastic sediments

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GEOCHEMICAL TRENDS IN SELECTED LECHUGUILLA CAVE POOLS

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Abstract: Lechuguilla Cave is the deepest known limestone cave in the United States, with a surveyed length in excess of 185 km, and hosts some of the world's most exemplary speleogenetic features. Since its discovery in 1986, Lechuguilla Cave has provided researchers with a unique location to study speleogenesis, geology, microbiology, and geochemistry. Although approximately 200 water samples were collected by numerous researchers between 1989 and 1999, subsequently little water quality monitoring has occurred. The primary objective of this study was to collect recent major ion chemical data from pools which either have experienced chemical changes in the past, or which have been designated as drinking-water sources for cavers, and to use those results in conjunction with previous data to evaluate historical trends. The study locations consisted of Lake Lechuguilla, and three pools designated as drinking-water supply (Lake Louise, Pearlsian Gulf Water Supply, and Tower Place Water Supply). In conjunction with sampling for general chemistry, the oxidation-reduction (redox) states of the pools were also assessed by conducting additional measurements for dissolved oxygen, dissolved organic carbon, redox potential (Eh), ferrous iron (Fe^{2+}), total dissolved iron, manganese, and nitrogen (NH_3-N and NO_3-N). Although Lake Lechuguilla experienced unexplained increases in nitrate and sulfate between 1988 and 1990, the major ion chemistry has apparently returned to baseline conditions. Results also show that between 1988 and 2006, the major ion chemistry of Lake Louise, Pearlsian Gulf, and Tower Place has remained relatively constant. Evaluation of redox status in these pools between 2005 and 2006 indicate an oxic (aerobic) environment, with dissolved oxygen levels in equilibrium with the atmosphere, and concentrations of dissolved organic carbon, NH_3-N, iron, and manganese below detection limits.

Introduction

Lechuguilla Cave, located within Carlsbad Caverns National Park in the Guadalupe Mountains of southeastern New Mexico, is currently the fifth longest cave in the world and the deepest limestone cave in the United States. Lechuguilla Cave, Carlsbad Cavern, and numerous other Guadalupe Mountain caves were formed during the late Miocene through early Pliocene (12 to 4 Ma) through a unique process of speleogenesis whereby sulfuric acid (H_2SO_4), derived from oil and gas accumulations in the Delaware Basin, dissolved limestones and dolostones of the Capitan Reef Complex (Hill, 2000; Jagnow et al., 2000). As a result, Lechuguilla Cave contains a vast array of unusual speleogenetic by-products, examples of which include massive gypsum ($CaSO_4 \cdot 2H_2O$) blocks and rinds, native sulfur, and minerals such as the alunite [$KAl_3(SO_4)_2(OH)_6$] group (alunite, jarosite, and natroalunite), hydrated halloysite or endellite [$Al_2Si_2O_5(OH)_4 \cdot 2H_2O$], and uranium-bearing minerals such as tyuyamunite [$Ca(UO_2)_2V_2O_8 \cdot 5\text{-}8H_2O$] (Polyak and Provencio, 2001). Lechuguilla Cave is renowned for hosting some of the world's most outstanding secondary speleogenetic features, including gypsum glaciers, sulfur masses, gypsum chandeliers, gypsum hairs, subaqueous helictites, hydromagnesite fronds, and corrosion residue (Davis, 2000; Hill and Forti, 1997).

Operating under the stewardship of the National Park Service (NPS) since breakthrough in May 1986, the exploration and scientific study of Lechuguilla Cave is still ongoing. Since that time, Lechuguilla has provided researchers with a unique natural laboratory for many important studies in the fields of speleogenesis, geology, geochemistry, and microbiology (e.g., DuChene, 2000; Polyak and Provencio, 2000; Polyak and Provencio, 2001; Hill, 2000; Northup et al., 2000). On the day following the initial breakthrough into inner Lechuguilla Cave, explorers discovered a small lake near the entrance which they named Lake Lechuguilla (Reames et al., 1999). As exploration continued, it became apparent that a large number of isolated pools existed throughout the cave. The first pool samples were collected from Lechuguilla Cave during June 1986, and since that time over 200 pool and drip samples have been collected and analyzed for a variety of major ions and trace elements.

Major ion chemical data collected from Lechuguilla Cave pools by various researchers between 1986 and 1999 were eventually compiled and published by Turin and Plummer (2000). Evaluation of these data show that the chemistry of most Lechuguilla pools is dominated by

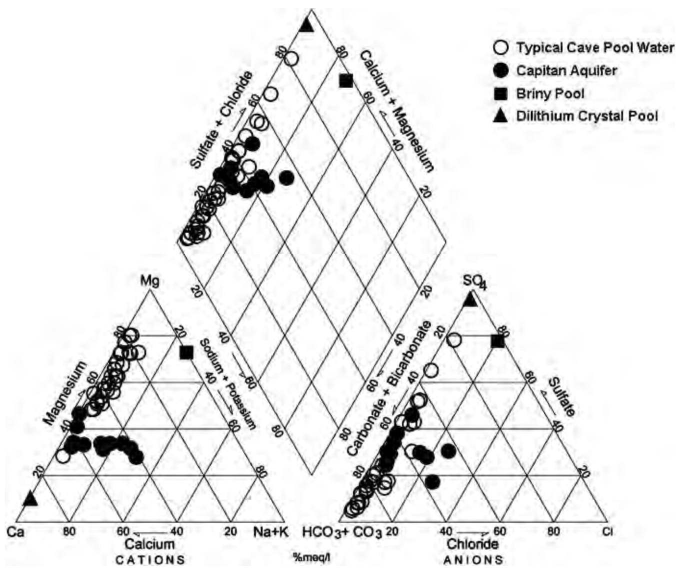

Figure 1. Trilinear diagram illustrating the major ion compositions of the four categories of Lechuguilla Cave water described by Turin and Plummer (2000): (1) Typical Cave Pool water, (2) Capitan Aquifer water, (3) Briny Pool water, and (4) Dilithium Crystal Pool water.

calcium, magnesium, bicarbonate, and sulfate due to interaction of ground water with calcite ($CaCO_3$), dolomite [$CaMg(CO_3)_2$], and massive gypsum deposits within the cave. Supersaturation with respect to calcite and dolomite occurs as a result of carbon dioxide [$CO_2(g)$] outgassing, the degree of which is largely controlled by the partial pressure of carbon dioxide [$P_{CO_2}(g)$] in the cave atmosphere. Pools in both Lechuguilla Cave and Carlsbad Cavern are recharged through flowstone seepage and ceiling drips originating from the overlying vadose zone; water can also be lost from the cave pools by processes such as overflow, evaporation, and leakage. Consequently, pools display a range in chemical composition due to a combination of factors such as variations in bedrock mineralogy along recharge flow paths, differences in localized evaporation rates, and residence times of water in the pools (Forbes, 2000; Turin and Plummer, 2000).

Based upon their evaluation of the 1986–1999 pool chemistry data, Turin and Plummer (2000) identified four types of water in Lechuguilla Cave: (1) Typical Cave Pool water, (2) Capitan Aquifer water, (3) Briny Pool water, and (4) Dilithium Crystal Pool water (Fig. 1). Typical Cave Pool water has a pH between 7.5 and 8.5, a magnesium to calcium (Mg:Ca) molar ratio greater than 1.0, a P_{CO_2} greater than atmospheric ($10^{-3.5}$ atm), and is oversaturated with respect to calcite and dolomite. Capitan Aquifer water is similar in composition, but is characterized by a higher P_{CO_2}, a lower Mg:Ca molar ratio, and has been shown to contain detectable concentrations of dissolved iron (0.2 to 0.9 mg L^{-1}) indicating that reducing conditions can exist in the regional aquifer (Turin and Plummer, 2000). The Briny Pool and Dilithium Crystal Pool represent two chemical extremes of unique composition when compared to most Lechuguilla Cave water. The Briny Pool water contains higher proportions of sodium and chloride when compared to Typical Cave Pool water (Fig. 1) and is apparently extremely evapoconcentrated, with a total dissolved solids (TDS) concentration of approximately 45,000 mg L^{-1}. The Dilithium Crystal Pool (TDS approximately 2,500 mg L^{-1}) contains the highest proportions of calcium and sulfate for any water sampled in the cave (Fig. 1), and is the only pool yet identified which is oversaturated with respect to gypsum.

Repeated sampling and analysis of certain Lechuguilla Cave pools has shown that individual pools tend to maintain fairly consistent chemistry. Lake Lechuguilla, however, experienced significant increases in the concentrations of sulfate and nitrate between 1986 and 1990. Turin and Plummer (2000) noted that these changes may be an indication of variations in local precipitation chemistry, or anthropogenic contamination due to proximity to the cave entrance, and suggested continued monitoring in Lake Lechuguilla. A number of other pools in Lechuguilla Cave also have the potential to be affected by human activities because of their proximity to designated camps and their continued use as drinking-water supply by scientists and explorers for 20 years. For example, coliform bacteria, a potential indicator of human fecal contamination, have been identified in a number of Lechuguilla Cave pools (Hunter et al., 2004; Barton and Pace, 2005), prompting closure of the Red Lake Camp in the Western Branch by the NPS until further notice.

The current study presents the first major ion chemical data that have been collected in eight years from Lake Lechuguilla and over 15 years from three other designated drinking-water sources in Lechuguilla Cave (Lake Louise, Pearlsian Gulf, and Tower Place). The primary objective of this study was to collect additional pool samples and characterize current chemical conditions in selected Lechuguilla Cave pools to better evaluate historical major ion trends and potential impacts to water quality from human activities. Although hundreds of samples have previously been collected and analyzed from Lechuguilla Cave pools, few data exist to evaluate the oxidation-reduction (redox) status of the pools. Therefore, a secondary objective was to evaluate the redox status of the pools by characterizing dissolved oxygen (DO), dissolved organic carbon (DOC), oxidation-reduction potential (Eh), and concentrations of redox-sensitive elements such as iron, manganese, and the forms of inorganic nitrogen (NH_3-N and NO_3-N).

Study Locations

Water samples were collected during 2005 and 2006 from selected pools located in various branches of Lechuguilla Cave. The general areas of sample collection are shown on Figure 2 and include: (1) Lake Lechuguilla

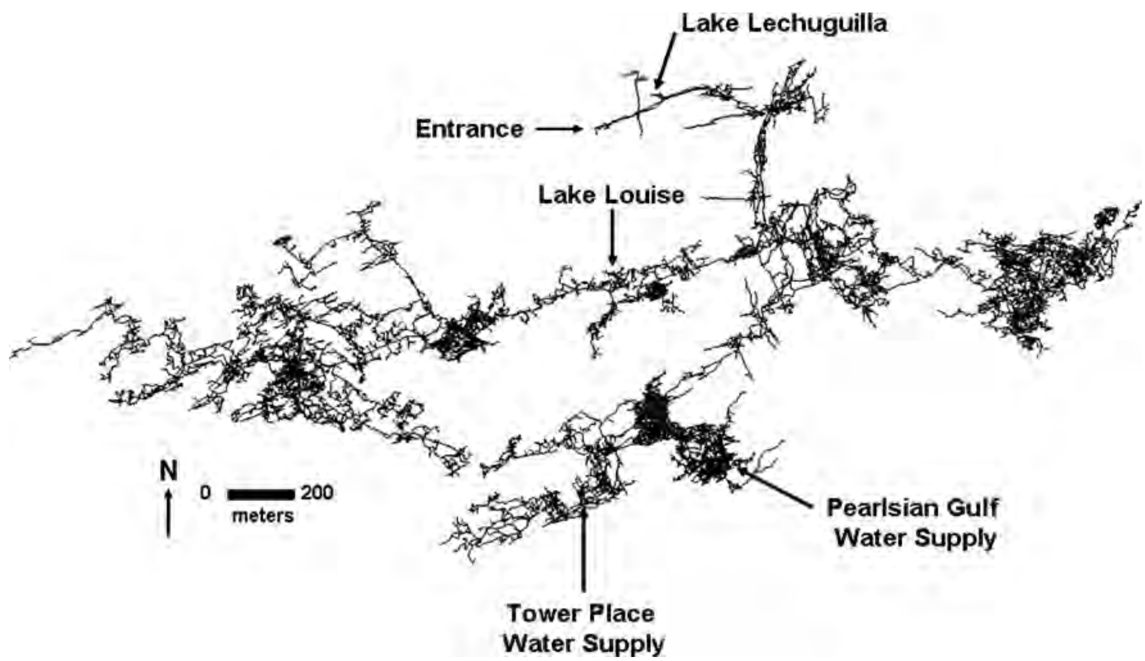

Figure 2. Map of Lechuguilla Cave (plan) showing the cave entrance and general locations of the pools sampled during this study (survey data provided by Carlsbad Caverns National Park, July 13, 2006).

(Entrance), (2) Lake Louise (Western Branch), (3) Pearlsian Gulf Water Supply (Southwestern Branch), and (4) Tower Place Water Supply (Southwestern Branch). Lake Lechuguilla is relatively close to the cave entrance and is located approximately 55.5 m below the entrance elevation (−55.5 m). Water levels in Lake Lechuguilla exhibit rapid responses to surface precipitation, and pool levels have decreased significantly over the past decade. Lake Lechuguilla is not a designated drinking-water supply for cavers, but the chemical trends in Lake Lechuguilla are of interest due to its proximity to both the main route of travel and the ground surface. Lake Louise is located in the Western Branch at approximately −307 m and is the designated drinking water supply for Deep Seas Camp. The Pearlsian Gulf Water Supply (−233 m) is the designated drinking-water supply for Big Sky Camp, and consists of a small pool near the Pearlsian Gulf in the Southwest Branch. The Tower Place Water Supply (−130 m) consists of a small pool located near the handline for the entrance to Tower Place and was only sampled once in 2005 during this study.

Materials and Methods

Field measurements of pH, temperature, and electrical conductivity (EC, corrected to 25 °C) were made using a combination HACH® (Loveland, CO) ion-selective electrode instrument, calibrated using standard pH and EC solutions prior to each use. Field measurement of ferrous iron (Fe^{2+}) and dissolved oxygen (O_2) were conducted using a HACH® DR-850 colorimeter. Redox potential (Eh) was measured using a combination Pt/AgAgCl electrode and standardized to the Standard Hydrogen Electrode using Zobell Solution (Eaton et al., 2005).

Water-sample collection followed the standard procedures for sampling and preservation of natural waters (Eaton et al., 2005). Pool samples were collected from the water surface using a sterilized plastic syringe and filtered through a 0.45 µm pore-size syringe filter and split into: (1) a hydrochloric-acid (HCl)-preserved sample for analysis of DOC, (2) a nitric-acid (HNO_3)-preserved sample for analysis of manganese plus total iron (Fe^{2+} + Fe^{3+}), (3) a sulfuric-acid (H_2SO_4)-preserved sample for determination of both ammonia-nitrogen (NH_3-N) and nitrate plus nitrite-nitrogen (NO_3+NO_2-N), and (4) an unpreserved sample for analysis of major dissolved cations and anions. Two field cave blanks (2005 and 2006) were also prepared by preserving and filtering analytical-grade distilled water into clean sample containers containing the appropriate preservative while in-cave to evaluate the presence of potential sample contaminants. Both cave blanks were prepared at Lake Lechuguilla.

Within one hour of exiting the cave, the water samples were stored under refrigeration and maintained at 4 °C or less during shipping to SVL Analytical, Inc. (Kellogg, ID) for chemical analysis. Chemical analyses were conducted using standard methods of the United States Environmental Protection Agency (USEPA, 1983): Dissolved organic carbon (Method 415.1), chloride (Method 300.0), dissolved calcium, potassium, magnesium, sodium, iron, manganese, silicon (Method 200.7), ammonia-nitrogen (NH_3-N, Method 350.1), carbonate alkalinity (Method 2020B), sulfate (Method 300.0), and nitrate+nitrite-nitrogen (NO_3+NO_2-

N, Method 353.2) (in this study, NO_3+NO_2-N concentrations are assumed to equal NO_3-N concentrations due to the instability of NO_2-N in the ambient aerobic environment). Laboratory quality assurance/quality control (QA/QC) samples included duplicates, matrix spikes, and laboratory control samples.

The analytical results were reviewed for QA/QC and chemical trends were evaluated in conjunction with historical pool chemistry data previously collected from the same locations (Turin and Plummer, 2000). The data were input into the geochemical speciation model PHREEQC (Parkhurst and Appelo, 1999), which uses the Debye-Hückel equation for ion activity calculations, to calculate P_{CO_2} values and mineral saturation states for the various carbonate, sulfate, and silicate minerals. The saturation index (*SI*) for a solid mineral phase is defined as:

$$SI = \log\left(\frac{IAP}{K_{sp}}\right) \tag{1}$$

where:

IAP = ion activity product observed in solution
K_{sp} = theoretical solubility product at field temperature

A positive *SI* indicates that the solution is oversaturated with respect to a given solid phase and that precipitation of the respective phase is thermodynamically favorable. A negative *SI* indicates that the solution is undersaturated and will dissolve the solid phase. When $SI = 0$, the solution and solid phases are in apparent equilibrium. In this study, apparent equilibrium is defined when *SI* values are between −0.50 and +0.50 due to inherent uncertainties in the thermodynamic data.

Results and Discussion

Quality Assurance/Quality Control

Analytical results from the two cave blanks (2005 and 2006) were below detection for all constituents except for low levels of calcium (0.085 to 0.235 mg L^{-1}), chloride (0.23 to 1.24 mg L^{-1}), and NH_3-N (0.04 mg L^{-1} in 2006). Cation-anion balances for all samples were within 5%. Percent recovery for laboratory control samples ranged from 95.3% to 108%, while percent recovery from matrix spikes ranged from 92% to 116%. Relative percent differences ranged from 0% to 8% for laboratory duplicate samples. All values for the laboratory control samples, matrix spikes, and laboratory duplicates were within acceptable limits (USEPA, 1994).

Field and Laboratory Results

The results for field and laboratory parameters collected from Lechuguilla Cave pools during the 2005 and 2006 study are provided in Table 1. The data are shown in conjunction with results from previous investigators for the Pearlsian Gulf and Tower Place water supply locations to demonstrate historical trends. Historical major ion chemistry for Lake Lechuguilla and Lake Louise (Turin and Plummer, 2000) are presented graphically and discussed in the following section, and therefore those data are not tabulated in Table 1. The discussion of field and laboratory results in this section pertains only to water samples collected during 2005 and 2006.

The field and laboratory results for selected Lechuguilla Cave pools studied during 2005-2006 are consistent with those of Typical Cave Pool water discussed by Turin and Plummer (2000). Field results show ranges in pH from 7.58 to 8.06, EC from 397 to 517 $\mu S\ cm^{-1}$, and temperature from 18.4 to 20.4 °C (Table 1). Dissolved oxygen ranged from 7.9 to 9.3 mg L^{-1} indicating the presence of aerobic conditions in the pools. The measured Eh values ranged from 416 to 466 mV and dissolved ferrous iron concentrations were <0.03 mg L^{-1} in all samples.

Laboratory results for the major cations and anions were used to generate a trilinear diagram illustrating the overall chemical composition of the pools (Fig. 3). The pool water compositions are predominantly Ca-Mg-HCO_3 waters, consistent with those of Typical Pool water (Turin and Plummer, 2000). The data indicate that each pool maintained consistent chemistry between 2005 and 2006, but there were slight differences in major ion composition between the pools. Lake Louise and the Pearlsian Gulf Water Supply contained higher proportions of calcium and sulfate when compared to Lake Lechuguilla and the Tower Place Water Supply (Fig. 3), perhaps due to a higher abundance of gypsum in these areas. Calculated total dissolved solids (TDS) concentrations ranged from 331 to 383 mg L^{-1} and were slightly higher in the Pearlsian Gulf and Tower Place water supplies when compared to Lake Lechuguilla and Lake Louise. As a result of preferential calcite precipitation over dolomite, the Mg:Ca molar ratios are greater than unity (Table 1), consistent with the majority of Lechuguilla Cave pools (Turin and Plummer, 2000).

Oxidation-Reduction (Redox) State

The redox state of the pools was evaluated by direct measurement of Eh and DO in conjunction with the concentrations of redox-sensitive elements (Table 1). The high DO concentrations indicate that the pools are in equilibrium with atmospheric oxygen. Consequently, the concentrations of both DOC and redox-sensitive metals (ferrous iron, total iron, and manganese) are below detection, and inorganic nitrogen is mainly present as the oxidized nitrate (NO_3-N) species rather than ammonia (NH_3-N) (Table 1). While the Eh measurements typically reflect oxidizing conditions, obtaining thermodynamically-meaningful Eh measurements when using a platinum electrode is not possible if the dominant redox-sensitive elements are carbon, nitrogen, oxygen, hydrogen, and oxidized sulfur (sulfate). These observations led to the development of a simplified redox classification scheme

Table 1. Recent (2005–2006) and historic chemical data for selected Lechuguilla Cave pools (mg L^{-1} unless otherwise indicated).

