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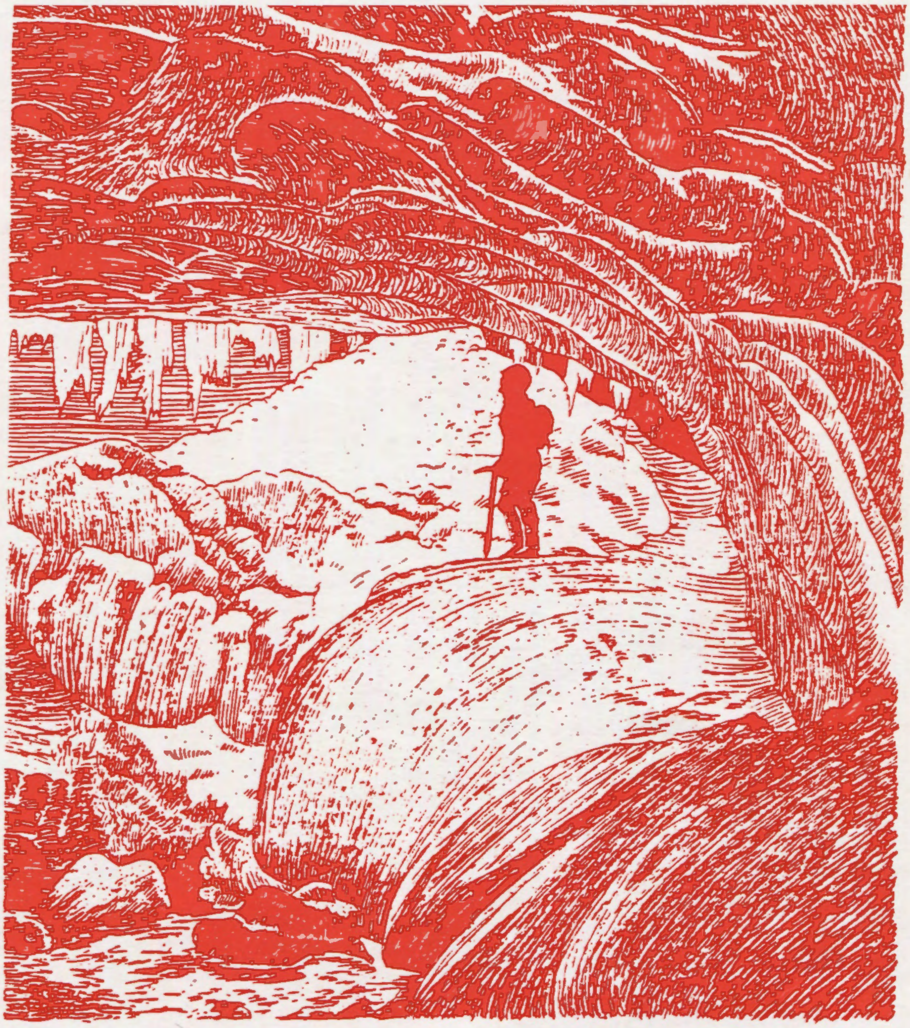

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BIOLOGICAL INVESTIGATIONS IN LECHUGUILLA CAVE

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A biological inventory of Lechuguilla Cave, Carlsbad Caverns National Park, Eddy County, New Mexico was conducted from July 1989 through December 1991. Various studies concentrated on the identification of invertebrates, fungi, and bacteria inhabiting the Entrance Pit and the Dark Zone of the cave. Invertebrates found in the Entrance Pit included a variety of accidental species (beetles, flies, ants, and grasshoppers) and several trogloxenic, troglophilic, and troglobitic species (camel crickets, rhadine beetles, mites, collembolans, and millipedes). A number of spider species were found, many of which are probably residents. Dark Zone invertebrates were limited to two species of camel crickets, and one species each of rhadine beetle, collembolan, dipluran, mite, and centipede. Thirty-seven different species of fungi in 13 different genera were cultured from a variety of habitats in the cave. Preliminary bacterial investigations identified 10 different bacteria from pools and corrosion residues.

INTRODUCTION

Lechuguilla Cave, isolated beyond the entrance pit from humans until May 1986, represents a unique opportunity to study organisms in a relatively undisturbed cave. Located 5.6 km WNW of Carlsbad Cavern, in Carlsbad Caverns National Park, Eddy County, NM, Lechuguilla Cave has been mapped to over 120 km long. The cave's vertical extent is approximately 485 m making it the deepest limestone cave in the United States. Lechuguilla currently consists of entrance passages and three main branches: the Eastern, Southwest and Western Branches (see Figure 1).

The lower passages of Lechuguilla are in the reef rocks of the Capitan Limestone and Goat Seep Dolomite; the upper passages are developed in the Seven Rivers Formation (Jagnow, 1988). Hill (1987, 1990) and Davis (1980) support a model of speleogenesis in which hydrogen sulfide rising along fissures reacted with oxygen to form sulfuric acid which dissolved the limestone.

Different habitats for invertebrates exist in the Entrance/Twilight Zone versus the Dark Zone of Lechuguilla Cave. The Entrance/Twilight Zone at the bottom of the Entrance Pit varies seasonally in moisture content. There is a relatively wet area at the bottom of the Entrance Pit extension, as well as some dry, dusty sediments in an alcove. The bottom of the Entrance Pit consists of loam, mixed with rubble and organic debris from the surface. The alcove to the east of the landing area has old, undated bat guano (bats no longer roost in Lechuguilla) and provides a secluded environment for invertebrates. Flooding does not occur in the cave. Habitats for invertebrates in the Dark Zone include (1) dry, dusty sediments with rock rubble, (2) wet, flowstone areas, (3) massive gypsum blocks (Glacier Bay), (4) silt floor areas, and (5) breakdown-covered floor areas. Recent organic material past the culvert is limited to that brought in by cavers and material that percolates down through the overlying rocks. The lack of organic matter keeps invertebrate populations low.

Habitats for microorganisms in Lechuguilla Cave include the many pools; human camping areas; sulfur, manganese, and iron deposits; and corrosion residues. Corrosion residues, which in most caves result from corrosive condensation water attacking limestone bedrock and/or calcitic speleothems, are found through Lechuguilla. These residues typically consist of ceiling-bound chestnut-brown to steel-gray colored filamentous material.