Parameter	Lake Lechuguilla Survey Station A10		Lake Louise Survey Station EC58		Pearlsian Gulf Water Supply Survey Station FUX9				Tower Place Water Supply Survey Station sFLVV2	
Depth Below Entrance (m)	−55.5		−307		−233				−130	
Approx. Pool Volume (m^3)	Variable[a]		8.7		1.6				2.6	
Sampling Date	6/17/05	6/17/06	6/13/05	6/12/06	4/2/90[b]	6/9/96[c]	6/15/05	6/15/06	5/29/89[b]	6/16/05
Field Parameters										
pH	8.06	8.03	7.66	7.62	7.80	7.58	7.62	7.63	7.90	7.62
Temperature (°C)	18.4	19.0	19.9	20.4	NR	NR	18.9	20.3	NR	18.9
Elect. Cond. (μs cm^{-1})	413	397	425	420	460	NR	517	476	430	517
Dissolved Oxygen	NM	7.9	7.9	8.4	NR	NR	9.3	7.9	NR	9.3
Eh (mV)	NM	416	455	451	NR	NR	442	466	NR	442
Fe^{2+}	< 0.03	< 0.03	< 0.03	< 0.03	NR	NR	< 0.03	< 0.03	NR	< 0.03
Laboratory Parameters										
Alkalinity (mg $CaCO_3$ L^{-1})	180	183	126	135	152	270	134	141	200	195
HN_3-N	< 0.03	< 0.03	0.04	0.05	NR	NR	< 0.03	0.04	NR	< 0.03
Ca	35.1	31.1	44.2	39.9	43.8	NR	48.3	43.7	31.7	29.7
Cl	3.4	3.65	3.02	4.16	2.3	NR	2.03	3.06	3.4	3.11
Dissolved Organic Carbon	< 1	< 1	< 1	< 1	NR	NR	< 1	< 1	NR	1.7
Fe	< 0.06	< 0.06	< 0.06	< 0.06	< 0.02	NR	< 0.06	< 0.06	< 0.02	< 0.06
Mg	32.8	32.7	27.8	27.6	33	NR	34.1	34.0	38.8	40.6
Mn	< 0.004	< 0.004	< 0.004	< 0.004	< 0.02	NR	< 0.004	< 0.004	< 0.02	< 0.004
NO_3-N	1.90	1.65	1.53	1.49	1.5	1.2	1.03	1.05	1.3	0.740
K	0.89	0.84	0.59	0.53	0.6	NR	0.73	0.65	1.1	0.74
Na	2.77	2.76	3.62	3.29	2.4	NR	2.52	2.26	3.0	2.92
Si	5.09	5.61	5.23	5.33	4.49	NR	4.91	4.95	4.81	4.95
SO_4	28.2	34.7	79.8	84.4	92	99.8	108	112	28	29.5
Total Dissolved Solids	342	348	331	342	376	NC	374	383	366	360
Mg:Ca Molar Ratio	1.54	1.74	1.04	1.14	1.24	NC	1.16	1.28	2.02	2.25

[a] 2.2 m^3 (June 2005) and 0.64 m^3 (June 2006).
[b] Collected by Gregg Oelker (Oelker, 1990).
[c] Collected by Helen Dawson (Turin and Plummer, 2000).
NR – not reported in cited study.
NM – not measured in current study.
NC – not calculated due to incomplete data.

which is broadly-based on the presence or absence of oxygen, organic carbon, iron, and manganese; according to the redox classification, the Lechuguilla Cave pool samples indicate an oxic environment (Langmuir, 1997).

GEOCHEMICAL MODELING

The results of geochemical modeling using PHREEQC (Table 2) indicate that the pool waters are generally in equilibrium with respect to calcite, ($CaCO_3$), dolomite, and magnesite ($MgCO_3$). High degrees of gypsum undersaturation were calculated, and silica concentrations in the waters appear to be controlled by chalcedony (SiO_2), as *SI* values were close to zero for this mineral. Calculated P_{CO_2} values were up to 12 times higher than atmospheric ($10^{-3.5}$ atm). The lowest calculated P_{CO_2} value ($10^{-2.80}$ atm) was for Lake Lechuguilla, while the highest calculated values ($10^{-2.39}$ atm) were for the Pearlsian Gulf and Tower Place water-supply locations. The low calculated ionic strength values (0.0062 to 0.0077 *M*) demonstrate that samples are within the range of ionic strength values considered valid for calculation of ion activities when using the Debye-Hückel equation (Langmuir, 1997).

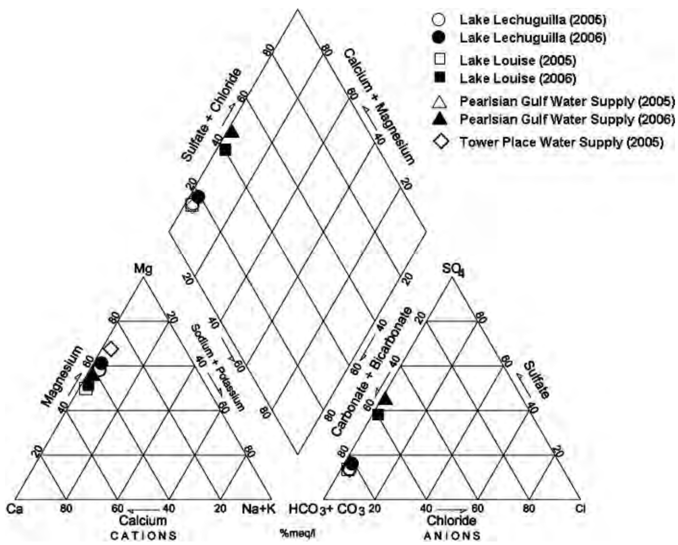

Figure 3. Trilinear diagram illustrating the major ion compositions for selected Lechuguilla Cave pools sampled during 2005 and 2006.

Historical Trends in Major Ion Chemistry

Pool chemistry data collected during 2005 and 2006 were used in conjunction with the data compiled by Turin and Plummer (2000) to examine historical major ion trends for selected Lechuguilla Cave pools. Between 1988 and 1990, Lake Lechuguilla reportedly experienced considerable increases in sulfate and nitrate concentrations, balanced by increases in calcium, magnesium, potassium and a decrease in bicarbonate (Fig. 4). During the same period, the concentrations of TDS also increased by 260 mg L^{-1}, although pH remained in the range between 7.4 and 8.4. The increases in sulfate and nitrate cannot be attributed to evapoconcentration because the associated increases in chloride were relatively small (Fig. 4) and the area has been shown to maintain a relative humidity > 95% year-round (Burger, 2005). Since 1996, the concentrations of sulfate, nitrate, and TDS have been decreasing, and the recent data collected during 2005 and 2006 indicate that Lake Lechuguilla has returned to baseline (pre-1989) chemical conditions (Fig. 4).

Water-level data have been collected from a staff gauge installed in Lake Lechuguilla since 1997. The relationship between precipitation and water level demonstrates the rapid hydrologic response of Lake Lechuguilla to precipitation, especially when water levels are closely monitored as demonstrated during 2004 and 2005 (Fig. 5). Above-average precipitation in 2004 produced considerable increases in Lake Lechuguilla water levels which declined rapidly thereafter. Major ion chemistry and lake level data collected during these recent fluctuations show that while water volumes changed considerably between June 2005 and June 2006 (from 2.2 to 0.64 m^3), the EC, TDS, and chloride concentrations remained constant (Table 1, Fig. 4). Together with observed rapid hydrologic responses to precipitation events at the surface, the absence of chemical concentration increases between 2005 and 2006 indicates that leakage, rather than evaporation, is the primary mechanism of water loss from Lake Lechuguilla.

Other possible explanations for the observed increases in nitrate and sulfate in cave pools are atmospheric deposition and either natural or anthropogenic biological activity (Turin and Plummer, 2000). Precipitation-weighted mean concentrations calculated using data from the National Atmospheric Deposition Program for Guadalupe Mountains National Park (Station TX22) (1986 through 1991) were 0.83 mg L^{-1} for nitrate, 0.17 mg L^{-1} for ammonium (NH_4^+), and 1.4 mg L^{-1} for sulfate. These concentrations do not explain the observed increases in nitrate or sulfate, however, when considering the enrichment factors (EF = pool:precipitation) calculated for nitrate (EF = 9) and sulfate (EF = 38) in Lechuguilla Cave pools (Turin and Plummer, 2000). It is interesting to note, however, that the maximum precipitation-weighted mean values for nitrate (3.17 mg L^{-1}) and sulfate (7.1 mg L^{-1}) occurred in 1989, corresponding to the time

Table 2. Mineral saturation index (*SI*), P_{CO_2}, and ionic strength (*I*) values for selected samples calculated using PHREEQC (Parkhurst and Appelo, 1999).

Mineral Phase	Lake Lechuguilla (6/17/06)	Lake Louise (6/12/06)	Pearlsian Gulf Water Supply (6/15/06)	Tower Place Water Supply (6/16/05)
Calcite ($CaCO_3$)	0.20	−0.19	−0.17	−0.17
Dolomite [$CaMg(CO_3)_2$]	0.64	−0.32	−0.17	0.01
Magnesite ($MgCO_3$)	−0.06	−0.62	−0.52	−0.32
Gypsum ($CaSO_4$•$2H_2O$)	−2.35	−1.88	−2.45	−2.45
Chalcedony (SiO_2)	−0.11	−0.15	−0.16	−0.16
Quartz (α-SiO_2)	0.40	0.36	0.35	0.35
SiO_2 (amorphous)	−0.93	−0.97	−0.67	−0.67
P_{CO_2} (atm)	−2.80	−2.54	−2.39	−2.39
Ionic Strength (*M*)	0.0062	0.0066	0.0077	0.0077

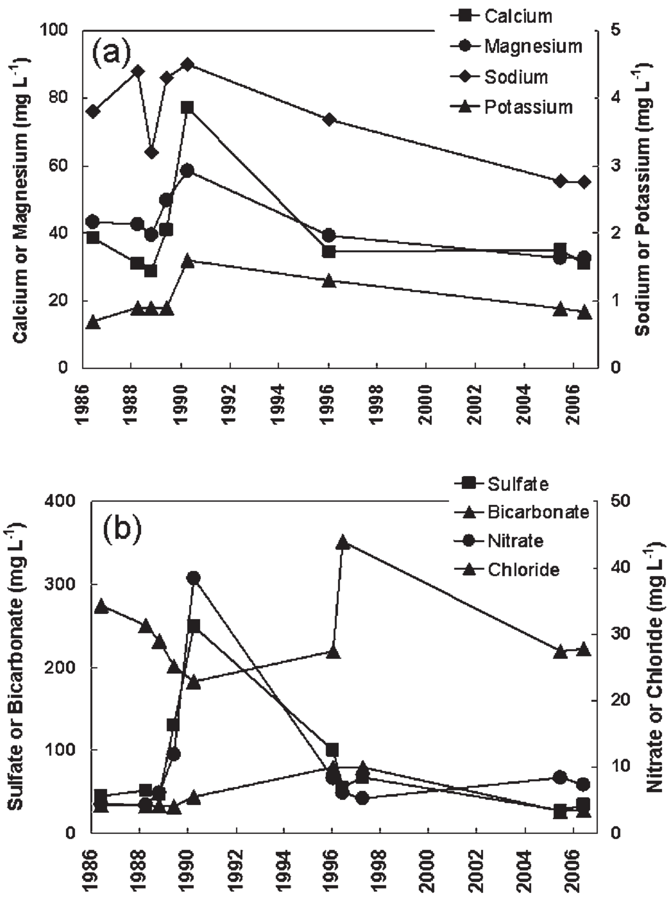

Figure 4. Historical trends in major ion chemistry for Lake Lechuguilla (1986–2006): (a) cation concentrations and (b) anion concentrations. The 2005 and 2006 data are from the present study.

when historical nitrate and sulfate concentrations began to increase (Fig. 4).

Lake Lechuguilla is in close proximity to the main trail, and therefore the potential also exists for anthropogenic contamination of the lake. The trail is narrow and steeply-sloping toward the lake, and therefore it is conceivable that disturbance and sloughing of rocks, mud, or other debris from the heavily-traveled route past Lake Lechuguilla could release constituents into the water. Anthropogenic contamination could also have resulted from dropping of food or foreign objects into the water, or tracking of bat guano on boots from the cave entrance, which was released to the water and slowly mineralized or dissolved over several years to produce the observed trends (Fig. 4). Nonetheless, simple mass balance calculations indicate that significant mass would have to be added to produce the observed concentration increases. For example, mineralization of the nitrogen contained in bat guano to produce a 30 mg L^{-1} increase in nitrate concentrations in Lake Lechuguilla, assuming a pre-1990 volume of 4 m^3, would require approximately 900 g of guano. It seems unlikely that the mass of guano or other foreign matter required to produce the observed concentration increases in Lake Lechuguilla could have been introduced into Lake Lechuguilla by human activities.

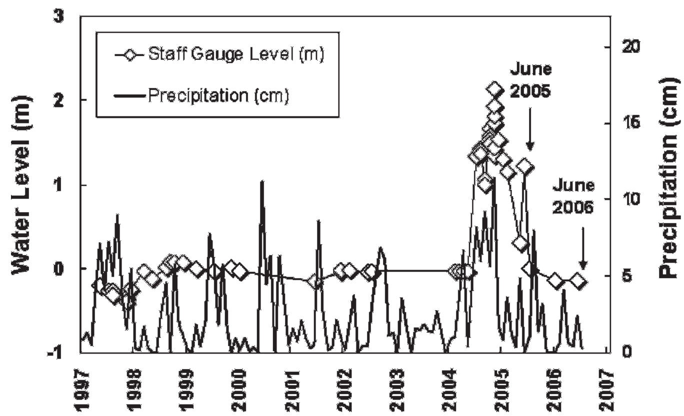

Figure 5. Lake Lechuguilla water levels and precipitation hydrograph for Carlsbad Caverns National Park for the period 1997–2006.

The increase in nitrate and sulfate concentrations in Lake Lechuguilla was relatively gradual and occurred over a period several years (Fig. 4), yet monitoring has shown that Lake Lechuguilla water volumes respond rapidly to surface precipitation events. Gradual changes in water quality would not be expected in such a dynamic system if anthropogenic contamination had occurred. Rather, the chemical trends are probably natural and related to a combination of variation in factors such as climate (chemistry, duration, and intensity of local precipitation events), soil biological activity, and the degree of water-soil-rock interaction of water percolating through the overlying vadose zone. Between 1990 and 2006, nitrate concentrations in seepage entering the Entrance Series near Lake Lechuguilla (Liberty Bell Room) ranged from 2.2 to 21.7 mg L^{-1}. The maximum concentrations of nitrate in seepage (21.7 mg L^{-1}) and in Lake Lechuguilla (38.5 mg L^{-1}) were both measured in 1990 and are of the same magnitude. Sulfate concentrations in seepage have varied from 11.5 to 29 mg L^{-1} but are generally an order of magnitude less than Lake Lechuguilla and other Entrance Series pools (Turin and Plummer, 2000). These observations indicate that nitrate concentrations in Lake Lechuguilla may be more closely related to those of vadose-zone seepage, whereas enrichment of sulfate in pools occurs to varying degrees due to chemical and mineralogical variations along cave seepage flow paths.

Historical trends in major ion concentrations for Lake Louise indicate minimal variation between 1988 and 2006 (Fig. 6). The consistent chemistry of Lake Louise (−307 m) in comparison to Lake Lechuguilla (−55.5 m) could reflect isolation from near-surface hydrologic processes, a lower degree of anthropogenic disturbance, or the longer flow path of water through the cave which results in chemically-consistent inflow to the pool. Examination of

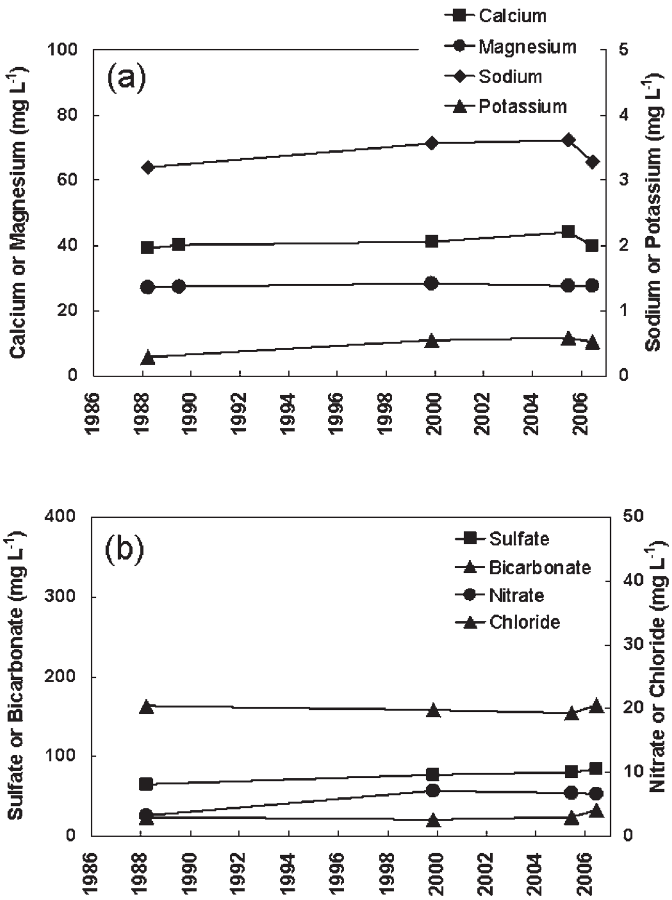

Figure 6. Historical trends in major ion chemistry for Lake Louise (1988–2006): (a) cation concentrations and (b) anion concentrations. The 2005 and 2006 data are from the present study.

both the historic and current major ion chemistry for Pearlsian Gulf and Tower Place Water Supply also indicates that the major cation and anion compositions of these waters have not changed significantly since they were first sampled and analyzed (Table 1).

Conclusions

Recent major ion chemistry data collected during 2005 and 2006 were used to supplement previous data collected from Lechuguilla Cave pools to evaluate historical trends in water chemistry. Lake Lechuguilla experienced unexplained increases in sulfate and nitrate between 1988 and 1990, but the major ion chemistry has returned to pre-1990 conditions. Evaluation of the historical chemical trends and hydrologic properties of Lake Lechuguilla indicate that the increases in sulfate and nitrate probably represent natural variations in the chemistry of vadose zone water and cave seepage near the surface. Both historical and recent major ion analyses from three other significantly deeper pools designated as drinking-water sources for cavers (Lake Louise, Tower Place/Pearlsian Gulf water supplies) indicates that their major ion chemistry has remained relatively constant since the first water samples were collected over 15 years ago. The pools were close to equilibrium with calcite, dolomite, and chalcedony, and calculated P_{CO_2} were 10 to 12 times greater than atmospheric. Evaluation of pool redox status indicates an oxic environment, with dissolved oxygen levels in equilibrium with the ambient atmosphere, and concentrations of DOC, NH_3-N, iron, and manganese below detection limits. Because the major ion composition of most Lechuguilla Cave pools generally remains stable, routine monitoring for inorganic constituents in Lechuguilla Cave pools is not necessary. However, current and future researchers are encouraged to incorporate general inorganic water-quality characterization into their research when appropriate, because periodic monitoring could possibly identify chemical variations which could occur from natural climatic, anthropogenic, or biological activities.

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OXIDATION-REDUCTION CHEMISTRY OF LECHUGUILLA CAVE SEEPAGE

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Abstract: Groundwater generally becomes increasingly reduced (decreasing Eh) with depth from the soil surface, and therefore seepage is a potential source of dissolved Mn, Fe, and NH_4 to caves. In Lechuguilla Cave, both abiotic and biotic processes have contributed to the origin of a vast array of secondary speleogenetic features which are enriched in Fe and Mn oxides. Existing chemical and physical properties of Lechuguilla Cave pool water indicates oxidizing conditions, with dissolved Fe and Mn below detection, and N existing primarily as NO_3. However, the redox chemistry of the cave seepage has not been well-studied. The objective of this study was to characterize the redox status of Lechuguilla Cave seepage and to test the hypothesis that seepage entering the cave from the overlying vadose zone is a potential source of dissolved Fe, Mn, and inorganic N (as both NH_4 and NO_3). If present in seepage, Fe, Mn, and NH_4 will oxidize in the cave environment, resulting in non-detectable concentrations in cave pools. Seepage was collected from eight locations in the cave and analyzed for field parameters (pH, EC, dissolved O_2(g), Eh, temperature) and concentrations of dissolved Fe (Fe^{2+} + total Fe), Mn, NO_3 + NO_2-N, and NH_4-N. Results indicate that low organic C concentrations prevent the occurrence of complete anaerobic conditions in seepage, but the concentrations of Mn and NH_4 indicate that slightly reducing conditions can exist. Iron concentrations were below detection (<0.06 mg L^{-1}) in all samples, and N existed primarily as NO_3. Field-measured Eh values obtained using a Pt electrode (Eh_m) did not correlate with computed Eh values for various redox couples (Eh_c), and the poor agreement between Eh_c values for the different couples indicates the absence of redox equilibria in the samples. Rather than characterization of redox status according to Eh, seepage is classified as ranging from oxic to suboxic. This redox classification indicates that Lechuguilla Cave seepage can generally be expected to contain low concentrations of organic C and dissolved Mn, dissolved O_2(g) ranging from 1 μM to >30 μM, but with Fe below typical analytical detection limits.

Introduction

Lechuguilla Cave is located in the Guadalupe Mountains of southeastern New Mexico and is known as one of the world's finest examples of H_2SO_4 speleogenesis. Since its discovery in 1986, Lechuguilla Cave has provided researchers with unique opportunities in the study of speleogenesis, geology, microbiology, and geochemistry (e.g., Davis, 2000; DuChene, 2000; Northup et al., 2000; Polyak and Provencio, 2001). Numerous isolated pools of water exist throughout Lechuguilla Cave; and consequently, many of these pools have been studied to characterize their major ion and trace element compositions. Results from approximately 200 water samples collected by various researchers between 1986 and 1999 show that the majority of Lechuguilla Cave pools are dominated by Ca, Mg, HCO_3, and SO_4 due to interaction of groundwater with calcite ($CaCO_3$), dolomite [$CaMg(CO_3)_2$], and massive gypsum ($CaSO_4 \cdot 2H_2O$) (Turin and Plummer, 2000). Typical Lechuguilla Cave pool water has a pH between 7.5 and 8.5, a Mg:Ca molar ratio greater than one, contains a CO_2(g) partial pressure (P_{CO_2}) greater than atmospheric ($10^{-3.5}$ atm), and is usually oversaturated with respect to calcite and dolomite. Water at Lechuguilla's deep point (Lake of the White Roses, −480 m) contains a higher P_{CO_2} and a lower (<1) Mg:Ca molar ratio, and therefore is believed to represent the regional Capitan Aquifer (Turin and Plummer, 2000).