Pools, which vary from very small puddles to lakes that can be as much as 28 meters deep, occur in all three branches and at elevations from the deepest point to near the surface. Human camping areas, because of the potential for organic enrichment, may be potential habitats for bacteria and fungi. They occur in all three branches of the cave.

Sulfur, manganese, and iron deposits are potential sites for chemolithotrophic bacteria. Sulfur is found in major, multi-ton deposits in the Void, North and South Ghost Town sites, and in a small occurrence at the Rift. Appreciable (2-5%) sulfur in encrustations is found all over the cave, but particularly at the two deep points (Sulfur Shores and Lake of the White Roses), in wall rocks underlying bound corrosion residues, and sometimes associated with altered clays harboring alunite and halloysite. Iron and manganese, of unknown oxidation state, are ubiquitous components of the cave, with certain areas such as Todo Corrodo, Carnegie Hall, Upper Ruby Chamber, Hudson Bay, and numerous others, representing areas of enrichment.

The goals of this study were to inventory invertebrates, and to begin to study fungi and bacteria present in Lechuguilla Cave, with a secondary goal of assessing possible human impacts on these biota. Invertebrate, fungal, and bacterial results will be discussed in the following three sections.

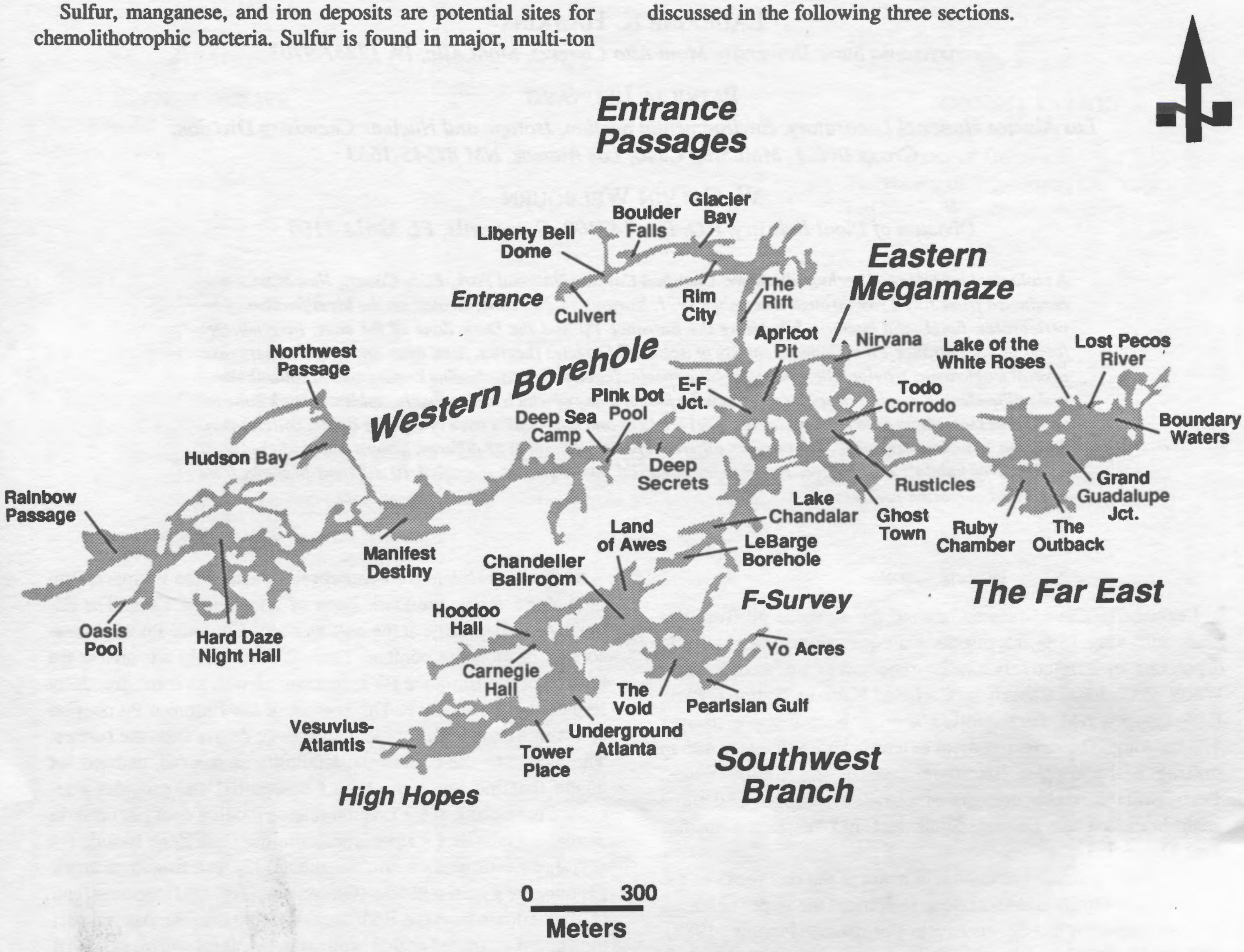

Figure 1: Schematic map of Lechuguilla Cave, Carlsbad Caverns National Park, NM, showing the three major cave branches and landmarks. Map courtesy of U.S. Geological Survey and Lechuguilla Cave Project, Inc., 1991.

ABIOTIC CONDITIONS

Lechuguilla's air temperature varies from 17.3° C at the Liberty Bell Dome (Fig. 1) to 20.4° C at Lake of the White Roses, the deepest point in the cave. Soil temperatures vary from 16.5° C at Liberty Bell Dome to 20.0° C in the Outback in the Far East. The temperature variation is a function of proximity to the entrance, the strong air currents near the entrance, and elevation. Beyond Boulder Falls, humidity was measured at 99-100% with a soil psychrometer. The water temperature of pools sampled for bacteria ranged from 18.6° C to 20.0° C.

INVERTEBRATES

Methods

Macro- and microarthropods were sampled four ways: (1) pitfall trapping, (2) visual inspection, (3) Berlese funnel extraction, and (4) sediment floats.

Pitfall trapping was conducted eight times between September 1989 and October 1991 using a standard set of trap sites from the entrance culvert to the top of Apricot Pit (Fig. 1). Fifty-three, unbaited, sixteen-ounce cups (Solo™brand) with inserts (Cozy Cup™) were buried to their rims in soil or rubble.

Traps were set during July 1989, September 1989, July 1990, December 1990, January 1991, May 1991, July 1991, and October 1991, and were left in place for approximately 24 hours. Traps were set only from the culvert to the top of Boulder Falls during the July 1989 trip; locations of traps were standardized as of July 1990. Invertebrates in the pitfall traps were identified and released. Adult crickets and rhadine beetles were marked on the dorsal side of the abdomen with water-based paint, starting December 1990. Marking experiments in Carlsbad Cavern suggest the paint remains in place for up to six months on crickets (Northup, unpublished data).

Intensive visual searches for invertebrates were conducted at the bottom of the entrance pit and its lower extension. These involved inspecting cracks, crevices, walls, and floor, and turning over rocks and debris. Invertebrates found were photographed and first-time captures were collected for identification. Pools beyond the culvert were checked visually for invertebrates.

To investigate the presence of protozoans, samples from pools in the Southwest were attained by immersing wide-mouthed polyethylene or Nalgene bottles (500ml) beneath the surface. Samples were collected from the surface as well as from the water column and contamination was minimized by using sterilized gloves. Samples were maintained in the dark near cave temperature in route from New Mexico to Ohio and then were placed in an environmental chamber in continuous darkness at 18.0° C. Subsamples were examined using small dishes and a dissecting microscope and also utilizing microscope slides and a compound microscope. Filtered leaf infusion and rice grain infusion media were used and cultures were examined after 24, 48, 72, and 96 hours.

Three samples of soil (approximately 0.275 l) were removed from the bottom of the entrance pit in October 1991 for extraction of small invertebrates including mites using Berlese funnels (Murphy, 1962).

Three soil samples (3-4 l each) were collected from the entrance passages of Lechuguilla Cave for soil washing (Kethley, 1991). Following volume reduction, five to eight subsamples from each soil sample were floated in concentrated salt solution (NaCl) to extract invertebrates as described by Hart and Fain (1987).

Three half-liter samples of corrosion residue were collected from the top of Apricot Pit, Ruby Chamber, and The Void (Fig. 1), and placed in 95% ethanol for examination. Five subsamples from each sample of corrosion residue were floated in concentrated NaCl (Hart and Fain, 1987).

RESULTS

"Accidental" species found at the bottom of the entrance drop were identified to family. All spiders were identified to genus where possible, and camel crickets were identified to species.

Accidentals, spiders, and camel crickets predominate in the bottom of the entrance drop. Most of the camel crickets (*Ceuthophilus*) were found in the alcoves and crevices. Spiders were the most diverse group found at the entrance drop, and usually were found under rocks and debris or in crevices in the walls. Many of the spiders are not entirely accidentals. Accidentals, troglophiles, trogloxenes, troglobites, and a guanophile were found at the bottom of the entrance drop and its extension (Appendix A).

Each sampling trip revealed a different assortment of accidentals. In addition to the invertebrate accidentals mentioned, snakes (*Pituophis melanoleucus* (Daudin)), lizards (*Scaloparus poinsetti* Baird and Girard and *Eumeces obsoletus* (Baird and Girard)), and toads (*Bufo punctatus* Baird and Girard) were found at the bottom of the entrance pit. The only troglobitic organisms found in this area were a millipede (*Speodesmus tuganbius* Chamberlin) and a mite (*Ceuthothrombium cavaticum* Robaux *et al.*, 1976).

Invertebrates found beyond the culvert, in the Dark Zone, include the following (troglobite = TB, trogloxene = TX, troglophile = TP and accidental = A):

Class: Myriapoda:
- Subclass: Chilopoda (Centipedes)
  - Order: Scolopendromorpha: *Thalkethops grallatrix* Crabill (TB)

Class: Chelicerata:
- Subclass: Arachnida
  - Order: Araneae
    - Agelenidae: *Cicurina* sp. (TX)
  - Order: Acari (Mites)
    - Histiostomatidae: *Histiosoma* sp. (TP?)

Neothrombiidae: *Ceuthothrombium cavaticum* Robaux, *et al.* (TB)
Class: Insecta
Order: Coleoptera
Carabidae: *Rhadine longicollis* Benedict (TP)
Order: Collembola
Entomobryidae: *Pseudosinella violenta* (Folsom) (TP)
Order: Diplura
Campodidae: *Plusiocampa* sp. (TB)
Order: Orthoptera
Rhaphidophoridae:
Ceuthophilus carlsbadensis Caudell (TX)
Ceuthophilus longipes Caudell (TX)

The number of organisms trapped at sampling times is shown in Figure 2.

Camel crickets (*C. longipes and C. carlsbadensis*) dominated the pitfall captures; a few *Rhadine longicollis* (Carabidae) and *Plusiocampa* sp. (Campodidae) were censused (Fig. 2). Most invertebrates, especially camel crickets, were caught in the first 61m of the cave (Fig. 3). Invertebrates were not found beyond the beginning of the Rift. No marked individuals were recaptured or seen.

Three invertebrate trapping trips occurred before and after major survey and exploration expeditions into the cave. The September 1989 (Fig. 2) census was done during an expedition and the number of invertebrates captured was very low. The December 1990 (Fig. 2) and January 1991 trips occurred right before and right after, respectively, a major expedition with no significant difference in number of captures noted.

A troglobitic centipede (*T. grallatrix*) with a histiostomatid deutonymph (*Histiosoma* sp.) attached to a leg was collected on the trail near the beginning of Rim City. Collembolans were observed on the surface of pools above Boulder Falls. No protozoans were found in water samples taken from the Southwest branch of the cave (Hobbs, unpublished data) and no arthropods were found in any of the corrosion residue or soil subsamples.