Although the chemical and physical characteristics of Lechuguilla Cave pool water have been well-characterized, the chemical composition of seepage has received less attention. Seepage is defined as water which enters the cave environment from the overlying vadose zone, usually as ceiling drips or slow-flowing water emanating from bedrock. Conceptually, typical Lechuguilla Cave pool water will be different from seepage to the extent that it is influenced by CO_2(g) outgassing, oxidation, mineral precipitation, dilution, or evaporation. Cave seepage originates primarily as surface water which infiltrates into overlying soils, and aerobic microbial decomposition of dissolved organic C tends to deplete the available O_2(g) and increase the (P_{CO_2}) in percolating waters. As a result, the oxidation-reduction (redox) potential, expressed in terms of Eh, typically decreases in ground water isolated from the

Table 1. The standard potential (E°) and Eh (pH = 7, 25 °C) for selected redox couples in groundwater.[a]

Reaction	$E°$ (Volts)	Eh (Volts)
$4H^+ + O_2(g) + 4e^- = 2H_2O$	1.23	0.816
$MnO_2 + 4H^+ + 2e^- = Mn^{2+} + 2H_2O$	1.23	0.544
$NO_3^- + 2H^+ + 2e^- = NO_2^{-\,-} + H_2O$	0.845	0.431
$NO_2^- + 8H^+ + 6e^- = NH_4^{+\,+} + 2H_2O$	0.892	0.340
$Fe(OH)_3 + 3H^+ + e^- = Fe^{2+} + 3H_2O$	0.975	0.014
$SO_4^{2-} + 10H^+ + 8e^- = H_2S(aq) + 4H_2O$	0.301	−0.217

[a] Langmuir, 1997. Eh assumes P_{CO_2} = 0.2 bar, $[Mn^{2+}] = 10^{-4.74}$ M, $[Fe^{2+}] = 10^{-4.75}$ M, and $[NO_3^-] = [NO_2^-] = [NH_4^+]$.

atmosphere. Eh is related to the activity of electrons (e−) in solution, and similar to pH, is a master geochemical variable which controls the chemical behavior and mobility of nutrients and trace metals in groundwater.

The rate and extent of Eh decline in percolating ground water is a function of both the rate of $O_2(g)$ replenishment and the availability of organic C and other reductants (Langmuir, 1997). Accompanying the decrease in Eh are the shifts in chemical equilibria between various redox couples (Table 1). In the absence of $O_2(g)$, microbial oxidation of organic C is followed by reduction of NO_3 and NO_2, MnO_2, and $Fe(OH)_3$; under extremely reducing conditions, SO_4 can be reduced to $H_2S(g)$. Under neutral pH conditions, the Eh of natural shallow and deep ground water environments generally ranges between 0 and 0.20 V (Garrels and Christ, 1965). Therefore, depending on the extent of locally-reducing conditions in the vadose zone, seepage is a potential source of redox-indicator elements to the cave, such as Fe, Mn, and various forms of N (NO_3 plus NH_4) (Table 1).

Some of the most exemplary features of Lechuguilla Cave are the result of H_2SO_4 speleogenesis which occurred during the late Miocene and Pliocene, under conditions much different than exist today (Jagnow et al., 2000). However, Lechuguilla Cave also contains many spectacular examples of actively-growing dripstone and flowstone speleothems, in contrast to nearby Carlsbad Cavern where the majority of speleothems are inactive (DuChene, 1997). Dripstone and flowstone in Lechuguilla Cave tend to be concentrated in areas containing seeping water, and occur in various colors, such as white, brown, yellow, red, and orange. Some spectacular examples of colored dripstone and flowstone in Lechuguilla Cave occur in the Liberty Bell Area, Tower Place, Treehouse, and Vesuvius (Fig. 1).

The presence of dissolved Fe, Mn, and humic substances in cave seepage is known to influence the color of

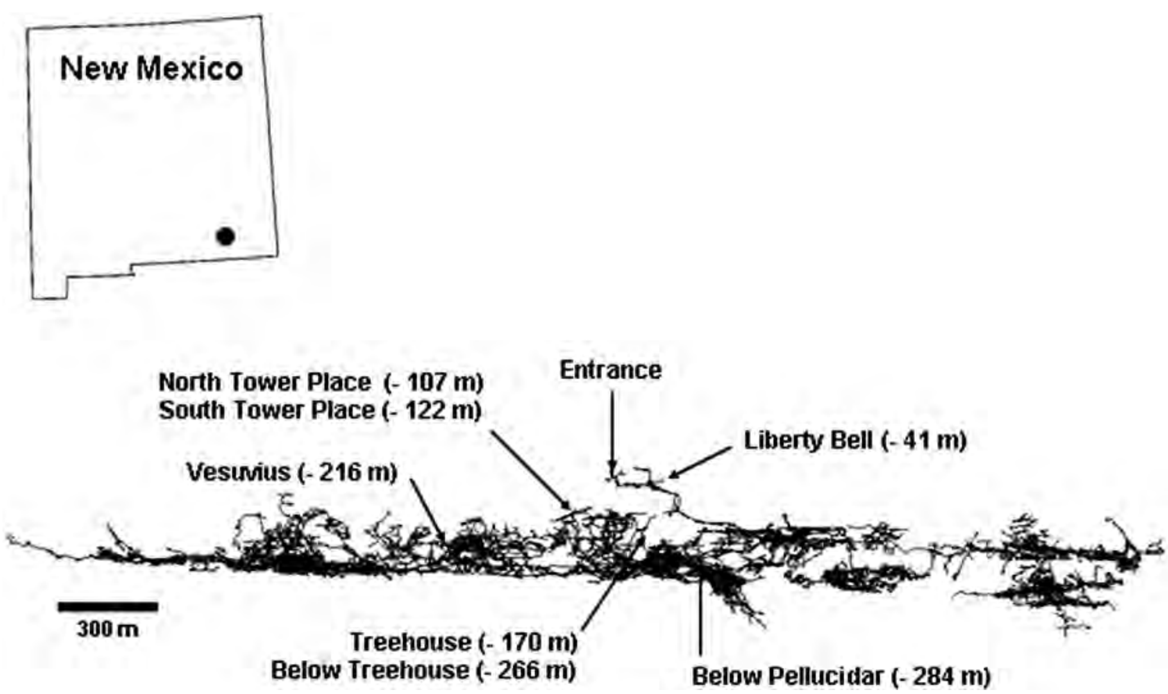

Figure 1. Map of Lechuguilla Cave (profile) showing the general locations and depths below entrance for cave seepage sampled during this study (survey data provided by Carlsbad Caverns National Park, July 13, 2006).

Table 2. Summary of historical analyses for redox-sensitive elements in Lechuguilla Cave pool and seepage water (compiled from Turin and Plummer, 2000).

	Fe		Mn		NH_4		NO_3		NO_2	
Parameter	Pools	Seepage	Pools	Seepage	Pools	Seepage	Pools	Seepage	Pools	Seepage
No. Observations	87	8	87	8	32	1	151	10	25	1
No. Detections	6	0	1	0	17	0	151	10	0	0
Detection Frequency (%)	6.9	0	1.2	0	53	0	100	100	0	0
Mean of Detectable Values	0.01	NC	0.002	NC	0.05	NC	10.7	10.2	0	0.02
Median Detection Limit	0.02	0.02	0.02	0.02	0.02	0.05	NR	NR	0.02	0.02
Minimum Detection Limit	0.01	0.01	0.002	0.01	0.02	0.05	NR	NR	0.02	0.02
Maximum Detection Limit	0.20	0.20	0.02	0.02	0.05	0.05	NR	NR	0.02	0.02

NC = not calculated due to 0% detection.
NR = not reported due to 100% detection.

many speleothems (White, 1997) and may also serve as a potential energy source for a variety of microorganisms (Northup et al., 1997). However, the role of dissolved Fe and Mn in present-day Lechuguilla speleothem formation has not been evaluated. Poorly-crystalline Mn oxides are common in the cave environment, and it has been suggested that certain types of hydrous Mn oxides in Lechuguilla Cave may be secondary speleogenetic by-products, or perhaps even unrelated to speleogenesis (Polyak and Provencio, 2001). Both abiotic and biotic precipitation of Fe oxides is also common in Lechuguilla, with possible sources of reduced Fe existing as impurities in limestone, or as ferrous iron (Fe^{2+}) in infiltrating water and cave pools (Northup et al., 2000; Northup and Lavoie, 2001). Elevated concentrations of inorganic N in selected Lechuguilla Cave pools (Turin and Plummer, 2000) raise additional questions regarding sources of N in the cave. While inorganic N in caves is sometimes derived from guano, the only known guano deposits in Lechuguilla are the historic deposits mined in 1914 from the entrance pit. The source of N in most caves is believed to originate as either NH_4 or NO_3 in ground-water seepage (Northup and Lavoie, 2001).

In a recent study of Lechuguilla Cave pools, Levy (2007) evaluated the redox status of selected pools by measuring dissolved O_2(g), dissolved organic C (DOC), Eh, Fe^{2+} plus total Fe, Mn, NO_3, and NH_4. Results of the redox evaluation indicated an oxic pool environment (Langmuir, 1997) with dissolved O_2(g) levels in equilibrium with the ambient atmosphere, N present as NO_3, and non-detectable concentrations of DOC, Mn, Fe, and NH_4. A review of historical data indicates that the number of both pool and seepage samples previously analyzed for Fe, Mn, and inorganic N is limited (Table 2). While the frequency of historic Fe and Mn detection was higher for the pools when compared to seepage, the number of pool samples analyzed (N = 87) was greater than the number of seepage samples (N = 8), and the measured Fe and Mn concentrations were near the limit of detection. Nitrite (NO_2) is an unstable intermediate produced during nitrification (Stumm and Morgan, 1996) and was below detection in all pool (N = 25) and seepage (N = 1) samples. Thirty-two pool samples were analyzed for NH_4, with a 53% frequency of detection and a mean concentration also near the detection limit. A single seepage sample was analyzed for NH_4 (<0.05 mg L^{-1}). Prior analysis for NO_3 in pools (N = 151) and seepage (N = 10) indicate that NO_3 was detected in 100% of the samples, and that the mean NO_3 concentration in both types of water is approximately 10 mg L^{-1} (Table 2).

The objective of the current study was to characterize the redox status of Lechuguilla Cave seepage to test the hypothesis that ground water entering the cave from the overlying vadose zone is a potential source of dissolved Fe, Mn, and inorganic N (as NO_3 and NH_4) to the cave system. A sampling protocol was developed to chemically-preserve the various forms of inorganic redox species and to analyze the samples using lower detection limits. If present in seepage, dissolved Fe and Mn will eventually oxidize and precipitate in the cave environment, resulting in non-detectable concentrations in pools. Inorganic N may be present as NO_3 and/or NH_4 in seepage, but will oxidize to NO_3 which becomes the main species of inorganic N in Lechuguilla Cave pools. Therefore, there could be a higher frequency of detection for any given reduced species (Table 1) in near-surface seepage, compared to seepage from lower elevations which may be more oxidized due to relatively longer periods of exposure to atmospheric O_2(g) in the cave.

Study Locations

Seepage collection sites in Lechuguilla Cave were located in the Entrance Series (Liberty Bell Area), the

Table 3. Lechuguilla Cave seepage sampling locations (2005–2006).

Drip Location	Aproximate Seepage Elev. (m)[a]	Collection Station	Tie-in Station	Distance (m)	Azimuth (degrees FS)[b]	Inclination (degrees FS)
Liberty Bell Area (sADR1)	−41	sADR1	sADR0	5.73	10	−34
		sADR0	ADR0	6.25	40	+7
Liberty Bell Area (sADR2)	−41	sADR2	sADR1	9.14	178	+30
Below Pellucidar	−284	sEC30A	EC30	10.5	272	+39
North Tower Place	−107	sFLVV7	FLVV7	3.05	267	−27
South Tower Place	−122	sFLVV8	FLVV8	12.2	75	+21.5
Below Treehouse	−266	EY24	…	…	…	…
Treehouse (sECR11B)	−170	sECR11B	sECR11A	29.8	30	+17
		sECR11A	ECR11	5	0	+90
Vesuvius	−216	sJF11A	JF11	4.90	165.5	−6.5

[a] Below entrance datum.
[b] Degrees foresight with Suunto from tie-in station.

Western Branch (Below Pellucidar, Treehouse), and the Southwestern Branch (Tower Place, Vesuvius) of Lechuguilla Cave (Fig. 1). Eight specific drip locations were sampled during four separate trips into Lechuguilla Cave led by the author during June 13 to 18, 2005 and during June 12 to 17, 2006 (trip reports on file at the Cave Resources Office, Carlsbad Caverns National Park). The specific sampling locations with survey tie-in information are given in Table 3 and represent elevations ranging from −41 m below the Entrance (Liberty Bell Area) to −284 m below the Entrance (Below Pellucidar).

MATERIALS AND METHODS

SAMPLE COLLECTION AND FIELD MEASUREMENTS

Water sampling procedures followed standard methods used for the collection and preservation of water samples (Eaton et al., 2005). Seepage samples were collected from the various drip locations into polyethylene beakers and immediately transferred into clean-certified sample bottles. Samples collected for determination of redox-sensitive species (Fe, Mn, NH_4-N, NO_3-N) were not filtered to minimize the effects of sample oxidation. Each sample was split into four bottles: (1) a filtered (0.45 µm), unpreserved sample for analysis of Ca, Mg, HCO_3, Cl, K, and SO_4, (2) an HCl preserved sample for analysis of total organic carbon (TOC), (3) a HNO_3 preserved bottle for analysis of Fe and Mn, and (4) a H_2SO_4 preserved bottle for determination of both NH_4-N and NO_3 + NO_2-N. (Note: because NO_2-N is an unstable intermediate in the environment, the concentration of NO_3 + NO_2-N is used as a measure of NO_3-N because it allows for chemical preservation of the sample). Two field cave blanks (2005 and 2006) were also prepared by preserving and filtering analytical-grade distilled water into clean sample bottles containing the appropriate preservative while in-cave (Lake Lechuguilla) to evaluate the potential for sample contamination during sampling.

Field measurements of pH, temperature, and electrical conductivity (EC) were made using a combination HACH® (Loveland, CO) ion-selective electrode instrument which was calibrated using standard solutions before each use. Determination of Fe^{2+} and dissolved O_2(g) was also conducted in the field using a HACH® DR-850 colorimeter. Redox potential (Eh) was measured using a combination Pt/Ag-AgCl electrode and standardized to the Standard Hydrogen Electrode using Zobell Solution (Eaton et al., 2005).

Following collection and transport to the surface, the samples were stored at approximately 4 °C and then shipped to SVL Analytical, Inc. (Kellogg, ID) for chemical analyses using methods of the United States Environmental Protection Agency (USEPA, 1983): TOC (Method 415.1), Cl (Method 300.0), Ca, K, Mg, Na, Fe, Mn, Si (Method 200.7), NO_3 + NO_2-N (Method 353.2), NH_3-N (Method 350.1), carbonate alkalinity (Method 2020B), and SO_4 (Method 300.0). Laboratory quality control samples included duplicates, matrix spikes, and laboratory control samples.

GEOCHEMICAL MODELING

The major ion chemistry data were input into the geochemical speciation model PHREEQC which uses an extended Debye-Hückel equation for ion activity calculations (Parkhurst and Appelo, 1999). PHREEQC was used to calculate P_{CO_2} (g) and mineral saturation index (*SI*) values for various carbonate, sulfate, and silicate minerals, defined as:

$$SI = \log\left(\frac{IAP}{K_{sp}}\right) \quad (1)$$

where:

IAP = ion activity product observed in solution
K_{sp} = theoretical solubility product at field temperature

A positive *SI* indicates that the solution is oversaturated with respect to a given solid phase which could potentially precipitate, while a negative *SI* indicates undersaturation with a solid phase which could potentially dissolve. When $SI = 0$, the solution and solid phase are in apparent equilibrium. In this study, apparent equilibrium is defined when *SI* values are between −0.50 and +0.50 due to inherent uncertainties in the available thermodynamic data.

Redox equilibrium was evaluated by comparing Eh values computed using PHREEQC (Eh_c) for the following redox couples: $O_2(aq)/H_2O$, NH_4^+/NO_3^-, $N_2(aq)/NO_3^-$, and $Mn^{2+}/MnO_2(s)$. The theoretical voltages for these couples are related to their standard electrode potentials (E°) (Table 1) through the Nernst equation:

$$\mathrm{Eh} = E^\circ + \frac{2.303RT}{nF}\log\left(\frac{a_{\mathrm{Ox}}}{a_{\mathrm{Red}}}\right) \qquad (2)$$

where:

$R = 8.314 \times 10^{-3}$ kJ deg^{-1} mol^{-1}
T = absolute temperature
n = number of electrons (e−)
F = Faraday's constant (96.42 kJ volt^{-1} mol^{-1})
$\frac{a_{\mathrm{Ox}}}{a_{\mathrm{Red}}}$ = ratio of the activity products of oxidized to reduced species

In theory, redox equilibrium exists when values of Eh_c for the various redox couples are in agreement; however, dissimilarity between Eh_c values would indicate redox disequilibrium, and the absence of a master system Eh (Lindberg and Runnells, 1984).

Results and Discussion

Quality Assurance/Quality Control

Calculated percent recovery from the laboratory control samples ranged from 95.3% to 108%, while percent recovery from matrix spikes ranged from 92% to 116%. Relative percent differences ranged from 0% to 8% for laboratory duplicates and cation-anion balances for all samples were within 5%. Therefore, all values for the laboratory control samples, matrix spikes, and laboratory duplicates were within acceptable limits (USEPA, 1994). Analytical results from the two cave blanks (2005 and 2006) were below detection for all constituents except for low levels of Ca (0.085 and 0.235 mg L^{-1}), Cl (0.23 and 1.24 mg L^{-1}), and NH_4-N (0.04 mg L^{-1} in 2006).

Field Measurements

The pH of seepage ranged from 7.67 to 8.50 and the EC ranged from 357 to 583 μS cm^{-1} (Table 4), comparable to the chemistry of typical Lechuguilla pools (Turin and Plummer, 2000; Levy, 2007). The measured Eh values (420 to 460 mV) in seepage are consistent with water that is in contact with the atmosphere and saturated with dissolved $O_2(g)$ (Langmuir, 1997). Field results for Fe^{2+} were below detection (<0.03 mg L^{-1}), also reflecting the presence of dissolved $O_2(g)$ and an absence of moderately-reducing

Table 4. Selected field and redox parameters for Lechuguilla Cave seepage samples.

Location	Sample Date	pH	EC (μS cm^{-1})	Eh (mV)	Total Fe (mg L^{-1})	Fe^{2+} (mg L^{-1})	Dissolved $O_2(g)$ (mg L^{-1})	TOC (mg L^{-1})	Mn^{2+} (mg L^{-1})	NO_3/N (mg L^{-1})	NH_4/N (mg L^{-1})
Liberty Bell Area (sADR1)	6/18/'05	8.30	390	NM	<0.06	NM	NM	<1.0	<0.004	0.84	0.03
	6/17/'06	7.79	380	420	<0.06	<0.03	7.8	<1.0	<0.004	0.85	0.04
Liberty Bell Area (sADR2)	6/18/'05	NM	NM	NM	<0.06	NM	NM	1.1	0.0066	2.16	0.15
	6/17/'06	7.77	412	419	<0.06	<0.03	7.7	1.3	<0.004	2.36	0.05
Below Pellucidar (sEC30A)	6/13/'05	7.87	357	454	<0.06	<0.03	8.8	<1.0	<0.004	0.68	<0.03
North Tower Place (sFLVV7)	6/16/'05	8.50	583	460	<0.06	<0.03	7.0	1.3	<0.004	0.71	<0.03
South Tower Place (sFLVV8)	6/16/'05	7.92	567	460	<0.06	<0.03	7.1	1.2	0.0063	0.71	0.04
Below Treehouse (EY24)	6/13/'06	7.67	423	434	<0.06	<0.03	7.7	<1.0	<0.004	0.84	0.20
Treehouse (sECR11B)	6/13/'06	7.74	381	425	<0.06	<0.03	7.8	<1.0	0.013	0.74	0.19
Vesuvius (sJF11A)	6/16/'06	8.03[a]	547[a]	NM	<0.06	NM	NM	<1.0	<0.004	1.32	0.04

NM = not measured.
[a] Laboratory measurement.

conditions. Although dissolved $O_2(g)$ measurements were conducted immediately upon sample collection, introduction of atmospheric $O_2(g)$ could not be completely avoided. However, the mean concentration of dissolved $O_2(g)$ in seepage (7.7 mg L^{-1}) is lower than the mean of 8.5 mg L^{-1} measured in selected pools (Levy, 2007). This suggests that seepage is probably not completely devoid of dissolved $O_2(g)$ prior to entering the cave, but also that the samples had not yet completely equilibrated with atmospheric $O_2(g)$. No significant correlations existed between dissolved $O_2(g)$ concentrations in seepage and either temperature or elevation within the cave.

REDOX-INDICATOR SPECIES

The TOC values in Table 4 are the first reported for Lechuguilla Cave seepage, and ranged from <1.0 to 1.3 mg L^{-1}, consistent with those previously reported for Lechuguilla pools (Turin and Plummer, 2000; Levy, 2007). Although the TOC concentrations are probably too low to produce complete anaerobic conditions, the detectable concentrations of NH_4-N and Mn in some samples indicates that slightly reducing conditions can exist in seepage. The reduced form of N (NH_4) was detected in the majority of samples, ranging from 0.03 to 0.20 mg L^{-1} as NH_4-N (Table 4). Nitrate, however, was the dominant form of inorganic N present, with NO_3-N concentrations on the order of 1 to 2 mg L^{-1} (4.5 to 8.9 mg L^{-1} as NO_3). While Fe concentrations were below detection (<0.06 mg L^{-1}) in all samples, seepage from certain locations near the surface (Tower Place, Liberty Bell, Treehouse) contained higher concentrations of Mn (0.006 to 0.013 mg L^{-1}) compared to those collected from greater depths (Below Pellucidar, Below Treehouse, Vesuvius). The higher frequency of Mn detection near the surface relative to the deeper samples can be explained by shorter exposure time to the cave atmosphere, allowing less time for Mn to oxidize and precipitate.