DISCUSSION

Seven trogloxenes, four troglophiles, four troglobites and one gaunophile were found in the Entrance, Twilight, and Dark Zones of Lechuguilla Cave. All have been reported from other caves in the area (Barr and Reddell, 1967, Robaux, *et al.*, 1976, Welbourn, 1978). Two of the four troglobites (*S. tuganbius, Plusiocampa* sp.) in Lechuguilla Cave are widespread in caves of the area (Barr and Reddell, 1967; Shear, 1974, and Welbourn, 1978). Welbourn (1978) reported two additional troglobites, *Brackenridgia* sp. (Crustacea: Trichoniscidae) and *Leptoneta* sp. (Araneae: Leptonetidae) from Slaughter Canyon caves that have not been found in Lechuguilla Cave. *Thalkethops grallatrix* previously had been reported only from Carlsbad Cavern, but Welbourn (1978) reported undetermined "small and pale" centipedes

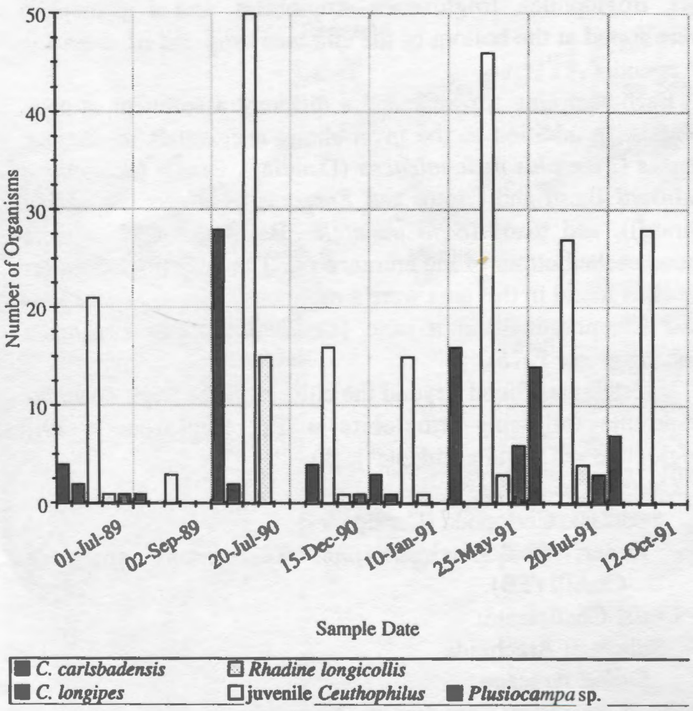

Figure 2: Numbers of invertebrates caught in pitfall traps from the entrance culvert to the top of Apricot Pit. Juveniles = immature crickets of either species.

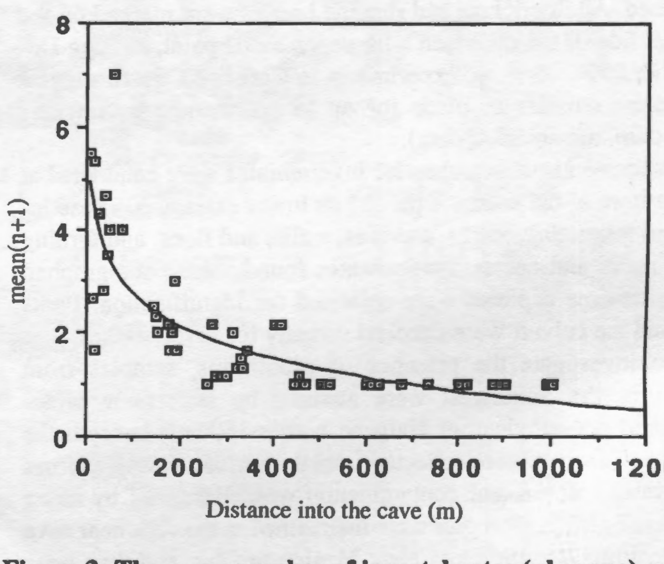

Figure 3: The mean number of invertebrates (plus one) captured in pitfall traps, 1990-1991, versus distance from the entrance. Notable approximate distances are: Top of Boulder Falls—190m; Rim City—415m; Glacier Bay—440m to 500m; Beginning of the Rift—645m. The line is the best fit log_{10} decay model for the data and is ($y = 6.9288 - 2.0707 log(x)$; $R^2 = 0.641$; $p < 0.001$).

from two caves in Slaughter Canyon, suggesting this centipede may be more widely distributed. The other troglobite, *Ceuthothrombium cavaticum*, has been reported from Spider Cave, Lake Cave and Water Tank Cave in Carlsbad Caverns National Park (Robaux *et al.* 1976 and Webb *et al.* 1977) is widespread in caves of the Guadalupe Mountains and gypsum karst (Welbourn, unpublished data). The invertebrate fauna of Lechuguilla Cave is similar to that reported from caves in Carlsbad Caverns National Park, except for the *Histiosoma* sp. found on the leg of *T. grallatrix*. Unfortunately the mite was an immature and could not be identified to species, but this occurrence suggests there may be additional troglobitic invertebrates in the cave.

The entrance pit acts as a natural trap for surface invertebrates resulting in the mix of numerous accidental species and a few species that are true inhabitants (Appendix A). Compaction of the soil below the entrance drop by people entering the cave may contribute to low numbers of organisms. Based on repeat captures, it appears that the only true residents of the Entrance/Twilight Zone are the camel crickets, rhadine beetles, mites, spiders, collembolans, and possibly pseudoscorpions.

Camel crickets were the dominant invertebrates caught in pitfall traps. Sub-juvenile camel crickets have been caught in the pitfalls and observed along trails and near pools as far as Glacier Bay, indicating that camel crickets are breeding in the cave. The Lechuguilla population of the troglophilic carabid (*R. longicollis*), which is often associated with camel crickets and eats cricket eggs, was lower (Fig. 2) than in Sand Passage in Carlsbad Cavern (Northup, 1988).

The camel cricket seasonal patterns can be discerned from the data in Figure 2. More crickets, especially adults, are caught in late spring and in summer than in winter or fall. Sub-juveniles and juveniles were caught throughout the year. A larger number of camel crickets and other invertebrates was caught in July of 1990 than in July 1989 or 1991.

The mean number of invertebrates found as a function of distance from the entrance is shown in Figure 3. The number of invertebrates declines at approximately 61 meters beyond the culvert, well before Boulder Falls.

Other species of invertebrates were captured only rarely in pitfall traps or sighted. Diplurans (*Plusiocampa* sp.) are very secretive and were observed only occasionally in the cave and occurred only in pitfall traps in three of the eight sampling periods. They require high humidity and may be affected adversely by the wind currents between the entrance and Liberty Bell Dome. They were probably more common than trapping and observation suggest. Collembolans were rarely found, except on the surface of pools near the Liberty Bell Dome.

There is a limited number of species in the Dark Zone of Lechuguilla Cave and one or two species dominate. The low numbers of invertebrates can be attributed to the absence of organic matter beyond the culvert.

A concern is whether cavers are introducing additional organic matter that leads invertebrates deeper into the cave. Our studies indicate that this is not yet a problem. Unfortunately, we have no pitfall data for the first three years after the cave opened, but our data from 1990-1991 suggest there has been no farther penetration into the cave. Invertebrates have been caught in pitfall traps as far as the beginning of the Rift (Fig. 3). The lack of further progression into the cave may reflect the fact that cavers often eat at the bottom of Boulder Falls, but rarely stop to eat between there and the E-F Junction, located approximately 0.8 km farther into the cave. Invertebrates have been observed feeding on food cached at the bottom of Boulder Falls. Crickets and other invertebrates may not be finding enough food resources to encourage their travel further into the cave.

During 1991, the number of organisms caught in pitfall traps during a given sampling period never reached the same high value as during the July 1990 trip. There is no obvious reason why captures were higher in 1990 than in 1991. The December 1990 and January 1991 censuses resulted in low numbers of organisms.

These low numbers may be the result of seasonal fluctuations (lower densities in winter), or increased human traffic in the cave. The January 1991 pitfall trapping immediately followed a regular Lechuguilla Cave Project (LCP) survey/exploration expedition. However, the December 1990 biological expedition, with its low number of captures, did not immediately follow an LCP expedition. These data do not show a clear trend with regard to the imact of humans on the organisms, with the sole exception of the September 1989 census which occurred during an LCP survey/exploration expedition. Numbers of captures were the lowest during this census, suggesting high human activity has a short-term negative effect on cave faunas.

Although no observations were made during the first three years after Lechuguilla Cave was opened to humans, invertebrates found during this study probably already inhabited the cave. Invertebrates could easily get through small fissures and holes in the breakdown at the original dig site. The presence of troglobitic organisms (centipede, millipede, mite, and diplurans) suggests these invertebrates have existed in Lechuguilla Cave for a long time. More detailed studies of the troglobites in the Guadalupe Mountains area may suggest relationships not evident from the current studies.

In order to protect and conserve the currently known and any as yet undiscovered invertebrates, the investigators recommend limiting the introduction of organic matter and providing periods during which the cave and the fauna can rest from human intrusion. Limiting the introduction of new organic matter into the cave by humans will prevent artificial inflation of the invertebrate populations due to increased food resources and reduce the risk of other species invading the cave. Cavers should be encouraged to take care with eating, and food caches should be prohibited or sealed in sturdy containers. Although numbers of invertebrates appear to be impacted only during expeditions, providing periods of relatively low or no human activity following large expeditions will insure time for invertebrates to recover. Further study is needed to determine what an adequate period of inactivity is. Although the invertebrate fauna is limited, it is worth protecting.

FUNGI

Methods

Forty-four sites and 124 samples were acquired (Fig. 4) in the entrance passage, Eastern, Western, and Southwest branches of the cave between February 1990 and October 1991.

Fungal samples were obtained by gently rubbing a sterile, dry cotton or rayon swab over the flowstone, speleothems, or soil. Following sampling, the swab was placed in a sterile vial, sealed, labelled, and transported to the laboratory for culturing. The initial swabs were cotton, but from fall 1991 forward, all sampling used the CultureSwab Transport System with Stuart's media and rayon-tipped swabs.

Swabs from the cave were immersed in 1.0 ml of 0.01% Triton X solution to help extract spores. Aliquots of 0.2 ml were pipetted onto petri dishes containing potato dextrose agar (PDA). At least two plates were made from each sample. Plates were cultured at room temperature (22° C) for 8-10 days. Resultant colonies were subcultured in order to obtain pure cultures. Unique isolates were transferred to Sabouraud dextrose agar (SDA) and maintained as reference cultures.

Fungi in the original samples were sorted on the basis of colony morphology. Unique colonies were assigned unique isolate numbers. Colony morphology was described according to color, size of colony, texture, and pattern. To identify colonies from new samples, colony morphology was first compared to previous cave isolates. If colonies matched isolates already described, they were assigned the same number; otherwise a new isolate number was assigned.

Fungi were identified based on the morphology of their reproductive structures. Wet preps were prepared by teasing small