Generally consistent chemistry results were obtained at each of the two Liberty Bell Area locations when the 2005 and 2006 data are compared (Table 4). The higher NO_3-N and TOC concentrations at location sADR2 compared to sADR1, however, also illustrate the chemical variation that can occur between two seepage locations in close proximity. In 2005, Mn (0.0066 mg L^{-1}) and NH_4-N (0.15 mg L^{-1}) concentrations at location sADR2 were higher compared to 2006, perhaps due to increased soil saturation levels following above-average precipitation (Burger, 2005). However, a shelfstone pool which receives seepage directly from sADR2 contained Mn, Fe, and NH_4-N either at or below the detection limit (Levy, 2006). These observations support the hypothesis that such redox-indicator species in seepage eventually oxidize in the cave environment, resulting in lower concentrations in pools. The lower Mn concentration measured Below Treehouse (<0.004 mg L^{-1}) compared to the higher concentration in the Treehouse (0.013 mg L^{-1}) provides additional evidence for Mn oxidation and precipitation along flow paths (Table 4).

The presence of low to non-detectable concentrations of Fe and Mn in Lechuguilla Cave seepage, coupled with measurable TOC concentrations in some of the more highly-decorated areas (Liberty Bell, Tower Place), is consistent with speleothem coloration by humic substances originating from decomposition of plant materials in overlying soils. Speleothem coloration can be caused by the presence of pigmenting substances, such as Fe and Mn oxides. However, humic substances have been shown to impart tan, orange, and brown colors when incorporated into calcite, and are considered to be the primary cause of most coloration observed in cave travertine (White, 1997).

MAJOR ION CHEMISTRY AND GEOCHEMICAL MODELING

The major ion chemistry of seepage is difficult to distinguish from typical cave pool water, which is variable with respect to Ca:Mg:HCO_3 ratios, contains elevated P_{CO_2} (g) concentrations and a pH between 7.5 and 8.5. The results of geochemical modeling (Table 5) indicate equivalent mineral solubility controls and calculated $P_{CO_2}(g)$ concentrations previously reported for Lechuguilla pools (Turin and Plummer, 2000; Levy, 2007). Seepage was usually in equilibrium with calcite and magnesite, and sometimes oversaturated with respect to dolomite, while high degrees of gypsum undersaturation were calculated. Silica concentrations appear to be controlled by chalcedony rather than quartz. The majority of calculated $P_{CO_2}(g)$ levels were approximately 10 times higher than atmospheric (Table 5). The similarities in pH and calculated $P_{CO_2}(g)$ values between seepage and pools are at least partially attributed to disequilibrium of seepage chemistry as it unavoidably contacts the cave atmosphere during sampling.

Nernstian Eh_c values computed using PHREEQC are shown in relation to their respective field-measured Eh_m values on Figure 2. These data illustrate that a relatively narrow range in Eh_m values exists compared to the wide range in Eh_c values computed for the various redox couples. The poor agreement between the Eh_c values illustrates the lack of internal redox equilibrium in the seepage samples, and deviation of the data points from the 1:1 line indicates the difficulty in determining a controlling system Eh when using a Pt electrode in the field. The lack of agreement between Eh_c and Eh_m values in ground water has been documented in many natural waters and is attributed to factors such as: (1) inaccuracy of the Pt electrodes caused by surface poisoning and/or electrode drift in poorly-poised systems, (2) slow redox kinetics and disequilibrium between redox couples, and (3) Eh_m values resulting from measurement of mixed potentials which do not correspond to a single redox couple (Langmuir, 1971; Lindberg and Runnells, 1984; Langmuir, 1997).

EVALUATION OF SEEPAGE REDOX STATUS

The aqueous concentrations of the redox-sensitive species of O, N, Mn, and Fe in conjunction with field-measured Eh values (Eh_m) are consistent with the presence of oxidizing conditions in Lechuguilla Cave seepage. The

Table 5. Mineral saturation index (*SI*) values and P_{CO_2} (g) values calculated using PHREEQC (Parkhurst and Appelo, 1999).

Mineral Phase	Liberty Bell Area (sADR1)	North Tower Place (sFLVV7)	South Tower Place (sFLVV8)	Vesuvius (sJF11A)	Treehouse (sECR11B)	Below Treehouse (EY24)	Below Pellucidar (sEC30A)
Calcite ($CaCO_3$)	0.18	1.13	0.20	0.36	−0.06	−0.05	0.18
Dolomite [$CaMg(CO_3)_2$]	0.43	2.4	0.77	1.2	0.20	0.02	0.61
Magnesite ($MgCO_3$)	−0.24	0.72	0.07	0.36	−0.24	−0.43	−0.07
Gypsum ($CaSO_4{\cdot}2H_2O$)	−2.4	−2.2	−2.6	−2.6	−2.9	−2.0	−2.8
Chalcedony (SiO_2)	−0.22	−0.20	−0.23	−0.15	−0.12	−0.12	−0.17
Quartz (α–SiO_2)	0.28	0.30	0.27	0.35	0.39	0.38	0.34
log P_{CO_2}(g)	−2.5	−3.1	−2.6	−2.5	−2.4	−2.4	−2.5

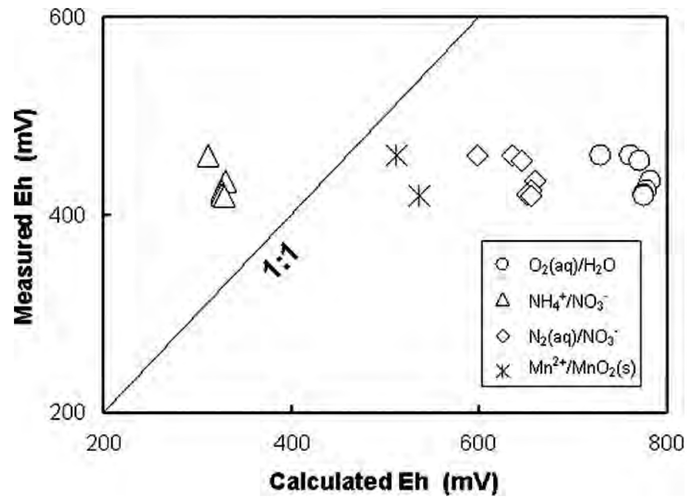

Figure 2. Nernstian Eh values (Eh_c) computed using PHREEQC versus field-measured Eh values (Eh_m) measured with a Pt electrode.

seepage contains around 1 mg L^{-1} of TOC, compared to the median DOC concentration of 0.7 mg L^{-1} for U.S. ground water (Leenheer et al., 1974). However, approximately 3 to 4 mg L^{-1} of organic C is typically required for groundwater to become completely anaerobic (Langmuir, 1997). The low concentrations of Mn and NH_4-N and non-detectable Fe concentrations are consistent with the low concentrations of organic C present in the seepage.

Because of the difficulty in obtaining thermodynamically-meaningful Eh measurements in most natural waters, Berner (1981) proposed a simplified redox classification scheme which is broadly-based on the presence or absence of either dissolved O_2(g) or H_2S(g). According to Berner's widely-accepted classification, measurable dissolved O_2(g) indicates an *oxic* environment, whereas the absence of dissolved O_2(g) indicates an *anoxic* environment. In recent years, scientists have suggested that the Berner (1981) classification of oxic environments be divided into *oxic* and *suboxic* (Langmuir, 1997). With this revision, oxic environments contain more than 30 μM (1 mg L^{-1}) of dissolved O_2(g) with Mn below detection and organic matter absent. Suboxic environments contain low amounts of dissolved organic matter and dissolved O_2(g) from $\geq$1 μM to $<$30 μM, with detectable Mn but with Fe below detection. While it was not possible to obtain in situ measurements of dissolved O_2(g) in ground water prior to exposure to the cave atmosphere, field sample preservation with subsequent analytical determination of redox-sensitive elements indicates that the redox status of ground water entering Lechuguilla Cave ranges from oxic to suboxic.

Conclusions

Characterization of seepage redox chemistry from selected areas of Lechuguilla Cave supports the hypothesis that ground water entering the cave as seepage is a potential source of dissolved Mn and inorganic N (as both NH_4-N and NO_3-N) to the cave environment. Organic C concentrations in the seepage are generally low, and therefore redox conditions can be classified as ranging from oxic to suboxic, with N present primarily as NO_3-N and dissolved Fe concentrations below detection. Once the seepage enters the cave environment, dissolved $O_2(g)$ concentrations increase, organic C continues to oxidize, Mn oxidizes and is precipitated or adsorbed, and NH_4 oxidizes to NO_3. As a result, water in standing pools has a tendency to contain concentrations of Fe, Mn, and NH_4-N most often below common analytical detection limits. Comparison of Eh_m values obtained in the field using a Pt electrode, and Eh_c values computed using the analytical results for various redox couples, demonstrates a lack of internal redox equilibrium in seepage. Therefore, future studies related to redox chemistry of Lechuguilla Cave pools or seepage should avoid the use of measured Eh_m values to calculate the aqueous equilibrium concentrations of redox-sensitive elements.

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SECOND APPALACHIAN KARST SYMPOSIUM

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Biospeleology

The Subterranean Fauna of Indiana

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Within Indiana are two distinct cave areas, the south-central karst containing most of the state's 2,000+ caves, and the glaciated southeastern karst. Field work from 1971 to present resulted in sampling over 500 caves for fauna. Approximately 100 species of obligate cavernicoles have been discovered, with over 70 of these occurring in the south-central karst area. Dispersal into the southeastern cave area was limited to the period after the recession of the Illinoian ice sheet, accounting for the paucity of fauna, with only 30 obligate cavernicoles known. The fauna of southeastern Indiana is believed to have dispersed into the area during the Wisconsin glaciation, whereas the south-central karst has been available for colonization over a longer time. Overall the largest numbers of taxa are beetles, including 14 species of *Pseudanophthalmus*, millipeds with 9 species of *Pseudotremia*, and springtails with 7 species of *Arrhopalites*. Several cave systems in the south-central region have faunas commensurate with the status of being global hotspots of subterranean biodiversity, with 20 or more obligate cave species. These sites include Binkleys Cave, Sharpe Creek (Wyandotte) Caves, and the Lost River Cave System. In addition to cavernicoles, an obligate subterranean invertebrate community exists in the epikarst as well as the saturated interstices of soil in the glacial and alluvial plains. Seven species of the copepod *Diacyclops* have been found by sampling cave pools fed by ceiling water migrating downward from the epikarst, hyporheic stream gravel via Bou-Rouche pumpwell, seep springs, wells and drain tile outlets.

The Vjetrenica Cave (Bosnia & Herzegovina): The World's Highest Biodiversity Cave

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Vjetrenica is a complex cave, 6,230 meters long and the biggest in Bosnia and Herzegovina, with numerous water flows and accumulations. The cave is located in the south dinaric karst, between Popovo polje (East Herzegovina) and Dubrovnik (Adriatic Sea, Croatia), as part of the Trebišnjica River system, the longest abyss river in Europe. The region is characterized by strong tectonic and geodynamic activity, high purity of carbonate (99.98%) and 2,000 millimeters of annual rainfall. Since 1950, the cave has been protected as a Geomorphological Nature Monument and in 1964 opened for tourists. Vjetrenica is first mentioned in *Historia naturalis* (77 A.D.) by Pliny the Elder. Hygropetric habitat, water film flow over speleothems, is first described here. Intensive research started in 2000, when the cave was ecologically and topographically surveyed. Permanent monitoring stations established in 2005 measure: air and water temperature, air humidity, air flow direction and speed, and air and water pressure.

In Vjetrenica, 199 taxa have been detected (37 protists and 162 animals) including 91 cave-dwelling taxa (48 troglobitic and 43 stygobitic). Vjetrenica has the world's highest cave biodiversity, including representatives of the following groups: Turbellaria (5), Hydrozoa (1), Gastropoda (12), Bivalvia (1), Nemertina (1), Polychaeta (1), Hirudinea (1), Palpigradida (1), Araneae (6), Opiliones (2), Pseudoscorpiones (3), Copepoda (5), Ostracoda (2), Decapoda (4), Isopoda (7), Amphipoda (12), Chilopoda (2), Diplopoda (4), Collembola (4), Diplura (1), Thysanura (1), Coleoptera (14), and Vertebrata (1). Vjetrenica is also the type locality for 37 taxa, including16 endemics and 3 monotypic genera: *Zavalia vjetrenicae* (Gastropoda), *Troglomysis vjetrenicensis* (Crustacea) and *Nauticiella stygivaga* (Coleoptera). Some groups have not yet been studied or described (Nematoda, Oligochaeta, Thysanura). Due to changes in hydrology, highway building, intensive agriculture, garbage delay, local quarrying, and lack of state protection mechanisms, Vjetrenica is strongly endangered. Besides continuing research, protection of the whole drainage area, along with sustainable cave management, is necessary.

Mark-recapture Population Size Estimates of the Madison Cave Isopod, *Antrolana lira*

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I conducted a series of single mark, single recapture estimates of population size (N) of *Antrolana lira* at Madison Saltpetre Cave and nearby Stegers Fissure in Virginia in 1995, 1997, 2004, and 2006. Initial estimates in 1995 and 1997 based on a 24-hour sampling interval between mark and recapture obtained low recapture rates (2.1% – 5.2%), and yielded unreliably high N values of 103 and 104 with large SEs and thus wide 95% CIs. Subsequent estimates based on a two week sampling interval obtained high recapture rates (6.5% – 29.4%) and yielded consistent N values with small SEs and 95% CIs. N values in Madison Cave ranged from 0.36 to 1.02×10^3, while N values in Stegers Fissure were consistently higher, and ranged from 2.24 to 3.42×10^3. Estimates from both locations showed little fluctuation from 1997 to 2006. Among a combined total of 2,250 individuals marked and 2,390 individuals recaptured, only two individuals marked in Stegers Fissure were recaptured in Madison Cave and no movement of marked individuals in the opposite direction was detected. The *A. lira* populations at the two locations thus exhibit a classic source-sink relationship. Stegers Fissure serves as the source because it is open to direct input of organic matter and thus can sustain a larger population size than can Madison Cave with no direct access to organic matter input. The situation at Stegers Fissure is likely unique among all known locations where *A. lira* is found.

Invertebrate Colonization and Deposition Rates of Guano in a Man-Made Bat Cave, the Chiroptorium, Texas

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A man-made bat cave was built in Texas on the Bamberger Ranch Preserve near Johnson City, Texas, by Margaret and J. David Bamberger. The Chiroptorium was built in 1998 on the principle of "if we build it, they will come." It took a few years, but the Chiroptorium was colonized by *Tadarida brasiliensis* bats in summer 2003 and 2004. We began monitoring the bat guano to see when the full community of guano invertebrates would develop in what amounts to a primary succession in a virgin environment. In the winter of 2004–05, average guano depths in both domes were about 5.5 centimeters, and the invertebrates very limited in number and diversity, with none of the characteristic beetles. A pseudoscorpion, probably *Hesperochernes mirabilis*, was common in the guano and on walls from the beginning. Spiders *Spermophora senoculata* Duges and *Tidarren sisyphoides* Walckenaer, some with egg cases, were found on the walls. By the winter of 2005–06, guano depth had roughly doubled to about 10.5 centimeters, and a diverse community of invertebrates was described, including the beetles *Metoponium* sp. and *Dermestes* sp. In the third winter (2006–07), all structure of the guano deposits had been reduced to dust, probably by the action of a large population of beetles and aided by cattle. Several spiders, *Oecobius annulipes* Lucas, were found on the walls. The Bambergers built it, and the bats and the invertebrates did come, and very quickly.

Genetic Divergence Among Populations of the Madison Cave Isopod, *Antrolana lira*

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The Madison Cave Isopod, *Antrolana lira*, is a federally threatened isopod that inhabits phreatic aquifers in the Shenandoah Valley of Virginia and West Virginia. In this study, I analyze a 658 bp region of mtDNA corresponding to the cytochrome oxidase *c* subunit I gene obtained for 70 individuals from 9 locations. Analysis revealed three highly divergent haplogroups, which are found in separate geographic areas. Within these haplogroups genetic divergence is low, suggesting gene flow between sites. Over 99% of the genetic variation of the species corresponds to among group variation. Haplogroups became isolated between 3 and 21 mya.

The synclinal nature of the Shenandoah Valley and the presence of non-soluble rock likely contribute to genetic isolation. Invasion of the Shenandoah Valley probably occurred during the early Miocene. This may have occurred in the north followed by dispersal. Conversely, haplogroups may represent three independent invasions.

Microbially-Derived Carbon in Karst Waters

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Cave and karst ecosystems can be severely impacted by the scarcity of a continuous nutrient supply. However, some subsurface, and specifically cave, ecosystems do not rely exclusively on surface-derived (allochthonous), photosynthetically-produced organic matter. Although microbes in general are largely responsible for the availability and fate of dissolved organic matter (DOM), the role of microbes in the autochthonous production and overall processing of DOM in karst is poorly understood. We used fluorescence spectroscopy to characterize DOM from sulfidic caves and springs where microbial communities have been previously described. Because few studies have been conducted on systems with significant microbial contributions to DOM in the absence of allochthonous influences, our results uniquely provide an array of signatures constrained by microbial influences. We applied these signatures to understand DOM types from the saline-waters of the Edwards Aquifer, Central Texas. Cave and aquifer DOM had very different spectral features and was significantly less fluorescent than allochthonous DOM from surface and sediment pore waters. In contrast to most surface samples with quinone-like fluorophores, a significant shift in emission maxima over the range of excitation wavelengths for the cave and aquifer waters indicated a more heterogeneous collection of fluorophores and higher relative amounts of protein-like and microbial DOM. The cave, spring, and aquifer waters also lacked any significant contribution from humified DOM. These results, indicating a microbial source for DOM in the saline-waters, have important implications for carbon sources and cycling in the Edwards Aquifer ecosystem.

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Identification of the Microbial Communities Associated with Roots in New Mexico Lava Tubes

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Although roots have been found to be an essential energy source in lava tubes around the world, the role of roots in New Mexico lava tube ecosystems and their microbial communities is unknown. We investigated root and associated fungal and bacterial communities from two lava tubes in the El Malpais National Monument using culture-dependent and culture-independent methods. Samples of these communities were taken aseptically. R2A culture medium was inoculated and incubated on site with small samples of root material or sterile swabs of the wall or root microbial mats. Root and fungal samples were studied using scanning electron microscopy (SEM) to detect microbial interactions with the roots. DNA was extracted and purified using the MoBio Power Soil DNA Extraction Kit, amplified using polymerase chain reaction (PCR), cloned using TopoTA Cloning and sequenced using Big Dye Terminator v1.1 sequencing to identify closest relatives of genetic sequences from the cave materials. Alignment was done using ClustalW and a neighbor joining phylogenetic tree with 100 bootstrap replicates was constructed using Paup version 4.0b10. Preliminary results show that microorganisms cultured from the roots are grouping with known root-associated bacteria. Fungal DNA sequences also were detected associated with the roots. This study suggests that the roots support a diverse microbial community in the lava tubes and is one of the first projects to look at root associated microorganisms in cave environments.

The Comparative Role of Microbial Metabolic Activity Versus Inorganic Processes in the Precipitation of Calcite

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In order to investigate whether active metabolic microbial process dominates over passive geochemistry in the formation of calcite polymorphs, we are examining calcium carbonate ($CaCO_3$) precipitation and dissolution by bacterial species from hypogean cave environments. Microbial species were isolated from $CaCO_3$ "popcorn" deposits within Grayson-Gunnar Cave, Kentucky, based on their ability to deposit $CaCO_3$ crystals on Boquet B4 media or to dissolve calcite in a $CaCO_3$ enriched "top" agar. Current research is aimed at determining if an organic calcium salt is a possible energy source that drives such phenomenon and to identify the gene(s) responsible for this cellular function. Examination of the crystal structure produced by precipitating species using scanning electron microscopy demonstrates bacterial-like footprints in, and on, the surface of these crystals. These data have shown the same species can precipitate various mineral forms of $CaCO_3$, including calcite, vaterite, and aragonite. By correlating the structure of the $CaCO_3$ crystals with environmental growth conditions of individual species using powder x-ray diffraction (XRD), we hope to correlate microbial metabolic activities with CaCO3 precipitation. By studying the conditions that similarly allow dissolution of $CaCO_3$, we hope to better understand the role that $CaCO_3$ plays on microbial growth, Ca_{2+} detoxification and metabolic adaptation to $CaCO_3$ rich environments.

Enhancing Communication and Knowledge Discovery Among Karst Biospeleologists: The Role of the Karst Information Portal (KIP)

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Speleology is an intrinsically multidisciplinary field of study that draws upon a substantial grey literature (for example, agency research reports) that is poorly indexed, difficult to access, and generated in many different languages. The creation and implementation of the Karst Information Portal (KIP) beginning in 2005 addresses these and other information access and management problems by focusing on providing a global portal that will provide a gateway to the Web for karst information and services. Digital versions of many karst resources will be available through KIP. Databases, datasets, bibliographies, images, grey literature, and the like that have been created by karst scientists worldwide will be accessible through KIP federated searching (simultaneous search of multiple data sources) of identified karst sites on the Internet. The core idea is not to recreate databases that have been developed by others, but to make those that exist (or are being developed now and in the future) more universally available and provide advanced tools for using them. In June 2007, an enhanced KIP was launched that includes *The Guide to Speleological Literature* database, a scanning electron micrograph repository, and links to key electronic karst resources. Knowledge discovery, commenting by users, and collaborative workspaces are being tested through the SEM (scanning electron microscopy) database in a joint project with Los Alamos National Laboratory. Biospeleology partners are needed to create and maintain databases of information and resources pertaining to biospeleology that can be linked to KIP.

A Multidisciplinary, Collaborative Approach to Cave Science Education at Belen Middle School

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Nationwide, K-12 teachers are facing many challenges in teaching science, including inadequate funds to purchase supplies, inability to allow students to participate in labs because of the disciplinary issues, and an overall decrease in general science understanding among students. Here, we illustrate how caves can be used to effectively teach ecology and geology to 7th and 8th grade science students. As part of the NSF-funded GK-12 program, we combined a biologist, a geologist, and a teacher to develop and teach science in an interdisciplinary, inquiry-based and research-based lesson for a full inclusion Title I public school classroom. Cave-based lessons were developed to cover New Mexico state science standards for 7th and 8th grade. Students investigated adaptation in troglobites in a lab where students pretended to be blind cave fauna. Students graphed their results and further discussed how troglobites adapt to constant darkness, as well as levels of cave adaptation. On day two, students drew their favorite animal as if it was a troglobite. Students then learned about basic speleogenesis, observed dissolution of limestone compared to other rock types, and virtually toured a cave using the 360° Lechuguilla Cave Virtual Tour. Finally, students watched a cave science video and had an open discussion with cave scientists about cave research and exploration. Overall, students were very interested in caves and cave science, and all three labs in our lesson could be used to teach science in a public school classroom.