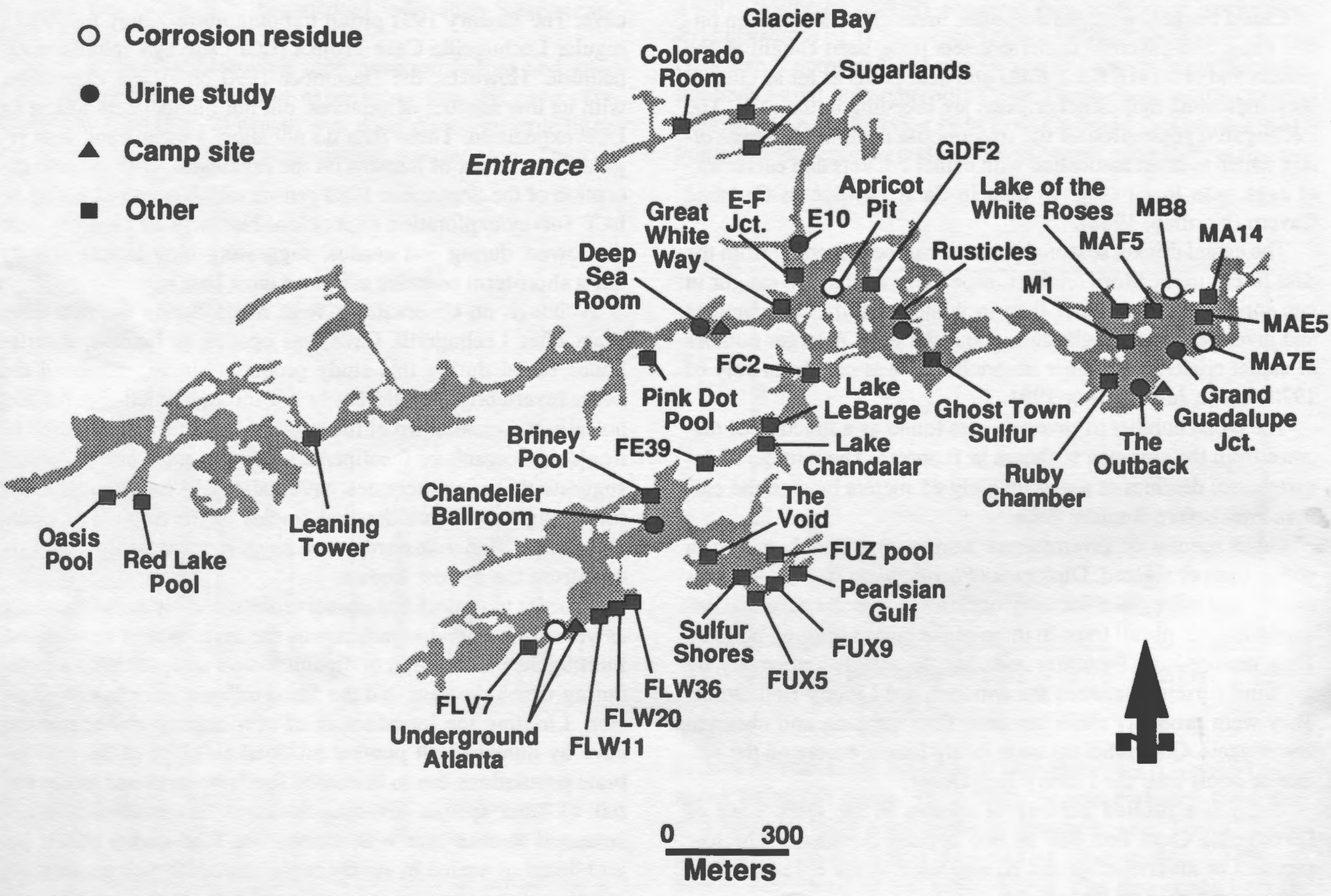

Figure 4: Schematic map of Lechuguilla Cave, Carlsbad Caverns National Park, NM showing fungal sampling sites. Map courtesy of U.S. Geological Survey and Lechuguilla Cave Project, 1991.

pieces of colonies apart in Lactophenol cotton blue or potassium hydroxide on a microscope slide and covered with a cover slip. Slides were examined microscopically for characteristic mycelia and conidia. Keys by Barnett and Hunter (1987), Domsch *et al.* (1980), and Malloch (1981) were used to identify the isolates to genus.

Results

Fifty of the 124 samples (40.3%) produced fungal colonies. These colonies represented 37 different species of fungi and 13 different genera. More samples from the Western Branch contained fungi (51.6%) than those from the Eastern Branch (30.6%) or Southwest Branch (39.6%). This difference was not statistically significant (Chi-Square = 3.08, d.f. = 2).

Generic identification and frequency of occurrence of a particular species are shown in Figure 5. Note that when two isolates have the same generic identification this indicates that they are putatively different species, based on colony morphology. Several colonies were sterile but differed in their gross morphology. These were all designated *Mycelia sterilia.* Isolate identifications listed as "unknown" represent colonies which could not be subcultured, often due to overgrowth by other fungal colonies, and therefore could not be identified. The most extensive fungal growth came from Deep Sea Camp, Lake Chandalar, Underground Atlanta, and Apricot Pit. Zygomycetes (e.g., *Mucor*) and *Paecilomyces* were most commonly isolated (Fig. 5).

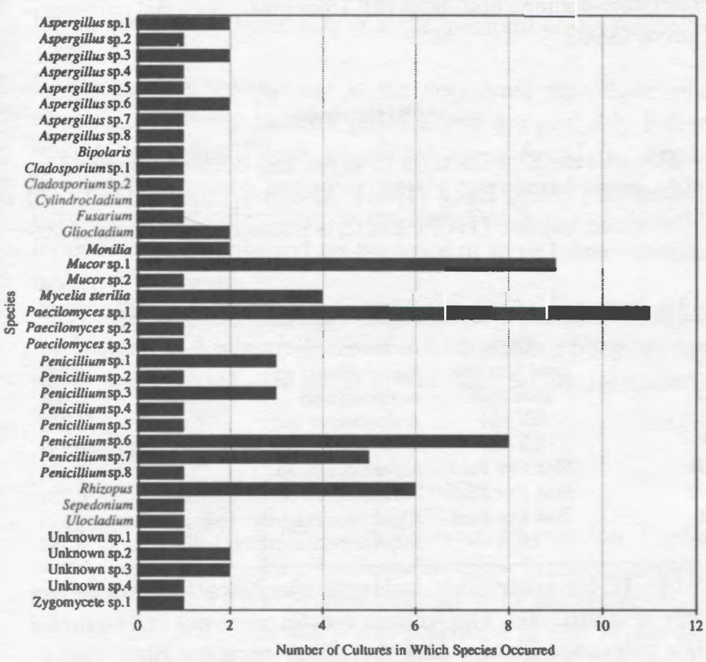

Figure 5: Identification and frequency of occurrence of fungal isolates sampled from Lechuguilla Cave.

Discussion

The occurrence of fungi in caves has been previously noted (Caumartin, 1963, Feldhake, 1986, Høeg, 1946, Lefevre and Laporte, 1969, Rutherford and Huang, 1994, and Went, 1969). Soil microorganisms in caves are probably carbon limited (Feldhake, 1986). Because Lechuguilla does not flood, whatever organic carbon is available comes from percolation of organic materials through the rocks, bacteria upon which the fungi may feed, or from humans entering the cave. In the distant past an occasional animal (bats, ringtails, etc.) wandered into the cave, died, and became a carbon source.

Many of the fungal genera found in Lechuguilla Cave are those commonly associated with humans and soils. *Mucor, Rhizopus*, and other zygomycetes are common saprophytic fungi and often play a role in the degradation of food. Several species of *Aspergillus* and *Penicillium* were found in Lechuguilla Cave. These genera also occur in Costa Rican caves (Febbroriello, personal communication, 1991). He also found *Fusarium, Mycelia sterilia*, and *Blastomyces*, the former two of which were also found in Lechuguilla Cave. *Penicillium* is the "most abundant genus of fungi in temperate soils" and *Aspergillus* is one of the most ubiquitous of microorganisms (Al-Doory and Wagner, 1985).

Several fungal genera found in Lechuguilla Cave are common on decaying matter, especially plants. *Bipolaris* is parasitic on grasses. *Cladosporium* is common on decaying plants and is the fungus most commonly isolated from the air (Malloch, 1981). *Gliocladium* occurs in soils or on decaying plant matter. *Gliocladium* and *Sepedonium* also parasitize other fungi. These genera may have been introduced to the cave. Obligate plant parasites could not grow within the cave.

Other genera, e.g. *Fusarium*, are common soil fungi and may or may not have been brought in by cavers. *Fusarium* was isolated from corrosion residue. Other fungi, one of which was identified as *Aspergillus*, were found at both deep points during early exploration of the areas.