CAVE CONSERVATION AND MANAGEMENT

Human Dimensions Research and the Karst Information Portal

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In the natural resources disciplines, human dimensions research aims to understand the role of human interactions in the various biological, physical, and social components of ecosystems. Successfully applying this knowledge to decisions affecting environmental processes and their societal outcomes depends on collaborations among interrelated disciplines in the social and behavioral sciences, humanities, communication sciences, and related interdisciplinary studies. Success is also based on access to reliable sources of scientific and technical information. Some of the difficulties in stewardship of karst and cave ecosystems arise from the limited availability of information concerning human-karst relationships.

The Karst Information Portal (KIP) is an evolving international community of scientists, information specialists, and other researchers seeking to promote information sharing and access to published and unpublished research in order to advance karst, cave, and aquifer research and stewardship via the Internet and information-related technologies.

Researchers at University of South Florida conducted a study to map the domain of karst literature. The data has been used to design strategies to aggregate and evaluate the representation of information within KIP. One finding was that a large amount of cave and karst scientific and technical information resides in gray literature, much of which is currently not readily available to researchers, decision makers, and the public.

KIP has the potential to facilitate communication of scientific and technical research and findings between cave and karst land stewards, policy makers, community planners, social scientists, and funding agencies. The resulting collaborations have the potential for generating innovative solutions to the critical challenges of karst and cave ecosystem stewardship.

Cave and Karst Protection Initiatives for Moderate and Low Income Landowners

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Numerous private, state, and federal programs can assist landowners to protect karst features and caves. Programs such as EQIP, CREP, and Agricultural Best Management Practices help fund projects on a cost-share basis. Sinkhole cleanouts, livestock exclusion, and establishing vegetative buffers around karst features are eligible projects. These programs require some level of financial commitment by the landowner. Landowners typically bear the initial cost of constructing conservation practices; government programs reimburse a portion, usually 50% to 75% upon installation. The Virginia Department of Conservation and Recreation Karst Program has negotiated with Division of Soil and Water Conservation staff to count donated volunteer labor value toward landowner share of project cost. The Karst Program is working with nonprofit land trusts and cave conservancies to establish a revolving loan fund to defer upfront landowner expenses. Many otherwise enthusiastic owners forego government sponsored conservation programs due to a lack of personal financial resources.

Private and government grants occasionally fund cave gating projects and cave management initiatives on private lands at little or no cost to the landowner. Landowners in Virginia may elect to protect biologically significant cave and karst resources through voluntary Natural Area Dedication, Natural Area Management Agreements, or Natural Area Registration through the Department of Conservation and Recreation Natural Heritage Program.

Landowner donations of conservation easements can serve to protect cave and karst resources. Conservation easement donations may generate significant federal tax deductions. In Virginia, conservation easement donors may realize substantial cash income through the sale of the resulting Virginia State Income Tax Credit.

Cave Restoration Forum

The Richard Blenz Nature Conservancy's Buckner Cave Graffiti Removal Project

Dave Everton

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Buckner Cave is located a few miles southwest of Bloomington, Indiana, in the south central part of the state, in an area referred to by cavers as the Garrison Chapel Valley. The area contains many caves, several of which are more than one kilometer in length, including Buckner at ~4.5 kilometers surveyed length.

Historically, the cave and property unfortunately received heavy abuse and vandalism. However, a major turnaround began to take place in the early part of the 21st Century due to the presence of a property caretaker. Improved stewardship led to the formation and incorporation of the Richard Blenz Nature Conservancy in 2005, which took over management of the property and cave. One of the restoration efforts has been The Buckner Cave Graffiti Removal Project, coordinated by Dave Everton. We used the Peppersauce Cave Conservation Project's sand-blasting equipment and process, which was specifically developed for removing graffiti inside caves. The project included documentation of historic signatures, assessment of impact to the cave environment, removal of contemporary graffiti, and restoration of the cave environment to a pre-mitigation level. Photographs illustrate the project methods, and show before and after conditions.

Restoration in Echo River and River Styx in Mammoth Cave Performed by National Speleological Society Volunteers

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Beginning in 1989, NSS volunteers began doing cave conservation projects in Mammoth Cave National Park. Over the past 18 years, a tremendous amount of work has been donated during roughly 80 restoration weekends and week long camps. The person-hours volunteered come to over 59,000, and if valued at the modest rate of $15 per hour, then the monetary value of the contribution comes to $888,000.00. This partnership has obviously been and continues to be a great benefit to Mammoth Cave National Park.

Among the most significant projects taken on by the NSS was the removal of an 1,100-foot-long elevated boardwalk in Echo River and River Styx plus removal of lighting infrastructure for this section of the cave. Over a nine-year period, the boardwalk was dismantled with pry bars and sledgehammers—volunteers often worked in deep water wearing wetsuits. A group of deaf cavers distinguished themselves in this work, especially through the invention of a piling puller by John Vargo. Dismantled pieces were carried to "chop shops," reduced to manageable size, and bagged. As many as 900 bags in a day were carried to Mammoth Dome, passed up the tower and out the Historic Entrance, loaded into a truck, hauled, and tossed into a dumpster. Removal of this rotting, creosote-treated wood has greatly benefited habitat for cave life including the endangered Kentucky cave shrimp.

Restoration at Parks Ranch Cave—A Youth-Initiated Cave Project

Lucas Middleton

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Parks Ranch Cave is a gypsum cave near Carlsbad, New Mexico, located on Bureau of Land Management land. On January 1, 2006, it was discovered that Parks Ranch Cave had been vandalized with spray paint and permanent markers. Lucas Middleton, a caver from the local Speleo Venture Crew, chose to make the restoration of Parks Ranch Cave his Boy Scout Eagle Project. Three trips were made to clean up Parks Ranch Cave. Help was received from Boy Scout Troop 86, Speleo Venture Crew, Pecos Valley Grotto, and other concerned cavers. The cave was restored as close as possible to pre-vandalism conditions using nylon-, brass-, and steel-bristled grout brushes along with rotary drills. For this restoration project the hope is that noncavers and perhaps many experienced cavers would not be aware of the vandalism and subsequent restoration that has occurred. It took a total of 115 caver-hours to restore the cave. A follow-up assessment trip indicated that another restoration trip will be planned in the future after the cave has had time to heal itself.

Cave Conservation and Restoration: New NSS Book is Catalyst for Networking State-of-the-Art Information

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Recently published by the National Speleological Society, the new book titled *Cave Conservation and Restoration* (Hildreth-Werker and Werker, 2006 edition, ISBN 1879961-15-6), is receiving attention from cave conservationists around the globe. The 600-page volume contains a wealth of detail from 46 contributors describing state-of-the-art tools and methods for cave conservation, restoration, speleothem repair, and minimum-impact caving ethics. There are more than 400 photos and illustrations with a 16-page color insert. This new publication includes philosophy and practical suggestions for making sound conservation decisions based on assessing interdisciplinary up-to-date information. The tome advocates that the foremost concern in every decision related to a cave should be the perpetuation of speleological processes, values, and resources. The new text is proving to be a catalyst for conservation-centered discussion, international information networking, quantitative conservation research, and interactive collaborations working to improve methods.

Public Education Equals Public Support

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In October of 1994, cavers gathered in New Braunfels, Texas, and established the Texas Cave Conservancy (TCC). We developed a new approach to urban cave management. "The Texas System" involves obtaining cave-related land management contracts and grants, building cave parks within urban areas, and conducting public education activities.

Through high-profile initiatives and public education efforts, the TCC has obtained grants. Cavers are "the cave experts" and there is money available to assist in the acquisition and protection of caves.

Highlights from TCC's history include:

1986 The City of Austin, Texas, passed the Comprehensive Watershed Ordinance requiring caves and sinkholes to be preserved.

1990 Seven species of cave invertebrates in the Austin, Texas, area were listed under the Endangered Species Act.

1994 The TCC was formed to conduct land management, cave preservation activities, and public education on tracts of open land containing caves.

1995 We built trails and picnic areas and placed signs at the cave preserves. Urban cave preserves create long-term cave protection opportunities.

2003 We celebrated moving into our new headquarters in Cedar Park, Texas. The house, along with three small caves and 4.25 acres, facilitates our fund-raising efforts.

2004 We hosted our first public education event, Cave Day, in Cedar Park, Texas. Two times a year, in April and in September, 300–500 visitors join us to learn about caves and cave life. The Texas Hotel Association donated $5,000 to develop educational material for Cave Day. Later they donated $6,500 to develop and place 40 cave signs at the Westside Preserve to create a new ecotourist attraction.

2005 The TCC assisted in the transfer of the $10,000,000 Discovery Well Cave property to the City of Cedar Park. This park will be the future Cave Day site.

2006 A $13,000 grant was obtained from the U.S. Fish & Wildlife Service to develop Avery Ranch Cave and Dies Ranch Cave for public education visitation. Upon obtaining a corporate sponsor, Avery Ranch Cave will be used an educational show cave.

The goal of the Texas Cave Conservancy is to create the same level of Texas support for cave protection that Bat Conservation International has created to protect bats.

Urban Cave Management—The Texas System

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More than 1,000 Texas caves in urban areas are threatened by rapid development. Many are set aside for water protection or for cave-related endangered species. This creates an opportunity for cave conservancies or grottos. The Texas Cave Conservancy builds parks and trails, develops educational materials, conducts fire ant control, and monitors the caves as part of our long-term cave protection efforts. How can a cave-related land management operation be started?

- Check the language in your Articles of Incorporation—can your conservancy or grotto act as a cave management business?
- Do you have General Commercial Liability and Volunteers Insurance?
- Do you have support from individuals with expertise in sales, geology, biology, accounting, public education, drafting, construction, cave laws, and the like?
- Some tasks such as monthly inspections do not work well through volunteers—are you open to hiring cavers as "independent contractors"?
- How can we work with developers to obtain contracts in such areas as site evaluation, cave gating, park building, development of educational material, and cave management? When they need surveyors or carpenters, they hire them. When they have caves, cavers have the ability to solve their "problems."
- Can you invest $10,000—$15,000 to obtain the donation of a significant cave and land from a developer? Can you build high-quality cave gates, lay out and build wood mulch trails, develop and places signs and picnic tables, and so on?
- Are you prepared to invest time and money into this exciting fund-raising, karst-protecting opportunity?

With urban caves in the hands of developers, you have at least two ways to negotiate. To obtain ownership of a good cave, offer to pay all costs: legal, gating, park building. If the caves are not ones that you want to own, offer to build a park for the developer for a reasonable price ($5,000–$10,000) and have them pay you a monthly fee ($100–500) to manage them. Either way, the "cave problem" is solved for the developer.

Caves of Our National Parks and Public Lands

Managing Caves in Ozark National Scenic Riverways: A Public-and-Private Partnership

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The Ozark National Scenic Riverways, a unit of the National Park Service, contains more than 340 caves. Managing these resources is difficult given the limitations of budgets and personnel. Through a series of agreements with Cave Research Foundation (CRF) and the efforts of caver volunteers, cave management at the Ozark Riverways is accomplished for relatively minimal funding. CRF works through the Resource Management office to coordinate the work of paid and unpaid help in performing a wide range of management activities on lands within the park. Special emphasis will be given to the mechanisms and personnel management through which this is accomplished.

The Hoosier National Forest: A Home for Rare and Diverse Cave Species, and a Case in Point for Karst Education and Preservation

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Located in southern Indiana, the Hoosier National Forest comprises approximately 25 percent of the public land in the state. Home to over 160 caves, the Hoosier has a vital role in cave conservation. Within the last few years, the Hoosier has completed an extensive amount of work to inventory cave fauna. The baseline inventory has described several species new to science and documented new distributions of previously described species. Due to the extreme isolation and harsh conditions of the cave environment, many of these species, especially cave obligates, are rarely found. A three year study of cave fauna on the Hoosier included the discovery of 53 troglobitic species, over 30 species new to science, and 75 species of significant global rarity. The high number of cave-associated species with global and state viability concerns underscores the importance of karst habitat on the Hoosier. Educating and engaging the public about the singular life forms that exist in the remarkable karst topography that stretches across the United States is an important component of cave management on the Hoosier. The film, *Caves: Life Beneath the Forest* was created to build support for cave conservation by giving the general public a chance to see creatures that they will likely never encounter on their own. By engaging the public, the Hoosier hopes to instill in them an appreciation for caves and cave species and to develop life-long stewards of this fragile resource.

The Draft Cave, Karst, and Mine Management Plan, and the Rapid Cave Assessment and Classification System, Grand Canyon National Park

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Grand Canyon National Park's™ (GCNP) vast cave and karst resources are poorly understood. Concomitantly, these resources are experiencing increasing pressure from visitors. The National Park Service is mandated to proactively manage and protect these resources. GCNP has developed a draft Cave, Karst, and Mine Management Plan that provides guidelines for the protection and management of cave and karst resources. The plan contains specific rules, regulations, and protocols designed to protect resources while safeguarding visitor enjoyment. The plan outlines procedures for systematic inventory, mapping, classification, and assessment of cave resources and for permit issuance. This plan recognizes visitor use demands and addresses recreational use, resource protection, research, education, and public safety. This plan will enable managers to make decisions on each cave use by:

- identifying resources at risk
- setting appropriate recreational use levels and/or restrictions and
- identifying monitoring, research and restoration needs.

A Rapid Cave Assessment protocol was developed to provide consistent, detailed information needed to begin the classification process, make determinations, and build a database. Cavers are asked to provide general information on the cave and information specific to biologic, physical, paleontological, cultural resources, and human impact. The Park requests that cavers rank caves according to specific values and provide management recommendations. This information provides the basis for cave classification and helps define its management. Effective implementation of the plan is largely dependent on establishing strong partnerships with stakeholders and the general public. Volunteer recruitment will greatly accelerate this process and help in solidifying partnerships and support.

Multidisciplinary Management at Mammoth Cave National Park

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In 2006, Mammoth Cave National Park received 740,500+ visitors, with over 358,000 of those visiting the cave. Recent infrastructure projects include:

- A new water system that connects the Park to a regional system, eliminating 30-year-old leaking water lines.
- A new cave electric-lighting system that will be energy efficient and protect the resource by reducing algae growth

The Park has no authority on lands outside the administrative boundaries, but the land, water, and air quality outside the park affect the park. Partnerships with local groups to protect resources are vital to Park health.

The Park provides support and space to the Director of Central Kentucky Personal Responsibility in a Desirable Environment, which coordinates community sinkhole cleanups. The park supports the Green River Conservation Reserve Enhancement Program to create riparian buffers between agricultural discharge and pollutants and the water flow. The Friends of Mammoth Cave National Park will help individuals and groups to support the park financially and through in-kind contributions.

Park volunteers perform sinkhole clean-ups, cave mapping, research projects, and visitor contacts. In August 2005, volunteers from the National Speleological Society finished an eight-year project, removing 150 tons of creosote-soaked timbers from Mammoth Cave. Since 1989, the NSS has contributed more than 54,000 hours of work.

Research and teaching partnerships include the Mammoth Cave International Center for Science and Learning, the Cave and Karst Center at Western Kentucky University, and over 50 individual science research partnerships. Multiple tourism partnerships play an important role in planning, marketing, and decision making.

Mammoth Cave International Center for Science and Learning

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The Mammoth Cave International Center for Science and Learning (MCICSL) is part of the national network of 17 research learning centers located within the National Park System. MCICSL was created in 2004 as a partnership between Mammoth Cave National Park and Western Kentucky University. Funding, logistical support, and governance of MCICSL are shared equally by the two entities. The overall goal of the national research learning center network and the MCICSL is to increase the amount and effectiveness of research and to improve science communications by:

- Facilitating park use for scientific inquiry
- Supporting science-informed decision making
- Communicating the relevance of research and providing access to research knowledge
- Promoting resource stewardship through partnerships

MCICSL has been active for only a short time. The director has only been in place for two years, and the education specialist for about six months. In spite of its youth, MCICSL has positively impacted resource management and educational outreach at Mammoth Cave. The center hosted an NEH-funded workshop for community college professors on place-based history and humanities education. It developed a multi-park, multi-region, NPS-funded project to study controlling algal growth through optimal cave lighting. MCICSL hosts international researchers and cave managers during park visits, provides technical assistance for Mammoth Cave staff, helps coordinate park research, and works with environmental education staff in programming for students and adult learners. Recently the center began managing the park research permitting system and providing summaries of recent research to the interpretive staff at the park.

Camp Bullis Military Training Reservation: A Center of Multidisciplinary Karst Research

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Federal support and funding of karst research at the Camp Bullis Military Training Site, Texas, has proved a role-model for karst investigations and been key to the discovery of hydrogeological and biological relationships for improved management of karst resources in the central Texas region. Nearly 100 caves and 1,300 karst features have been located to date on the 113.3-square-kilometer reservation. Their study has redefined concepts of groundwater movement in the area by demonstrating groundwater flow between formations previously believed hydrologically separate, identifying modes of cave development distinctive to particular lithologies, delineating flowpaths in units once thought impermeable, and using the information to identify zones of contaminant movement, and endangered and rare species distribution. Specific examples follow. The upper 39 meters of the Glen Rose Formation, regionally the lower confining unit for the Edwards Aquifer, are highly permeable and hydrologically continuous with the Edwards, traced at velocities as great as nearly 4 kilometers per day. Detailed surveys, exceeding state standards, have found one to two orders of magnitude more caves and karst features than in geologically identical neighboring properties, prompting review of existing survey requirements. The Dolomitic Member of the Kainer Formation in particular forms topographically subdued features that often appear insignificant, but if excavated, prove to host hydrologically and biologically important caves. Federally listed endangered karst invertebrates have been found in 23 caves, and their distribution is defined by continuity of lithologic units. Fourteen endangered species caves in the Dolomitic were discovered or their known extents substantially expanded by excavation.

Compromise: The Impact of Cave Survey in Gap Cave, Cumberland Gap National Historical Park, Middlesboro, Kentucky

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The Cave Research Foundation has been surveying Gap Cave since 2003. Cavers had logged over 10,000 hours creating more than 2,600 stations in 12.53 miles (20.165 kilometers) through March 2007. The means, methods, and materials of the survey are under scrutiny. Cave survey is seen as a means of defining the resource that is the cave and a tool for preservation of a fragile environment. Does the way cavers prepare for a survey trip and conduct themselves underground make a difference in the level of impact? Are some tools, supplies, and materials better for a low impact survey? A brief look at these issues raises questions about what is normally permitted or prohibited. More permit restrictions may be justified, but regulators need to provide reasonable solutions so the survey of caves on public lands can continue.

Update on the Systematic Inventory and Survey of the Caves In Grand Canyon – Parashant National Monument, Arizona

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Cave resources of Grand Canyon – Parashant National Monument are virtually unknown. During summer 2005 and early-spring 2006, we surveyed all 26 known caves on the Monument. Systematic procedures for mapping and inventorying geological, hydrological, paleontological, archeological, and biological resources were developed and refined. Our study was the first regional systematic survey of caves in Arizona. Geologically, caves were found within Permian Kaibab Limestone, Mississippian Redwall Limestone, sandstone and basalt. We also documented airflow in 10 caves. Several caves may offer great opportunities for paleoenvironmental reconstruction. Two potentially significant archaeological sites were identified, and most caves were used during prehistoric and historic times. Several of the caves act as swallets and may be significant aquifer recharge points. We also inventoried vertebrates and invertebrates. Data collected during this study should be considered baseline data, which will be useful in identifying additional research needs on the monument. These data will also be used in developing cave resource management plans for these caves. The protocols developed have proven themselves in the field and are currently being used throughout the state.

In the last year we have incorporated the use of volunteers and have discovered over 20 new caves and numerous new species of invertebrates.

Geology and Geography

Monitoring Systems in Hyperthermic and Hypercarbic Caves

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Unlike industrial exposures to hypercarbia (dangerously elevated CO_2), spelean hypercarbia has two radically different scenarios: (1) replacement of oxygen by CO_2 (as occurs in confined spaces in the industrial setting) and (2) simple addition of CO_2 to the atmosphere from volcanic or other sources. Further, quasi-political factors essential to promulgation of industrial standards are irrelevant in quantifying standards for investigations in caves. A refereed field study by Howarth and Stone has shown that investigations are feasible in normothermic caves containing 6% CO_2 (60,000 ppm) and 15% oxygen. In hyperthermic caves in Kilauea Caldera, HI studies have been performed in temperatures up to 68 degrees Celsius (140 degrees F); theoretically they should be possible in such caves up to about 24% CO_2 (240,000 ppm) and 15% oxygen. Field trials and web search demonstrate that current American CO_2 monitors are designed for industrial environments, not cave environments. In cave environments, hypoxia (dangerously decreased oxygen) actually is the acute killer, not hypercarbia and use of exercise oximeters supplemented by clinical observation may be a desirable alternative to CO_2 monitors. Resolution of the issue is hampered by limited documentation of field observations, variations in composition and velocity of cave air, instrumental artifacts, limited access to recent aerospace data, and administrative incompetence. It is proposed that the 2009 International Congress of Speleology schedule a special session on this topic.

Underappreciated Caves of the Southwest: Speleogenesis in the Castile Formation, Eddy County, New Mexico and Culberson County, Texas

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The Castile Formation crops out over ~1,800 square kilometers in Eddy County, New Mexico, and Culberson County, Texas. Evaporite diagenesis has resulted in significant alteration of sulfate rocks, producing variable lithologic fabrics, including laminated, massive, nodular, and tabular (selenite) gypsum, gypsite, and calcitized evaporite. In addition to fabric alteration, speleogenetic processes abound within the outcrop region as evidenced by abundant sinkholes and caves. Over 500 individual features (caves and sinkholes) have been physically identified in the field; over 3,000 features have been identified from GIS-analyses; and over 9,000 likely exist.