The occurrence of fungal spores in the cave is not significant, but the real question is whether they are biologically active (Lavoie, personal communication, 1991). Around camps and on major trails, cavers are beginning to observe patches (up to 20 cm in diameter) of growing fungi, which indicates that organic matter for them to feed on is increasing, or that they have been recently introduced. Fungi and bacteria do co-occur in the corrosion residues, but the exact relationship remains unknown. This relationship and the question of what role fungi play in the food chain within the cave ecosystem will be examined in future studies.

BACTERIA

Introduction

During this study the investigators focused on sampling bacteria from pools throughout the cave and from select sites of corrosion residue. The latter were chosen due to preliminary studies by Cunningham *et al.* (in press) that showed extensive presence of bacteria in the corrosion residues. Pools were chosen as study sites to examine whether they are safe for humans as a water supply and because they represented a major potential habitat for bacteria within the cave.

The bacteria for which we have obtained identifications are all chemoheterotrophs (bacteria which utilize organic sources of carbon as their energy source). Additional studies underway will identify whether chemoautotrophic bacteria (those that utilize minerals such as sulfur, iron, or manganese as their energy source) are present.

Methods

Bacteria were sampled two ways: glutaraldehyde fixed water samples for SEM examination and culturing of water and corrosion residue. Two-milliliter water samples were removed from pools in the entrance passage (N = 5) and the three branches of the cave (West: N = 10; Southwest N = 13; East: N = 4) and fixed in 2% glutaraldehyde using sterile techniques. Pools in the two deepest areas of the cave were sampled. The glutaraldehyde fixed samples were examined by scanning electron microscopy (SEM) at the University of New Mexico. At least one sample, and usually two, from each pool was prepared for SEM. Water samples were filtered through a 0.25 micron nucleopore filter, dehydrated in ethanol, critical point dried in CO_2, and coated with gold/palladium.

SEM pictures were taken of the original samples. Thereafter, only the kind and number of organisms were recorded for each sample. Bacteria seen in the SEM's were grouped by morphology into six types (cocci-shaped, rods with no mineral encrustations, rods with mineral encrustations, braided (later identified as *Seliberia*), long tailed (*Caulobacter*-like), bacillus-shaped, and vibrio-shaped).

Unfixed samples of pool water and corrosion residues were taken for bacterial culturing. Water samples were taken at the water-air interface, and at the water-sediment interface of each pool using sterile techniques. Corrosion residues were collected from near Hudson Bay in the Western Branch by "coring" using sterile vials.

Pool water and corrosion residue samples were cultured using trypticase soy agar (TSA), dilute trypticase soy agar (D-TSA), Brewer's anaerobic agar, *Seliberia* media (Holt, 1984-1989), *Caulobacter* media (Poindexter, 1964) and chemoautotrophic media (Baross *et al.*, 1982).

Eight unique isolates were sent to Microbial ID, Inc. for fatty acid analysis. This microbial identification system is based on cellular fatty acid analysis as detected by gas chromatography. Results are matched against a reference library of organisms.

SEM photographs of the original fixed water culture bacteria were checked against photographs in Bergey's Manual of Systematic Bacteriology (Holt, 1984-1989) and against those in Morgan and Dow (1986).

Results

Examination of Bergey's Manual of Systematic Bacteriology (Holt, 1984-1989) and Morgan and Dow (1986) indicated *Seliberia* spp. and *Caulobacter*-like bacteria were in the pool samples. Additional bacteria with less distinctive morphology could not be identified in this manner. The number of bacteria observed in each sample was low (2-16 bacterial cells/approximately 0.5ml), but consistent with an extremely oligotrophic (low nutrient) environment. Because of bacterial holdfasts, we are probably sampling only part of the population present (Pace, personal communication, 1992). The *Seliberia, Caulobacter*-like bacteria and the rods are found in the greatest numbers in the pools examined. They are also the bacteria identified from virgin pools (occurring in newly discovered passage with no prior human contact). Because these bacteria are known to grow under oligotrophic conditions, they may occur naturally in the cave.

Eight unique isolates (seven aerobes and one anaerobe (which can also be a facultative aerobe)) were identified from TSA, Brewer's and chemoautotrophic media plates inoculated with pool waters and corrosion residues. Identifications for these isolates based on Microbial ID's analysis of fatty acids are shown in Table 1. All bacteria identified were heterotrophic.

An examination of the corrosion residues showed that they contain abundant organics ($4.0–4.5 \times 10^5$ CFU g^{-1}) as heterotrophic bacteria and fungi (D. Updegraff, personal communication, 1990).

Discussion

The existence of bacteria in caves has been documented by Caumartin (1963), Høeg (1946), Mason-Williams (1967) and Lefevre and Laporte (1969). Bacteria found in caves include het-

Isolate Number	Site	Presumptive Identification	Sim. Coeff.
A	RBD1	Actinomycete	NA
C	pool bottoms	*Pseudomonas* sp.	0.370
D	pool tops	Actinomycete	NA
E	EYA21	*Arthrobacter* sp.	0.272
F	EYA21	*Arthrobacter ureafaciens*	0.533
G1	Pink Dot Pool	*Acinetobacter* sp.	0.374
G2	Pink Dot Pool	*Pseudomonas aureofaciens*	0.734
H	Pink Dot Pool	*Rhodococcus erythropolis*	0.690
I	MN14	*Staphylococcus capitis ureolyticus*	0.742

Table 1: Heterotrophic bacteria identifications based on fatty acid analysis. The Actinomycetes were not in Microbial ID's reference library and therefore were not identified to genus/species level. Species identifications with similarity coefficients below 0.5 are highly suspect and were truncated to generic name.

erotrophic and chemoautotrophic forms in terrestrial or aquatic habitats. Some of these may be actively involved in the erosional or precipitational phases of speleothem development (Viles, 1984).

A community of heterotrophic bacteria exists in the pools of Lechuguilla Cave. Bacteria are found in pools throughout a range of elevations from the entrance passages to pools located at both deep points (Lake of the White Roses at -485 meters and Sulfur Shores at -458 meters), and at the far ends of all three branches. While the population size in any pool is not large, there are several bacterial species.

Two of the common bacteria in pools, *Seliberia* and *Caulobacter*, are oligotrophic chemoheterotrophs found in soils and freshwater environments. Because they are found in oligotrophic environments within the cave and because they are consistently found in pools throughout the cave, they might be considered indigenous to the cave. The other chemoheterotrophs isolated from pools and corrosion residues and identified by fatty acid analysis also include bacteria that are often isolated from soils and/or water (Starr, 1981).