Caves are developed in all lithologic fabrics and range from small, laterally-limited, epigenic caves to complex, hypogenic forms. Epigenic caves have simple morphologies, largely controlled by local brittle deformation. They generally exhibit well-developed, arroyo-type sinkhole entrances with rapid decreases in cave aperture away from insurgences. Hypogenic caves tend to occur in dense clusters, and range from simple, steeply dipping features to laterally extensive, maze-like forms. Specific morphological features within caves (that is, risers, cupolas, and half-tubes) provide unequivocal evidence of the free convection component of mixed convection dissolution within a confined speleogenetic system.

The extent, distribution, and geomorphic variability of karst development within the Castile outcrop region suggests that evaporite karst in the southwestern United States deserves greater recognition in North American cave and karst science. Not only do caves exhibit patterns and morphologies indicative of a complex, confined hydrologic system, but diverse secondary mineral deposits indicate that the system continues to evolve through the epigenic phase.

Hypogenic Speleogenesis South of the Guadalupe Mountains: Caves, Breccias, Castiles, and More

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Hypogenic speleogenesis is common within the Castile Formation of the Western Delaware Basin (southeastern New Mexico and far west Texas), as evidenced by the clustered distribution of karst features within the outcrop region and extensive free-convention features observed in individual caves. Dense clusters of hypogenic caves are commonly associated with calcitized evaporites and selenite masses, suggesting a genetic relationship. Abundant diagenetic patterns within the region indicate extensive, regional, confined speleogenesis that is not limited to cave development.

Brecciation is common throughout the Castile Formation, indicating extensive subsurface dissolution and collapse processes. Breccia pipes, resulting from upward stoping of subsurface voids, suggest confined transverse flow, while blanket breccias and subsidence troughs suggest confined lateral flow component. Calcitized evaporites are extensive throughout the Castile Formation, resulting from bacterial sulfate reduction in the presence of ascending hydrocarbons. Large, economic native sulfur deposits associated with some calcitization indicate limited cross-formational flow of oxic waters contemporaneous with calcitization, while selenite masses associated with other calcitized masses indicate significant intrastratal flow of oxic waters locally.

Hypogenic caves, breccias, calcitization, native sulfur and selenite masses suggest that hypogene processes have dominated sulfate diagenesis within the Delaware Basin. Surface denudation and epigenic processes significantly overprint hypogene products, resulting in greater complexity in the speleogenetic evolution of the Castile Formation.

Interplay of Holocene Climate and Geomorphology in the Central Appalachians as Recorded by Cave Deposits

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Mid- to late-Holocene climate fluctuations are recorded in a stalagmite (BCC-002) recovered from Buckeye Creek Cave, West Virginia. The mid-Holocene Hypsithermal, a 2000-year-long warm period, is marked by larger values of δ18Ocalcite in BCC-002. Climate was apparently drier during the Hypsithermal; values of δ13Ccalcite are comparatively large during the Hypsithermal. Climate destabilized at the end of the Hypsithermal, which ended abruptly and was closely followed by several short, very cool climate excursions. The late Holocene was substantially moister than the mid-Holocene.

The climate fluctuations are inferred to have translated to changes in the geomorphology of the local master stream—the Greenbrier River. Colonial Acres Cave has received sediments from the river throughout the Holocene, but sedimentary structures and textures vary with time. Bat bones and other evidence of subaerial exposure between floods are found throughout silt-dominated sediments, except during the Hypsithermal, a period characterized by the deposition of clayey silts containing insoluble particles liberated from cave ceilings during sustained back-flooding. Three outlets must be blocked to backflood the cave, which would have occurred if the riverbed filled with sediment. Warm, dry periods, such as the Hypsithermal, are known to produce channel infilling. The Greenbrier River may have risen as much as 4 meters. Global warming may return the Earth to Hypsithermal-like conditions and possibly lead to renewed channel infilling. The latter would bring about deeper floodwaters on and more frequent flooding of floodplains, which bodes ill for the many riverside cities in the region.

Geologic and Hydrologic Investigations of El Capitan Peak Alpine Karst, Prince of Wales Island, Southeast Alaska

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The Tongass National Forest of southeast Alaska, USA, covers nearly 6.9 million hectares of mountainous offshore archipelago with extensive mature temperate rain forests. Because of the accretionary terrane geologic setting, the geology there is extremely complex and heterogeneous, and includes numerous blocks of limestone that have been intensively karstified. These extensive areas of carbonate bedrock are focused mainly on the northern portion of Prince of Wales Island. El Capitan Peak consists almost entirely of Silurian age Heceta limestone, stretching from sea level to 850 meters. Work during the 2005 and 2006 field seasons focused on two deep pit systems. Geomorphologically, the caves are located on a north facing cliff band which is likely the rim of a glacial cirque. The glacial chronology of this region is poorly understood, which makes it difficult to determine the age of these landscape features. Tracer techniques were used to delineate the flow paths of the two separate systems. While quite close, the two systems have distinctly different hydrology, as the water flows along west-southwest to east-northeast shear zones. These shear zones are conjugate to the major north-south trending strike slip faults which predominate in the region. The major north-south trending strike slip fault, which bisects El Capitan Peak, creates a hydrologic divide as previous traces on the west side of the fault all flowed to the west. This corresponds well with other karst areas on northern Prince of Wales Island where dye tracing has shown groundwater flow favors paths along the shear zones.

The Caves and Karst of Redmond Creek, Wayne County, Kentucky

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Redmond Creek, the headwaters of Otter Creek in southern Wayne County, Kentucky, flows south through a large sinkhole formed in Mississippian-age limestones within the Cumberland Plateau. Caves and karst features within the sink are prevalent, and an ongoing project of the Central Ohio Grotto of the National Speleological Society has focused on documenting, exploring, and surveying these features. To date this project has inventoried over 40 caves and initiated surveys in 10, surveying just over 10 miles of passage. Study of the caves within the Redmond Creek sinkhole has revealed several unique characteristics. The lithology within the sink has caused the development of cave "couplets" that transmit water across the Hartselle Formation. Paleo conduits were developed along the strike oriented piracy routes through ridges. Present day phreatic and epiphreatic conduits act as shallow phreatic system with bypasses and lift tubes. The phreatic conduits are alluviated, resulting in a stable baseflow, high clarity spring.

Show Me the Structure: How the New Discoveries in Grand Caverns Explain Cave Hill

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Caves have been overlooked by those doing geologic mapping. Caves are particularly good places to see structure. On the Grottoes, Virginia, geologic map produced by Gathright, Henika, and Sullivan for the Division of Mineral Resources, an accurate but confusing array of dips and strikes is denoted on Cave Hill. The then-known cave passages on the hill added to this confusion. While the bedding in the commercial section of Grand Caverns is near vertical, the dip angle of the bedding in Fountain Cave, immediately south of Grand, is approximately 35 degrees.

In the fall of 2004, new passage was opened in Grand Caverns. Among the discoveries was a room, Kentucky, that at its longest dimensions is 800 feet by 260 feet. The strata in Kentucky go from moderately south dipping in the east to near vertical in the west. Cross bedding and flute casts point west as up-strata, indicating that we were in the eastern limb of an inclined anticline. Pressure solution cleavage is well developed, especially near the fold axis and in the steep limb leading to that axis. The pressure solution cleavage is oriented roughly parallel to the inclined fold axial plane, suggesting that the structures are contemporaneous and that the rock was deformed under moderate temperature and ductile conditions.

The discovery of Kentucky unifies the disperse dips and strikes previously measured on Cave Hill into a single structure, an inclined anticline running oblique to the hill's escarpment.

Ground Water Tracing Results in the Almaville/Blackman Communities, Rutherford Co., Tennessee, to Aid in Emergency Spill Response along I-840

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Eleven ground water (dye) traces were performed in one of the fastest growing areas of Rutherford County along the Interstate Highway-840 corridor near its intersection with Interstate Highway 24. When possible, the dyes were injected into sinkholes within, or in close proximity, to cloverleafs where trucks are more prone to turn over and spill hazardous materials. The research results have made possible the delineation of three spring basins. Nearly 15 kilometers of interstate highway and other major highways are now known to drain to these springs. In addition, some of the tracing results, added new information to ground water flow from the 15 kilometer long Snail Shell Cave system. Nick Crawford conducted traces nearly 15 years ago from Snail Shell Cave to Walker Spring located along the West Fork of the Stones Rivers. Four of the new traces conducted by the authors split and emerged at both Asbury Spring and Military Spring, which are located significantly up-gradient and several kilometers away from Walker Spring. Thus, the research results show that

Asbury and Military Springs are high-level overflow springs and hydrologically connected to Walker Spring.

Thermal Behavior of Earth Caves and Possible Cave-like Structures Detected on Mars

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We have demonstrated caves on Earth may be detected using thermal imaging. From study of caves in western New Mexico, northern Arizona, southern California and northern Chile, we collected and analyzed ground-based hourly temperature data, ground-based thermography, and thermography via fixed wing aircraft and hot air balloons. Through this work, we have gained insights into detection of terrestrial caves in the thermal infrared. There are diurnal and seasonal temperature variations, and caves are most detectable when the temperature contrast between the entrance and ground surface is greatest. However, geological and structural aspects of caves and surrounding surface may affect thermal behavior and thus detectability. We are applying insights and lessons learned from Earth caves to explore the feasibility of using orbiter-based thermal imagery to detect caves on the Martian surface. Preliminary analyses of visual and thermal imagery have revealed possible cave-like structures in several regions on Mars. Many of these features have thermal characteristics similar to some of our terrestrial sample sites. While it is inconclusive whether these features lead to subterranean passage into the Red Planet, these results are compelling and warrant further research.

Evolution of the Karst Aquifers of the Shenandoah Valley, Virginia and West Virginia

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The Shenandoah Valley is underlain by a substantial thickness of Cambro-Ordovician aged carbonate bedrock. The karst topography is complex, with sinkholes, caves, and springs more common near base level streams. Larger, calcium saturated springs commonly occur at elevations up to 50 meters above these streams, with spring runs commonly captured by vadose cave passages before emerging near modern base level. Transitional zones separate the perennial springs from current base level drainage network that divided the valley into smaller, hydrologically distinct blocks. Dye traces within block interiors yield long travel times, high dilutions, and divergent flow. Dye traces in transition zones show short travel times, little dilution, and convergent flow.

Patterns of genetic divergence between populations of the Madison Cave Isopod, *Antrolana lira*, suggest that populations, once in genetic contact via migration through a more extensive karst aquifer could have become isolated via stream incision. High levels of genetic divergence for mtDNA (COI) (9.5 – 11.2%) indicate that isolation occurred roughly 7 ± 3 ma, based on a mutation rate of 1.25% per my (Ketmaier, 2003). *Antrolana lira* shared a common ancestor with *Cirolanides texensis* approximately 20 ± 7 ma, suggesting colonization by *A. lira* occurred during the Miocene sea-level high stand.

These two lines of evidence are consistent with a history in which the Shenandoah Karst is the eroded remnant of a regionally extensive aquifer much like today's Edwards Aquifer or the Yucatan. Antrolana's marine lineage suggests that a saltwater-freshwater interface may have influenced aquifer development.

The Karst Information Portal (KIP): Developing a Network of Geographic and Geologic Karst Information.

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The difficulty of sharing geologic and geographic karst information is well documented. While there is a significant body of internationally accessible literature, important works are largely unknown or inaccessible. Some of the more difficult documents to access include maps, databases, technical reports, graduate theses or dissertations, images, video, and government publications. Also, karst related documents published in less-accessible languages are hard to access or find—especially those published prior to the information age. In order to address this issue, the Karst Information Portal (KIP) was formed in 2005 and launched in 2007. KIP is an evolving international community of scientists, information specialists, and other researchers seeking to promote information sharing and access to published and unpublished research in order to advance karst, cave, and aquifer research and stewardship. The portal is a searchable database of a variety of karst information that is accessible anywhere in the world. Like other well-known portals, such as Chronos, the KIP will continue to grow as users and developers bring more information within the network. We seek to expand KIP by developing partners to populate the portal with pertinent databases, maps, gray literature, and other information of interest to the geoscience community. The KIP has the potential to transform geologic and geographic research in karst by creating new knowledge through the integration of international information in the discipline.

Late Holocene Paleoenvironmental Changes: Evidence from Cave Sediments in Florida

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Cave sediments collected from Jennings Cave in Marion County, Florida show δ13C variations in their organic acids, which indicate periods of vegetation change caused by climatic influences during the Late Holocene. The carbon isotope record ranges from −35‰ to −21‰, exhibiting variability of ∼14‰, which is within the range of C3 vegetation. This is to be expected in a humid, subtropical forested environment, and likely indicates changes in C3 plant abundance. The most negative δ13C value of ∼ −35 percent occurred around 1,870 cal yr BP, sharply becoming less negative to −21‰ around 1,800 cal yr BP. These changes in plant assemblages were in response to changes in available water resources, with increased temperatures and evapotranspiration leading to arid conditions and a shift toward less C3 vegetation (increased C4 vegetation) during the Medieval Warm Period. The cave sediment δ13C record agrees well with δ13C values from a speleothem collected nearby that covers the same time period. Prolonged migration of the Intertropical Convergence Zone and North Atlantic High affects precipitation in Florida and likely caused vegetation changes during these climatic shifts.

Determining the Sensitivity and Disturbance of Terrestrial Caves in West-Central Florida: An Inventory of Public and Private Cave Systems

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One of the most significant and extensive karst terrains found throughout the world is in Florida. Cavernous systems found here are dynamic natural resources that are affected by surface and subterranean environmental changes. Moreover, the management of caves presents a number of challenges given the non-renewability of cave contents and the environmental sensitivity of caves to anthropogenic disturbances. An on-going inventory is being conducted in terrestrial caves on both public and private land in west-central Florida. The goals of this inventory are to determine what relationships exist between cave sensitivity, human disturbance in caves, and land use, as well as ensure the preservation and protection of any non-renewable resources by establishing which caves necessitate management plans due to their high sensitivity levels. The inventory includes data at each cave survey station on entrance and passage characteristics, geological, hydrological, cultural, biological, special interest, and human disturbance areas in each cave. Hierarchal scales are used to determine the amount of human disturbance and relative sensitivity of each cave included in the inventory. To date, 30 caves have been inventoried throughout the west-central Florida karst landscape: 15 located on public, state-owned land and 15 located on private land. Data was collected *in-situ* and revealed that the majority of caves on private land should be classified as "significant" and are less disturbed than caves on public land. However, some caves located on public land should be classified as "significant," yet most were found to have high levels of human disturbance.

The Extent and Timing of a Pre-Late Wisconsinan Ice Margin in Central Indiana: A New View from Glacial-Lacustrine Sediments from Porter Cave

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Evidence for proglacial lakes in central Indiana has been well documented for over 100 years. These laminated sediments intercalate with glacial tills, loess and paleosols and record the advance and retreat of the Illinoian and Wisconsinian ice sheets. Karst and associated caves found within the mapped margins for the late Quaternary ice sheets have been previously suggested as high-stand outlets for these lakes. Glacial Lake Quincy, the oldest stratigraphically of the lakes in the Mill Creek area in central Indiana partially overlies karst terrain. Some caves in this area contain an abundance of glacial-lacustrine sediments and are associated with many mid-drainage waterfalls and under fit valleys reflecting a complex glacial history. A critical discovery is the ubiquitous presence of well-preserved proglacial lake sediments within Porter Cave that contain organic material ideal for radiocarbon dating and sediments amenable for optically stimulated luminescence (OSL) dating. Previously reported borehole records indicate that lake sediments were over run by the advancing ice margin subsequently depositing a glacial diamicton.

We report the first quantitative chronologic control derived from 14C and OSL ages on Glacial Lake Quincy sediments within Porter Cave. Those data indicate the formation of Glacial Lake Quincy about 30 to 45 ka in the paleo-Mill Creek coincident with the Roxana Loess deposition in the Midwest. Mapped ice sheet margin associated with common waterfalls and distribution of lake sediments indicates that the ice sheet margin during marine oxygen isotope stage-3 was similar in extent to the last glacial maximum.

How Does Outside Temperature Influence Inside Temperature in Focul Viu Ice Cave in Romania?

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The purpose of this study is to evaluate the influence of outside temperature on cave air temperature in Focul Viu Ice Cave in Romania. The cave is located in the central part of the Bihor Mountains, Romania, at an elevation of about 1200 m asl. It is a 700 meter long descendent cave that hosts a 25,000-cubic-meter ice block at its bottom. Between April 5, 2004, and April 4, 2005, air temperature was continuously recorded with one hour interval in three points inside the cave and one point outside of it. Using regression statistical analysis, we identified the best model fit to describe the relationship between external and internal air temperature variations. In this model, the quantitative variables are represented by the air temperatures outside and inside the Great Hall in Focul Viu Cave; while the qualitative variables are represented by the seasons (Spring, Summer, Fall and Winter) and times of the day (Morning, Afternoon, Night). The collected data show a strong correlation between the external and the internal air temperature as long as outside temperatures are below 0°C (generally during winter, when rapid inflow of cold air in the cave occurs). In summer, the presence of the ice block maintains internal air temperatures close to 0°C, thus no air exchanges are observed between the outside warmer and lighter air masses and the colder and heavier internal ones.

Applying the Karst Disturbance Index in West-Central, Florida

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A hierarchical and standardized environmental disturbance index, specifically designed for karst landscapes, was created by van Beynen and Townsend (2005). To assess the applicability of the index and provide recommendations for its refinement, the index was applied to four counties in West-Central, Florida. The karst disturbance index consists of 30 indicators contained within the five broad categories: geomorphology, hydrology, atmosphere, biota, and cultural. Data were readily available for most environmental indicators used to construct the index. Overall, levels of disturbance vary between the counties due to the level of urbanization, with the highly populated Hillsborough-Pinellas having higher degrees of disturbance than less developed Pasco-Hernando counties. While this result may seem obvious, the measure of disturbance using many indicators provides benchmarks of levels of disturbance that can be reassessed with time and highlights those aspects of the environment most in need of attention. However, several minor issues arose during the testing: the need for broader indicator descriptions that encompass a variety of scenarios, a new water quality indicator, obsolete data on sinkholes, and a lack of data for biota indicators. The lack of data for certain indicators suggests where future research efforts can be directed; for our region those include species richness and diversity changes in caves and urban groundwater quality.

Human Sciences

Cave Divers: A Mixed Methods Study of Lifestyle, Personality, and Psychobiology

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Cave diving is said to be the most dangerous sport. Why are these divers attracted to putting on 140 pounds or more of very expensive, complicated equipment and then swimming in an environment where the only breathable gas available is that which they carry with them? Cave divers seem to have unique personalities, as well as the ability to solve problems quickly and to survive in extreme environments. Since the 1960s more than 500 individuals have died in underwater caves. In the face of such great potential for personal and family loss, why do some people choose to dive in caves?

My research will be conducted in the summer of 2007 and features a blending of quantitative and qualitative approaches. The mixed methods design includes three online test instruments: the Adlerian Lifestyle Assessment, Zukerman-Kuhlman Personality questionnaire, and Family Assessment Measure III. These tests will be administered to 100 cave divers during the initial phase. Later, 10 cave divers will be qualitatively interviewed to examine patterns of their family dynamics. These same ten divers will be DNA tested for polymorphisms of the D4DR and 5-HTTLPR genes.The long form of the D4DR gene may be linked to the Novelty Seeking Personality Trait and the short form of the 5-HTTLPR may be linked to anxiety behaviors. This research furthers the study of novelty-seeking, sensation-seeking, risk-taking behaviors, and personality development. Specific variables that will be measured include: Extroversion/Introversion, Sensation Seeking, Cautiousness, Control, Anxiety, Venturesomeness, Social Desirability, Creativity, Affective Expression, and Family Communication.

International Exploration

What Are Mars Analogue Sites and Why Are They Important in the Search for Caves on Mars?

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Our ability to study the surface of Mars is still quite limited. Mars analogues are typically hyperarid, with wide diurnal temperature fluctuations, high ultraviolet radiation exposure, and are geologically similar to the areas on the Red Planet (for example, areas of surface basalt, dust, and the like.). However, rarely does any one site meet all these conditions. Thus, researchers study a range of sites, which are characterized incompletely by various suites of these conditions. We will discuss selected Mars analogue sites with documented speleogenesis or regions likely to contain caves here on Earth. These areas are of particular interest for developing techniques to locate caves on both Earth and Mars using thermal remote sensing imagery. We will also discuss the results of cave thermal behavior research at two premiere Mars analogue sites—the Atacama Desert of northern Chile and the Mojave Desert of southern California, and some possible cave-like structures recently identified on the Martian surface.

Sistema Tepepa: Recent Progress of the Mexpe Project

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The area of Sistema Tepepa (Puebla, Mexico) has been explored for the past 20 years by the Mexpe project of the Quebec Speleological Society (SQS). Sistema Tepepa is the second deepest through trip in the Americas and is now over 28 kilometers in length and 900 meters deep. Nearby Sistema Brumas Selvaticas (8 kilometers), La Ciudad (6 kilometers) and 20th Anniversary Cave (3.5 kilometers) are awaiting a connection to Sistema Tepepa. Recent exploration took place in these four (and several other) caves during the 2006 and 2007 month-long expeditions. These productive expeditions (8 kilometers in 2006; 10 kilometers in 2007, for teams of 14 and 19 cavers respectively) took advantage of the latest cave surveying technology such as Auriga and electronic data acquisition devices. The area offers a mixture of boreholes, raging rivers, digs in tight blowing passages, breakdown mazes, and well-decorated passages, and there's plenty more to discover.

The Quintana Roo Speleological Survey: Recent Cave Explorations in Quintana Roo, Mexico.

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The Quintana Roo Speleological Survey supports conservation, safe exploration and confirmed survey documentation of underwater and dry caves in Quintana Roo, Mexico. The present study area incorporates 6,300 square kilometers in eastern Quintana Roo; to include 676 kilometers of surveyed underwater passage, and 8 kilometers of surveyed dry cave passage

Current investigations in Sistema Sac Actun have succeeded in linking over 6 major underwater caves and one dry cave. Containing over 155 kilometers of passage, Sac Actun is the longest cave in Mexico and the longest underwater cave in the world. At this date, new explorations in Sistema Sac Actun are within 25 meters of Sistema Dos Ojos (58 kilometers in length).

Dry cave explorations proximal to a Pleistocene ridge are producing significant finds. Cave passage development is associated with both deeper underwater cave passages, and the initial upper level of the ground water table. Sump explorations within dry caves connect both dry and underwater caves. Connections between distant underwater caves through dry cave passage are under investigation.

Six Years of Exploration in China

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Since its formation in 2001, Hong Meigui Cave Exploration Society has mapped over 270 km of cave and recorded over 1,000 entrances throughout south-west China. Expeditions have explored karst areas of Chongqing, Guangxi, Hubei, Hunan, Sichuan, and Yunnan. Highlights include:

- Extensive vertical development in Tianxing, including numerous 200+ m vertical shafts, the second biggest natural underground vertical drop in the world, a 491 meter-deep shaft in Miao Keng, and the four deepest caves in China: Tianxing Dongxue Xitong (19,025 m, −983 m), Dong Ba Dong (7,646 m, −649m), Da Keng (4,273 m, −775 m,), Miao Keng (1,039 m, −681 m).
- Over 80 km of complex multi-level passage in Houping–Tongzi–Jielong, including the fourth and fifth longest caves in China: San Wang Dong (28,892 m, −300 m) and Er Wang Dong (25,320 m, −241 m).
- Over 65 km of classic cone karst and river caves in Nandan and Leye.
- The 200 m × 300 m Hong Meigui Chamber and some of the largest tiankengs in the world.
- The search for 2000+ m depth potential along the deeply-incised Jinsha Jiang (upper Yangtze).
- The longest and deepest conglomerate cave in China, Longmen Dong (13,190 m, −355 m).
- A new species of blind loach, *Triplophysa rosa*, and numerous likely-new undescribed species of springtails and millipedes.

With over 100 members from 13 countries, HMCES embraces high survey standards and openness with regard to data. Survey data, surveys, cave descriptions, and photos are all available at www.hongmeigui.net

Tantalizing Tongzi, Wulong County, Chongqing, China

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In April 2007 a British and American expedition of the Hong Meigui Cave Exploration Society explored the karst and caves near Tongzi and Jielong in Wulong County, China. The team surveyed 15 kilometers and identified numerous new karst features, caves, and springs. Highlights of the discoveries include: Yan Tang Ping Dong, a tortuous, Charco-esque cave explored to −154 meters; Lao Chang Dong (Old Factory Cave), a 3,146-meter-long and 98-meter-deep cave complex, including old trails and miner's artifacts; Shang Hetao Wan Dong (Upper Walnut Bend Cave), the town dump, which was connected to nearby Leng Dong (Cold Cave), forming a 249-meter-deep, 4,865-meter-long system; and Quan Kou Dong (Spring Mouth Cave), a 116-meter-tall entrance with a 3.5 cumecs/sec stream and amazing airflow. Reconnaissance of a several kilometer-long, closed-valley in Jielong township yielded beautifully decorated Xiniu Dong (length 846 meters, depth 56 meters), San Cha Dong, (length 1,391 meters, depth 74 meters), and many more cave entrances and shafts that were not entered. The team also continued dye tracing efforts in the Houping/Tongzi/Jielong area to delineate groundwater flow paths. Excellent leads and caves remain to be explored during expeditions planned for spring 2008.

Caves of Sardinera - Isla de Mona, Puerto Rico

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Isla de Mona, an uplifted reef platform of Miocene and Pliocene age, is known for its world-class flank margin caves. The caves were formed at sea level within the carbonate platform and the largest have developed along the contact between the Lirio Limestone and the Mona Dolomite.

Caves have also been found in the Mona Dolomite, but they tend to be smaller and less complex. Caves are exposed at various elevations through a combination of tectonic uplift, glacio-eustatic sea level changes, and cliff retreat. Though caves have developed along the entire perimeter of the island, Playa Pajaros on the southeast side, and Playa Sardinera on the west side, display the highest concentration of cave development. Beginning in 2005, the Isla de Mona Project began working in the caves at and near Playa Sardinera. As with caves on the southeast side, the Sardinera caves are characterized by multiple cliff-side entrances and skylights, and large, mazy passages. Most of the caves contain remnants of historical guano mining operations, and evidence of use by the Taino Indians. Exploration and mapping are ongoing in Cueva Murcielagos, which contains the largest bat colony on the island, and in Cueva Esqueleto, which has some of the biggest cave passages and has been heavily mined for guano. There are numerous smaller caves located along the cliff-lines of Sardinera where some survey work has been completed, but there are many more to be found.

Paleontology

The Karst Information Portal: A Virtual Tool to Facilitate Research and Collaboration in Paleontological Speleology

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Data access, management, and evaluation challenge the progress of speleology. Crucial information is both scattered throughout specialty mainstream journals and buried in the gray literature. The karst-information problem is exacerbated in paleontological speleology due to overlaps with other disciplines, such as geology, biology, paleoclimatology, and hydrology, increasing the number of potential journals in which paleontological resources in caves may be published. Important patterns and relationships can easily be overlooked, especially when no geographic or cultural connections are known between paleontological sites within caves.

The Karst Information Portal (KIP) is a solution to these paleontological research problems. Conceived in 2005 and launched in June 2007, KIP developed as a partnership between the International Union of Speleology, National Cave and Karst Research Institute, University of New Mexico, and University of South Florida. Key features present or in development include:

- Federated (simultaneous multi-source) searches of Web sites to more efficiently and reliably locate key research papers and information;
- A searchable database of multidisciplinary karst information;
- A library of on-line papers, reports, and theses on karst related topics;
- A collaborative international on-line workspace to post and evaluate images, maps, databases, and other published and unpublished information.

Like other virtual research portals, KIP will grow as existing and future partners contribute information and connect websites and databases into the network. KIP will not duplicate existing databases but will serve to more efficiently access and process them with superior search tools. A cave paleontology bibliography is under development, but additional partners are needed to fulfill KIP's potential in revolutionizing paleontological speleology through its advanced and collaborative integration of data and ideas.

A Giant Short-faced Bear (*Arctodus simus*) from Island Ford Cave, Virginia

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The remains of an extinct giant short-faced bear (*Arctodus simus*) were recovered from Island Ford Cave, Alleghany County, Virginia, in the 1990s. This individual represents one of the most complete skeletons known for the species. The worn teeth, fused epiphyses, and small body size suggest it was an adult female, and the location in the cave and partial articulation of elements indicate it may have died while denning. Extreme examples of exostosis on the skeleton also attest to the advanced ontogenetic age of this individual. A radiocarbon date on dentine provides a geologic age of 34,080 ± 480 14C yr BP for the bear.

New Finds from New Trout Cave, Pendleton County West Virginia

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Vertebrate remains are well known from New Trout cave, the first being reported during the 1979 NSS Convention. Work in 2006 resulted in the recovery of more than 200, 10-pound bags of bone bearing matrix, mostly from the main site. Most of this has been processed by screening. Two species not previously known from New Trout have been recovered from the main site, a single tooth of the river otter, *Lontra canadensis* and two maxillae and one mandible of the least chipmunk, *Tamias minimus*, a mid-western species. This latter species was previously reported erroneously from New Trout. Other rare taxa recovered from the main site include the gopher, *Geomys sp*, pika, *Ochotona sp*, and extinct vampire bat, *Desmodus stocki*. From Site 3, teeth of a small extinct muskrat, *Ondatra hiatidens,* indicate a much earlier age than previously thought, being on the order of 500,000 years before present. Additional remains, including two mandibles, of *Geomys* were also found in Site 3.

Spelean History

Cave Art in Cave History: A Global Consideration

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New interpretations of European cave art and new recognition of its North American counterparts open windows into the role of cave art in cave history worldwide. In a speleocentric viewpoint, interfaces exist between cave art and rock art, and between cave art, historical inscriptions, political assertions, and graffiti. However artificial religious grottoes, recreational (''garden'') grottos, meditation grottos, and burial grottos are architectural features, not caves. On a global basis, cave art may be classified as cave paintings (including pictographs), cave sculpture (including petroglyphs and mud glyphs) and manuport art (including religious statues, ornate chandeliers, and the like). Age and motivations reflected in existing cave art vary widely but each type contributes to the history of individual caves and their regions. Examples are presented from the eastern and western United States, eastern and western Europe, Mesoamerica, Venezuela and the Caribbean, Africa, India and Ceylon, China and southeast Asia, Australia, and Hawai'i.

The Cave Cure: Old and New Ideas on the Healing Properties of Caves

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Caves have long been associated with mystery, fear, and good health. Crushed stalactites were used in ancient China and 17th century Europe as sedatives, cough medicine, and to heal broken bones. In the 19th century, visitors at Mammoth Cave thought the cave air enabled people to walk much farther without fatigue than they could above ground. In the 1840s, tuberculosis patients were even housed in Mammoth Cave to take advantage of the healing properties. Even today, caves and mines in eastern Europe and Montana are visited by sick and injured people hoping to be cured by the radon or salt ions. Are visitors healthier because of the radon and ions they absorb? Exercise from caving is a health benefit, but don't expect to be cured of tuberculosis or other illnesses on your cave trips.

The Discovery of the First Cuban Blind Cave Fish: The Untold Story

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The first two species of blind cave fishes described in the scientific literature from outside the United States were from Cuba and their description was published in 1858. They were the Cuban cusk-eel *Lucifuga* (*Lucifuga*) *subterranea* and the toothed Cuban cusk-eel, *Lucifuga* (*Stygicola*) *dentata*. The description of those species was published by Felipe Poey, a Cuban lawyer turned naturalist. The original documents that relate the discovery of these species were recently found. Those documents reveal a complicated saga of events but show that those fishes were actually seen for the first time in 1831, 11 years before the publication of the first scientific description of a blind cave fish: the northern cave fish *Amblyopsis spelaea*, from Mammoth Cave, Kentucky. Poey relied on others to collect the blind cave fishes in Cuba. His anatomical and taxonomic analyses of these specimens were highly accurate, and these fishes helped to convince him to embrace the idea of evolution. He kept ample correspondence with contemporary colleagues from the U.S. and Europe and most likely sent the specimens he used for describing the two species of Cuban blind cave fishes to museums abroad, particularly the National Museum of Natural History in Washington, D.C. and the Museum of Comparative Anatomy at Harvard University.

The Historical Geography of Show Cave Development

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Show cave histories tend to focus on the sequencing of events that occurred at specific caves, researched and written independent of other caves. Historical geography, with its emphasis on spatial patterns through time, provides a perspective on cave commercialization for an entire region. Emphasizing commercial caves in the eastern United States, a set of periodic stages are presented as a national model for the historical development of show caves. Beginning in the 19th century and continuing to the present, the pattern of tourist cave development is related to the evolution of transportation systems and the changing interpretation of how entrepreneurs should present caves to the paying public.

History of Allens Cave, Warren County, Virginia

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Allens Cave is located near Front Royal, Virginia. The cave may have been known as early as 1774. It is shown on Charles Varley's *Map of Frederick, Berkeley, and Jefferson Counties in the State of Virginia,* published in 1809. In 1835, Joseph Martin published *A New and Comprehensive Gazetteer of Virginia*, in which there is an extensive detailed and surprisingly accurate description of the entire cave. In the mid-1930s there was apparently an attempt made to commercially develop the cave. This endeavor moved to the adjacent Skyline Caverns when it was discovered in 1937. Allens Cave was described in NSS Bulletin Number 2, in 1941, and was a frequent destination of cavers from the Washington area during the 1950s and 1960s. Due to vandalism and possible liability, the cave was sealed in the early 1970s, and remained so until the late 1990s, when it was re-opened to investigate its proximity to a potential highway widening project.

The cave is known for its large Ballroom, said to have been the site of social gatherings over the years. The walls of the room, and of many other of the passages, are covered with names. Recent examination of the walls has yielded the names and unit identifications of Confederate soldiers, apparently placed there following the Battle of Cedar Creek, in October, 1864. The walls of the cave also exhibit the names of some cavers, which is a measure of how our understanding of cave conservation has evolved over the years.

Some Little Known Episodes at Wyandotte Cave, Indiana

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Wyandotte Cave has a long and storied history, becoming a show cave in 1850. There were also visits by prehistoric Indians thousands of years prior. Oddly, the Indian group for whom the cave is named probably never set foot far inside. There are many other aspects of the cave that are either little known or just recently coming to light. Throughout the years the cave has been the site of suicide, windstorms, and early billboard advertising, of which little is known or written. Some of the cave's stories exist as folk tales, featuring lost passages, hidden underground rivers, and a supposed purchase by P.T. Barnum that never occurred. Monument Mountain was featured by *Ripley's Believe It or Not* in 1932, gaining national prominence for the cave. Presidents, governors, geologists, filmmakers, astronomers, and other famous people have visited the cave from time to time. One of the more curious incidents occurred in 1941 when a team of mules was led several thousand feet into the cave to excavate a newly found passage for tours. The cave is currently the site of scientific research, including a study of the major Indiana bat hibernacula and a working seismograph.

SPRINGHOUSES IN KENTUCKY: FORM AND FUNCTION IN AN EVOLVING CULTURAL LANDSCAPE

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Natural springs are characteristic features of karst landscapes and have been highly valued as water supply sources from prehistory to the present day. Springs are frequently modified to improve accessibility, increase flow, and to protect the discharge point. Spring modifications constructed in an earlier era are often maintained, renovated, or improved by later generations. Kentucky provides an exceptional study area in which to investigate the significance of springs upon the cultural landscape. The importance and use of springs from the earliest days of settlement and exploration are amply documented in the historical record, and springs in both highly modified and undisturbed states may be found. The author has documented and photographed nearly 1,000 springs within the state, focusing primarily upon the Inner Bluegrass karst region. The purpose of this study is to investigate the nature and variety of spring modifications in this region, their origins and distributions, their relation to settlement patterns, and their changing significance in relation to changes in land use and cultural context. A classification hierarchy for spring modifications was developed for this purpose.

USING HISTORICAL ARCHIVES TO DISCOVER FORGOTTEN CAVES

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Cave entrances, and even entire caves, can be "lost" when knowledge of their location or existence fades from collective popular knowledge. Caves disappear as a result of natural processes or human activity that may disguise, cover, or even destroy these features. Frequently, however, significant karst features have been documented in some manner, and the task of the researcher interested in locating such features becomes that of discovering obscure references within the vast array of archival materials. In the past, human society has generally attached more significance to springs, as invaluable sources of water and power, than to caves, most often considered as curiosities with little value other than a few folk usages. Accordingly, archival material tends to refer more to springs than to caves per se; but in karst terrains springs are often indicators for cave systems. This paper describes and evaluates some of the primary archival sources for locating information about forgotten caves, and provides illustrative case studies from the Inner Bluegrass karst region of Kentucky.

State Cave Survey

West Virginia Speleological Survey

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The West Virginia Speleological Survey was founded in 1967, after it became evident that the West Virginia Geological Survey had no plans to update William Davies' *Caverns of West Virginia*. WVASS' purpose is the collection and dissemination of cave and karst data, the stimulation of cave and karst research, and the protection of caves in accordance with the policies of the National Speleological Society.

To that effect, WVASS has produced, beginning in 1971, 18 publications. At present, we have 19 directors, who assimilate the data for approximately 20 areas throughout the state. Active areas of work in West Virginia include Greenbrier County, Shavers Mountain, Germany Valley, and Grant County. We are attempting to produce seven additional publications in the near future, including works on Monroe County, Culverson Creek, Grant County, the Western Slope of Greenbrier County, Pleistocene paleontology, saltpeter caves, and vertebrate fauna.

WVASS also maintains a significant cave list, which comprises 11 categories and contains about 200 caves at present, and we have on-line reporting so that any caver can report or update their discovery. WVASS does not have a fixed membership, but any interested individual is welcome to attend our meetings and participate in our organization. We have two meetings a year: one in the fall at Old Timers, and another in the spring at a location that varies throughout the state. The Executive Director of WVASS is Bill Balfour, who can be contacted at 304-497-0859 or bal4karst@hotmail.com, url: . Our Web site is http://www.pipeline.com/~caverbob/wvass.htm.

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The Texas Speleological Survey (TSS) was loosely organized in 1961 to compile available information on Texas caves and to publish as much of that information as is possible and prudent. The TSS is now a non-profit organization existing on monetary donations, material donations and in-kind donations of labor. Book sales, including shipping and handling, are somewhat better than a break even proposition. Our mission statement, *Texas cave and karst data collected and organized to support science, education, conservation and exploration*, expresses our long term goal and commitment.

Affiliated with the Texas Memorial Museum, the TSS has offices at the University of Texas Research Campus in north Austin. Monthly work sessions provide a forum for interested parties to visit the office, investigate both paper and electronic files and contribute some labor. It has no members, or rather, all cavers are members, but has a volunteer Board of Directors who vote on business matters and assist in publishing, archiving cave files, and office maintenance. The Board has up to a dozen members at any given time. Associates are selected and used ad hoc to organize county files and to carry out specific operational tasks.

Data on paper and electronic form covers over 4200 caves, 1500 sinkholes and karst features, and Texas springs. Data requests, both casual for cavers and formal for managers such as scientists, environmental services, and state agencies, are handled electronically. Our Web site: http://www.txspeleologicalsurvey.org/ posts publications for sale, has contact information, and provides links to other Web sites.

Kentucky Speleological Survey

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This year's session topic is membership. The mission and goal of the Kentucky Speleological Survey (KSS) is *"To preserve cave and karst data for the Commonwealth of Kentucky."*

The KSS is a kind of library of cave and karst related data for the state of Kentucky. To fulfill this mission the KSS welcomes as members any individual or organization, such as a grotto, who would like to join. We ask that a membership form be filled out and submitted with a small fee. Elected directors from the organizations, as well as two directors at large, plus members of the board are eligible to vote on KSS business. In addition, all members, individuals, or organizations agree to the following:

- Must agree to the goals of the KSS
- Must agree not to divulge data held by the KSS
- Membership is not limited to Kentucky residents and the organizations can be out of state.

Membership shows that you support the goals of the KSS. The KSS holds four meetings a years at different locations across the state. Elections are held at the January meeting. In addition, paper caving sessions are conducted at Lexington four or more times a year. All members are welcome to these meetings and sessions. The KSS is a volunteer organization and we welcome new members to join, get involved, and make suggestions and improvements. As a matter of history, Kentucky cavers had not been organized on a statewide basis before the KSS was formed in 2001.

Survey and Cartography

Roundtripping a Digital Map of Dry Cave with WALLS and Adobe Illustrator Software

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Cave cartographers commonly face the problem of adjusting cave maps to changes in survey data such as loop closures and additional survey. To avoid this problem, many cartographers wait to draft a cave map until after the survey project is finished. This results in maps not being available for ongoing survey, and occasionally never being completed.

Roundtripping solves this problem by registering digital cave maps to the digital survey data. This process involves exporting digital lineplots of cave survey data using WALLS cave data management software as a Scalable Vector Graphic (SVG) document. This SVG document is opened in Adobe Illustrator where walls, detail and other map elements are created in specific layers and then saved as an SVG. When new survey data or data changes are made to the survey data in WALLS the SVG modified by Illustrator is adjusted by WALLS so that the map elements will conform to the new survey data.

Dry Cave in the Guadalupe Mountains of New Mexico is an excellent test of the roundtripping process for drafting digital cave maps. Dry Cave is an extremely complex maze cave with many loops and at least five levels. The cave map is divided into five separate maps by level using WALLS. These Dry Cave level maps are updated after each survey trip using the roundtripping process with excellent results. Over 8.9 kilometers (5.5 miles) of survey have been drafted using the roundtripping process.

Open Data: Small Caves Example to Preserving Data on the Internet

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A recent look into my file cabinet revealed a sobering fact. Of the many data sets I had, a large number were from cartographers or surveyors that were no longer caving, and in some instance no longer had any links to the caving community. In several cases I was the only one with the data to undrawn caves. What would happen if I were to lose these data, either from catastrophic events, or plain indifference? Likewise, what happens to data when a caver passes away, and the family or spouse have no idea what to do with all those muddy notes?

Large cave projects are actively saving and distributing notes and work to make sure nothing is lost. I will share a similar proposal for small caves that uses the Internet to store and distribute data that can increase access, distribute projects, and warehouse, and backup data for an extended period of time.

Using Cave Radiolocations as a Control Grid for the Cave Survey in a Large Cave System

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Virtually all of the known portions of Jewel Cave have been mapped since 1958. This consists of over 224 kilometers of passages, lying beneath approximately three square miles surface area. Most of the cave has been surveyed with Brunton and tape, but the park is now regularly using Suuntos and Disto laser meters. The survey has over 24,000 stations with 423 loops.

Because the farthest point of the cave is nearly 11 kilometers of survey from the nearest entrance (the elevator), subsurface loop closures are not entirely adequate for determining the accuracy of the survey.

Consequently, the park has employed a variety of cave radio location techniques to correct for survey error. There are currently 38 radiolocated points that have been tied into a surface survey and/or GPS locations.

Although this technique has its limitations, the errors are less than could be obtained with a subsurface survey, so the radiolocations are used as control points to correct the cave survey. This allows the park to make management decisions based on a high level of certainty of geospatial relationships between surface and cave features.

U.S. Exploration

The Webster Cave Complex Survey Group (WCCSG)

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The WCCSG is dedicated to the exploration and survey of the Webster Cave Complex, Breckinridge County, Kentucky. Nestled in Sinking Creek Valley, surrounded by the 800-foot-high ridges, are the three known entrances of the Webster Cave System. The system is the longest of a dozen or so caves that make up the Webster Complex. The main trunk of this cave, thought to be one of the largest continuous trunks in the state, is over three miles long, 40 feet high, and more than 40 feet wide. In places, continuous lakes extend for over a half-mile with neck deep water from wall to wall.

Recently, the WCCSG has undertaken the challenge of resurveying and extending the known caves of the area, beginning in May, 2005. Currently surveyed at over 5 miles (including about 1 mile of newly discovered passage), the main cave survey is expected to net many additional miles. Many long leads remain unexplored.

This system contains a large river at its terminus and the source and resurgence of this water are not known. The potential for additional cave discovery in surrounding ridge areas is an impetus for continued work in the system.

Six Miles in Six Years: The Exploration and Survey of Jugornot Cave, Pulaski County, Kentucky

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Exploration and survey of Jugornot Cave in Pulaski County, Kentucky, resulted in approximately 10 kilometers of cave passage during a six-year period that began during the winter of 2001. Long-known under another alias, Old Kentucky Cave, Jugornot follows the nomenclature of the Dayton Area Speleological Society, who in 1974 surveyed the 1.5 kilometers of historically-known cave.

Our subsequent survey of Jugornot has revealed a complex vertical maze than spans a 90-meter-thick sequence of limestone. Passages are confined to a 50-meter-wide band that aligns along a fracture swarm associated with an ancient normal fault. The cave transects a ridge and conveys water from Jugornot Hollow into Pumpkin Hollow. Passages group into four principal levels and up to seven individual levels that are traceable over long distances. Since Jugornot is an entrenching canyon, these levels mark periods of quiescence when the level of the nearby Cumberland River remained stationary.

Wide passages partly filled with sediment and decorated with gypsum and epsomite characterize the upper two levels of Jugornot. The middle levels are smaller, less well defined, and often decorated by an array of speleothems. Vertical shafts up to 45 meters tall pierce the cave and transmit water to an active stream that occupies the lowest level. This stream penetrates a chert horizon and connects, via the Vindication Crawl, to the Pumpkin River. Airflow in the Vindication Crawl suggests significant cave beyond; however, determined efforts both upstream and downstream in the passage beyond have yielded less than 700 meters of survey.

Crystal Cave: The Resurvey of Wisconsin's Longest Cave

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Crystal Cave is Wisconsin's longest known cave, developed in the Willow River Dolomite, New Richmond Sandstone, and Oneota Dolomite members of the Ordovician Prairie du Chien Group. The cave was discovered in 1881 by William Vanaasse. At that time, the cave consisted of a sinkhole entrance dropping into a large room, with clay-filled passages extending from the main room.

After extensive excavation efforts, the cave was commercialized in 1941 by Henry Friede. The cave was purchased by geologists Blaze and Jean Cunningham in 1986. Since that time, Blaze and Jean have welcomed Midwest cavers in continuing the digging efforts in the cave, as well as other small caves in the adjacent valley.

Crystal Cave had been surveyed by a number of Midwest cavers through the years, but no comprehensive map of the cave was ever produced. In 2005, John Lovaas and Dawn Ryan began a resurvey of the cave using current cave survey techniques and tools. To date, they have surveyed 3,672 feet, and with digging ongoing in the Tree Fork Section of the cave, they expect to find more.

The completed map of the cave will prove to be a useful management tool for the current and future owners of the cave, as well as a research and study tool for speleologists.

Culverson Creek Cave System, West Virginia

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Culverson Creek basin in Greenbrier County flows from a 42-square-mile, closed karst and into the Culverson Creek Cave System at the base of a steep escarpment.

The 20.1-mile-long cave system has seven entrances, large passages, numerous streams, and plenty of challenges for exploration. A trunk passage extends from the main entrance for more than a mile and a half before being blocked by The Log Jam, where hundreds of saw logs and trees, some 75 feet in length, block the passage. Along the way logs have jammed across the passage 60 feet above the stream.

In the early years of exploration the system included three separate caves; Culverson Creek, McLaughlin, and Fullers. Each of these caves reached a section of the main Culverson Creek stream, but connection along the trunk was blocked by impassable sumps and constrictions. Connection of the system was knitted together along other passages and by-passes. The furthest downstream penetration—3 miles from the Culverson Creek insurgence—reaches a deep sump called Dream Lake, which has not yet been successfully dived.

Much of the cave floods during wet weather. Sediment deposits more than 100 feet high have inspired names like Mudderhorn and Mud Everest. Other names such as Death Canyon, Psycho Siphon, and Dread Pool are indicative of the challenges this wet cave system offers.

The potential for flooding, and the rapid response to surface weather, makes accurate weather forecasting essential for continued exploration.

If You Survey It, They Will Let You In: The Goliaths Cave Survey Minnesota

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Goliaths Cave, formed in the Ordovician Dubuque and Stewartville Formations, is located in Fillmore County, Minnesota. It is situated within the Jessies Grove/Cherry Grove blind valley, which is approximately 25 acres in size.

Goliaths Cave was first described as Coon Cave sometime between 1955–57 by members of the Niagara Cavers, a group of Midwest cavers and cave guides from Niagara Cave, Minnesota. They explored approximately a quarter of a mile of the cave.

Extensive backflooding from the cave would close the sinkhole entrance regularly, and exploration in the cave did not resume until 1980. Poor caver/landowner relations caused the cave to be declared "off limits" in 1988.

In 1999, the landowners sold the blind valley to the Minnesota Department of Natural Resources' Scientific and Natural Areas division. The entrance of Goliaths Cave was gated, and cave access was through a permit system.

After learning about the cave through historic exploration reports, John Lovaas and Dawn Ryan submitted a permit proposal to conduct a survey and inventory of the cave. The project consists of three components- survey, inventory, and stratigraphy. This permit proposal, approved in 2006, was the first proposal ever submitted to the Minnesota Department of Natural Resources for entry into Goliaths Cave for research or scientific purposes. The natural entrance is extremely flood prone, and monthly survey trips are run only when there is no threat of rain in the forecast. To date, they have surveyed 1,236 feet of cave passage.

Recent Efforts of the California Sea Cave Survey

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After several years of inactivity we've seen some renewed sea cave survey along the California coast. This has been centered in two areas:

Mendocino County has numerous unmapped caves and a rugged, rocky coast that is often characterized by rough seas. In the early 1990s, Derek Hoyle and I surveyed two large caves, Cave of the Lost Soles (467 feet long) and Peters Creek Cove Cave (412 feet). On a trip in 2003, we mapped a series of caves on the south shore of Peters Creek Cove, and began work on a cave with a huge collapse pit entrance. Little River Pit was finished up on a second trip and proved to be 80 feet deep and 150 feet across, providing a back door entrance into a cave 365 feet long. We surveyed another littoral sink cave on the Mendocino Headlands and discovered another on California Coastal Project images, a great asset to sea caving.

In May 2006 we spent five days on Santa Cruz Island, scouting and surveying new caves we'd located since publication of my book on the island caves (*Sea Caves of Santa Cruz Island*, 1988). One of them, Hidden Fissure Cave, was 240 feet long, developed on a fault that had fractured an 80-foot-high cliff. The entrance was hidden behind a collapse. We scouted over two dozen more caves, but conditions were too rough to survey most of them. A fall 2007 return trip is planned, typically the calmest time of year.

Exploration in Dry Cave 2005–2007, Guadalupe Mountains, New Mexico

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Dry Cave is an extremely complex, rectilinear, multi-level, maze cave located in the Guadalupe Mountains of New Mexico. The first documented trip to the cave occurred in 1933. Approximately 8 kilometers (5 miles) of cave were surveyed from the mid 1960s to the late 1970s. Many additional passages were explored but never surveyed during this time period and numerous unexplored leads exist.

A resurvey of the cave initiated in 2005 uses modern survey techniques such as backsights, detailed survey notes, and inventory. Digital cave maps are updated immediately after each survey trip, utilizing the Walls/Illustrator roundtripping process, and greatly aid further exploration and survey. In January 2006, this systematic cave survey resulted in the discovery of the McKittrick Avenue Section. More than 3.9 kilometers (2.4 miles) of cave have been surveyed in the McKittrick Avenue Section with many crawling leads remaining. The cave survey is currently up to 8.9 kilometers (5.5 miles) and should easily exceed 16 kilometers (10 miles).

Observations based upon exploration, survey, and cartography have shown that the major passages are aligned with the local bedrock dip. Strike oriented passages are often smaller but have proven to be the key to the discovery of extensive new areas. The cave appears to have formed in a dome-like shape that is wrapped around a topographic and geological high point. Future exploration may reveal that cave passages completely surround this high point.

Recent Exploration in Lechuguilla Cave, New Mexico

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Since the last NSS convention, nine expeditions have entered the cave. Survey and resurvey have taken place in all three branches. The 120th mile was reached in November 2006 on an expedition that surveyed more than 6,000 feet of virgin cave. In March 2007, Lechuguilla passed Holloch in Switzerland to become the fifth-longest cave in the world. Several of the recent expeditions have utilized low-impact technical climbing in order to discover new areas. Much of the new survey has been mop-up in boneyard maze areas, but other work has extended new sections found in the previous two years.

In the Western Branch, Chandelier Graveyard is being worked to remedy bad loops and bad sketches. Along the way, interesting new leads are being explored. Work continues in Southern Climes to define the edges of Hahd Coah Maze. Mother Lode has been resketched with several leads remaining. Widowmaker and Chocolate Factory continue to produce footage.

In the Southwest, continuing on the Flatlands breakthrough last year, four additional lead climbs were attempted. Three of the climbs were completed with minimal footage gained. The fourth climb remains a work in progress.

Three expeditions worked in the Near East to correct blunders and resketch large rooms. There were also two technical climbs attempted in this area.

In the Far East, one expedition discovered a new form of rusticle formation known as the Fence Wire. Another continued to explore Coral Sea in an area requiring multiple clothing changes in order to preserve pristine flowstone.

Recent Exploration at Jewel Cave

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Since July 2007, over 3.3 miles (5.3 kilometers) of passages were mapped. All but half a mile (800 meters) was discovered on five multi-day trips to the southeastern section of the cave and in the western section of the cave, beyond the VACC. There were no breakthrough discoveries this year, but the total amount surveyed was greater.

Because of the climbing expertise of some of the explorers, more effort was made to climb ceiling leads; one above Seventh Heaven is particularly promising. A few pits have also been checked this year.

Much of the PC Junction area has been mopped up, with a good lower-level lead remaining. A long day trip to the southeast surprised everyone when one lead opened into a new area above the Volksmarch, with over a dozen leads yet to be mapped. Also, there has been renewed interest in the Western Motif area. Most of the work done there has been mop-up, but a tight lead with large cave beyond has yet to be surveyed.

With over 139 miles (223.8 kilometers), Jewel Cave is currently the second-longest cave in the world.

10,000 Sinkholes and Caves: Castile Karst in Southeastern New Mexico and Far West Texas

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Gypsum karst development is complex and diverse within the Castile Formation outcrop region of southeastern New Mexico and far west Texas, generally occurring in dense clusters. Large, steep-walled sinks dominate the landscape. Most sinks occur as highly-incised arroyos, but near-vertical, collapse sinks are common. Caves are highly variable and diverse, ranging from small, morphologically simple features to large, morphologically complex and deep forms. Caves have been found with complete or partial development in laminated, massive, nodular, and tabular gypsum fabrics, as well as gypsite and calcitized evaporites.

Parks Ranch Cave is the best known and longest cave (6,596 meters) within the Castile Formation; however, recent exploration has made many significant discoveries. Crystal Cave has been extended to a depth and length of 93 meters and 669 meters, respectively. Dead Bunny Hole, which is developed in both gypsum and calcitized evaporite, was recently discovered and surveyed to a length of 420 meters with several leads remaining. Many newly discovered features have been pushed over 100 meters in length (for example, Bee Line Cave, Hassle Hole, and Birthday Cave). Two active stream caves have been documented (Brantley Stream Cave and Sinkhole Flat Stream System), as well as an isolated cenote-like feature (Cave Well Cenote). Recent exploration coupled with GIS-based analyses suggests that as many as 10,000 individual karst features (sinkholes and caves) occur within the Castile outcrop region.

Update on the Wind Cave Survey Project, Wind Cave National Park, South Dakota

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Since the last NSS Convention, the Wind Cave survey project has continued to document new areas of Wind Cave (as of 4/30/07). A total of eight Wind Cave Weekends have been held since the last Convention, where 3.08 miles were surveyed and inventoried during 44 trips. These trips averaged 369 feet of survey per trip and increased the official length of Wind Cave from 121.28 to 124.36 miles, maintaining its status as the fourth longest cave in the world. Except for the Gas Chamber (currently at 1,141 feet), the majority of new survey was in the interior of the cave. This exciting discovery, which is located on the southwestern edge of the cave, will be discussed in more detail in Carl Bern's talk, also being presented in the U.S. Exploration session. Additional survey was added to the two most extensive areas now being surveyed in Wind Cave, including the Ghost Town (currently at 4,637 feet) and the Mock October Room (currently at 3,625 feet). Another interesting discovery was the Flatlands, currently at 1,241 feet of survey. In addition to the new survey, a complete rewrite of the park's Cave and Karst Resource Management Plan has just been completed and is available as a PDF on the park's Web site. This plan establishes new policies governing the continued survey of Wind Cave. Additionally, the first ever Wind Cave Quadrangle book has also just been completed. This atlas contains 120 miles of cave survey drawn on 37 individual maps.

Challenge and Potential in the Southern Comfort Section of Wind Cave, South Dakota

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Wind Cave, South Dakota, is one of the world's great maze caves. The Southern Comfort section was discovered in 1991 in a breakout from the 1- by 1-mile-square boundary that previously constrained the known cave. Since then, nearly 8 miles of survey have been documented in this section. Southern Comfort is a significant extension past the main body of the cave, and lies along the major axis of passage development. The geology of Wind Cave and environmental monitoring of nearby blowholes suggest that another breakout may be possible. Air movement can be felt in certain passages even in this remote section, and many leads remain to be checked. However, exploration and the push for another breakout face significant challenges in Southern Comfort. The network maze structure of Wind Cave makes it difficult to evaluate the potential of any given lead on the map, or in the cave. That structure also causes airflow to be weak, confusing, and possibly meaningless in guiding explorers to the best leads. Marathon day trips also present a physical and logistical challenge. A strong team that travels quickly to the exploration front may only be able to devote 6 hours of a 17-hour trip to exploration and survey. Despite these challenges, 1.3 miles of new survey have been added to Southern Comfort since 2002. New strategies such as establishing a camp or bivouac might accelerate the pace of exploration, but would need to be weighed against impact on a National Park Service cave.

The Exploration of Claystone Caves in Western Colorado

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Numerous caves have been found in sandstones and claystones of the Jurassic Morrison Formation and the Eocene Wasatch Formation in western Colorado. The largest, Anvil Points Cave, has over 650 meters of surveyed passage in a multi-level dendritic pattern. Many smaller caves in claystones have been found and documented on South Shale Ridge near DeBeque, beneath Cactus Park to the southwest of Grand Junction, near the Gunnison Gorge northeast of Montrose, above abandoned uranium mines south of Uravan, and south of Mesa, Colorado.

The caves are similar to those found in limestone in that they are seasonal conduits for streams, they divert water from one drainage to another, contain both entrance drops and internal pits, and have a variety of passage sizes ranging from very low crawls to passages up to 12 meters across and over 8 meters high. Small crystalline, sulfate-based speleothems, including gypsum needles and thenardite, are found in the caves.

The caves are stable with walls and ceilings consisting of a hardened mud/rock matrix. Floors are either hard mud or sandstone bedrock. The caves occur in a variety of pseudokarst landforms containing dolines up to 50 meters across, blind valleys, resurgences, and vertical shafts up to 10 meters in depth. Surveyed lengths are usually in the 50–250 meter range with vertical extents up to 50 meters. Considering the areal extent of the Morrison and the Wasatch Formations and the number of caves found in cursory searches, there may be hundreds to over a thousand others.

Ursa Minor Cave, Sequoia / Kings Canyon National Parks, California

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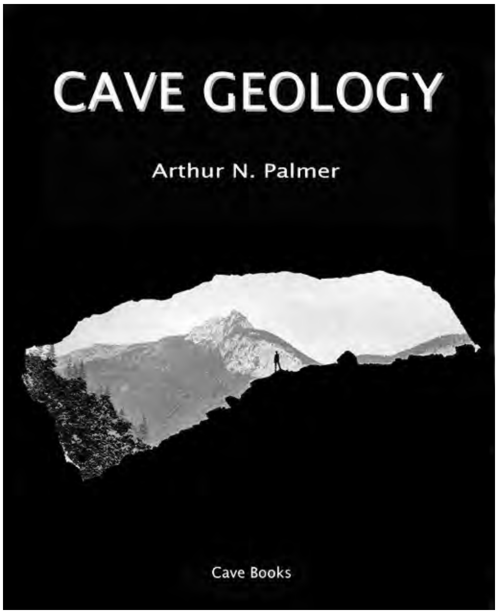
In August 2006 cavers discovered another wonder underground in Sequoia and Kings Canyon National Parks. Ursa Minor Cave abounds with large passages, beautiful lake beds, amazing formations, and other spectacular resources throughout its known extent. The cave length is now approximately 1,500 feet long with a number of leads still remaining.

BOOK REVIEW



Cave Geology

Arthur N. Palmer, 2007. Dayton, Ohio, Cave Books (www.cavebooks.com), 454 P., 8.5 x 11 inches. ISBN -13: 978-0-939748-66-2 hardbound, $38.

Arthur Palmer has produced an absolutely terrific book on cave geology, which necessarily includes substantial discussions on karst hydrology, water chemistry, geomorphology, and related areas, all for a remarkably affordable price of $38. This is not a skimpy paperback, but a large book (454 pages), with old-style heavy glossy paper. In addition, it includes more than 500 high-quality black-and-white photographs and 250 diagrams and maps.

Recently retired from teaching at the State University of New York at Oneonta, Palmer hasn't retired from active cave exploration, cave and karst research, or publishing. He is world renowned for his research into speleogenesis over several decades with his wife Margaret (Peggy) Palmer. Together, they have explored caves and karst landscapes all over the world and this book reflects the experience gained over those long years of work.

The book begins with a basic introduction into the science of speleology and moves on to geomorphology, soluble rocks, hydrogeology, chemistry, characteristics of caves, speleogenesis and so on. Hardly a subject is left out. Caves in volcanic rocks are also not necessarily one of Palmer's specialties, but he includes quite a lot about the subject anyway, which is helpful for those of us who have little experience with caves in volcanic rocks. Throughout, Palmer provides references to other readily available sources so that readers can explore the concepts in more detail.

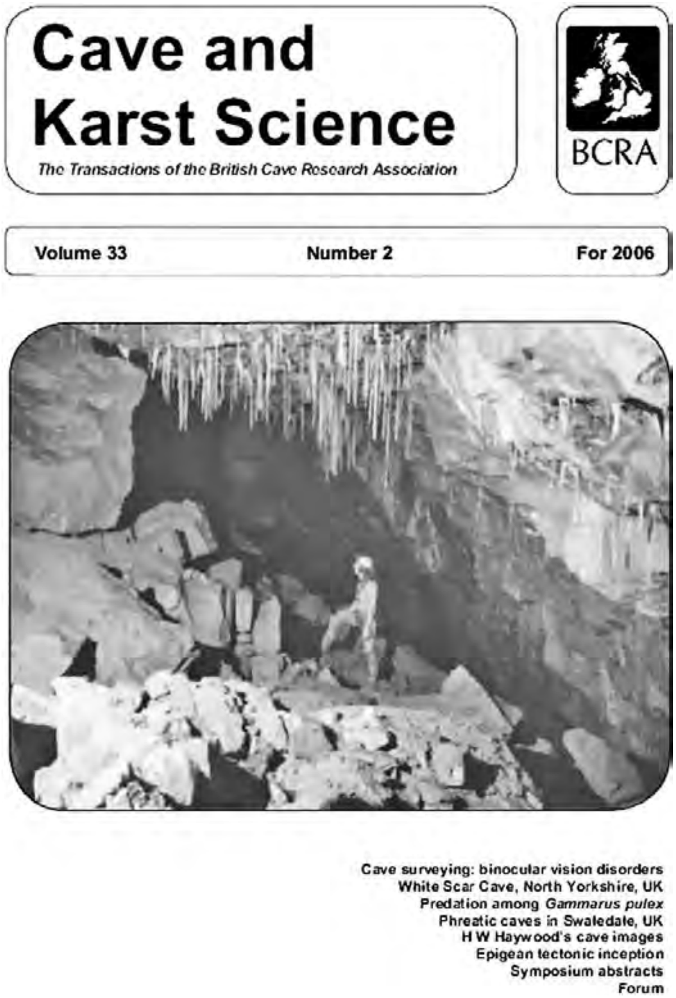
Palmer's real training is hydrogeology, geochemistry, and geophysics, so many of the technical aspects of this book are found in these subject areas. However, he does not waste space addressing the investigative hydrolgeological techniques typically applied to non-karstic terranes, as this information can be found in common hydrogeology textbooks. However, he does provide detailed discussions of methods more common to karst terranes, such as dye tracing. Palmer began conducting dye-tracing studies relatively late in his teaching career, but typical of his emphasis on really understanding a topic, he moved quickly to really learn the subject so as to be able to properly convey the subject to his students. His discussion of dye-tracing methods in this book is reasonably detailed, but also brief enough such that the reader won't lose interest while reading over the subject.

More significant are Palmer's discussion of such topics as cave patterns (chapters 8 and 9). Here, Palmer is clearly in his element. Any student interested in learning about cave patterns needs to read these two chapters (and other related sections of this book) because there are few other sources available anywhere that even come close to that which is presented in this book. Chapter 8 addresses cave patterns as a function of ground-water recharge, while chapter 9 addresses cave patterns as a function of geology. It is noted in chapter 8 how significant recharge is in the formation of cave patterns, but chapter 9 then emphasizes the local geology and landscape also have major impacts on cave patterns. An obvious geological effect is rock type, but geological structure is also evident and discussed in detail.

Throughout the book, Palmer includes good explanations of how studies in karstic terranes are typically conducted. Often these brief descriptions are provided in a boxed section to avoid disrupting the flow of the text in the book. In all instances Palmer achieves that which appears to most difficult for professional research scientists, conveying advanced complex topics to the reader in such a manner as to be very readable and understandable by the layman. In fact, this has got to be the most readable text on the subject of caves and karst that I have ever come across. Important mathematical concepts are included, but Palmer was careful to limit them to basic algebra so as not to overwhelm readers.

My overall opinion of this book? Every person with at least a passing interest in speleology should purchase a copy. For the remarkably low price of about $38 (prices vary insignificantly from place to place) there is no better buy anywhere, especially for the wealth of information contained. Do I have any complaints about the book? Well, it is a bit heavy because of the high-quality glossy paper used. And of the 760 figures/photos, none are in color. However, the high quality easily justifies the weight of the book and the lack of color figures/photos makes this a very affordable book, so my complaints are really just observations.

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@epamail.epa.gov).



Cave and Karst Science, 2006
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GUIDE TO AUTHORS

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