Pool bacteria, particularly the oligotrophic *Seliberia* and *Caulobacter*, were probably introduced to the pool by filtration through the overlying rocks. Some of the heterotrophs could have been introduced in the same manner. Chemoheterotrophs that appear to be more human associated, e.g., *Staphylococcus capitis ureolyticus*, may have been introduced by humans. Bacteria are floating in the air of the cave (aerosolization) as seen from analysis of the air condensate (Robbins, personal communication, 1990). Bacteria are known to float for long periods in the air due to their small size (Lavoie, personal communication, 1991).

The authors believe that at the very least the oligotrophic chemoheterotrophic bacteria noted above are probably indigenous to the cave. These organisms were found in samples throughout the cave, including newly discovered areas. Other bacteria, in particular those in the Pink Dot Pool, are probably introduced by humans and are evidence of some human contamination in the cave.

The bacterial investigations represent a preliminary study of the bacteria of Lechuguilla Cave. Additional sampling, including *in situ* culturing, will likely reveal many additional bacterial species.

ACKNOWLEDGEMENTS

Many people from the Cave Research Foundation, Lechuguilla Cave Project, Inc., Lechuguilla Cave Precision Survey, and the National Park Service assisted with the collection of samples and data. This study was supported in part by the National Park Service, the University of New Mexico, and the National Speleological Society. The Lechuguilla Cave Project, Inc. provided maps for the study. We wish to thank David Ek, Ron Kerbo, Rick Bridges, Fritzi and James Hardy, Bob and Debbie Buecher, William Ziegler, Carol Sanchez, Dick Desjardins, Kenneth Ingham, Duke McMullan, Carol Morris, Angela Welford, Dick Venters, Peter Febbroriello, and Drs. Kathy Lavoie, Cliff Dahm, Larry Barton and Cliff Crawford. Reviews were provided by John McLean, Mitch Henry, and Michael Reimer of the U.S. Geological Survey, Denver, Colorado. Identifications were done by: Sandra Brantley, Fred Heinzelmann and Carlos Blanco, of the Biology Department, University of New Mexico, (many of the invertebrates captured from the bottom of the entrance pit); Collembolans by Dr. Ken Christiansen, Grinnell College; Millipede and the centipede by Dr. Rowland M. Shelley, North Carolina Museum of Natural History (Raleigh). Dr. Philip Morgan, Shell Research, Ltd., confirmed the identifications of the *Seliberia* and *Caulobacter*-like bacteria. Dr. Horton Hobbs III, Wittenberg University, examined pool waters for protozoans.

LITERATURE CITED

Al-Doory, Y. and G. E. Wagner. 1985. Aspergillosis. Springfield, Illinois: Charles C. Thomas Publisher.

Barnett, H. L. and B. B. Hunter. 1987. Illustrated genera of imperfect fungi. New York: Macmillan Publishing Company.

Baross, J. A., C. N. Dahm, A. K. Ward, M. D. Lilley and J. R. Sedell. 1982. Initial microbiological response in lakes to the Mt. St. Helens eruption. *Nature* 296 (5852): 49-52.

Barr, T. C., Jr. and J. R. Reddell. 1967. The arthropod cave fauna of the Carlsbad Caverns region, New Mexico. *Southwestern Naturalist* 12: 253-274.

Caumartin, V. 1963. Review of the microbiology of underground environments. *The National Speleological Society Bulletin* 25: 1-14.

Cunningham, K. I., Northup, D. E., Pollastro, R. M., Wright, W. G., and E. J. LaRock. (in press). Bacteria, fungi and biokarst in Lechuguilla Cave, Carlsbad Caverns National Park, New Mexico. *Environmental Geology*.

Davis, D. G. 1980. Cave development in the Guadalupe Mountains; a critical review of recent hypotheses. *The NSS Bulletin* 42(3): 42-48.

Domsch, K. H., Gams, W., and T-H Anderson. 1980. Compendium of Soil Fungi. 2 v. London: Academic Press.

Feldhake, D. J. 1986. Microbial activity and biomass of limestone caves. Unpublished Masters Thesis, Department of Biological Sciences, University of Cincinnati.

Hart, B. J. and A. Fain. 1987. A new technique for isolation of mites exploiting the difference between ethanol and saturated NaCl: qualitative and quantitative studies. *Acarologia* 28(3): 251-254.

Hill, C. A. 1987. Geology of Carlsbad Cavern and other caves in the Guadalupe Mountains, New Mexico and Texas. Socorro: New Mexico Bureau of Mines & Mineral Resources. *Bulletin (New Mexico. Bureau of Mines and Mineral Resources)* 117.

Hill, C. A. 1990. Sulfuric acid speleogenesis of Carlsbad Cavern and its relationship to hydrocarbons, Delaware Basin, New Mexico and Texas. *AAPG Bulletin* 74(11): 1685-1694.

Høeg, O. A. 1946. Cyanophyceae and bacteria in calcareous sediments in the interior of limestone caves in Nord-Rana, Norway. *Nytt Magasin for Naturvidenskapene* 85: 99-104.

Holt, J. G. (editor-in-chief) 1984-1989. Bergey's manual of systematic bacteriology. 4 v. Baltimore: Williams and Wilkins.

Jagnow, D. H. 1988. The geology of Lechuguilla Cave. *NSS News* 46(11): 422-425.

Kethley, J. 1991. A procedure for extraction of microarthropods from bulk soil samples with emphasis on inactive stages. *Agricultural, Ecosystems and Environment* 34: 193-200.

Lefevre, M. and G. S. Laporte. 1969. The "Maladie Verte" of Lascaux. *Studies in Speleology* 2: 34-44.

Malloch, D. 1981. Moulds: their isolation, cultivation, and identification. Toronto: University of Toronto Press.

Mason-Williams, M. A. 1967. Further investigations into bacterial and algal populations of caves in South Wales. *Speleology II*: 389-395.

Morgan, P. and C. S. Dow. 1986. Bacterial adaptations for growth in low nutrient environments. In: Herbert, R. A. and G. A. Codd (eds.), Microbes in extreme environments. New York: Academic Press, pp. 187-214.

Murphy, D. W. (Editor) 1962. Progress in soil zoology. London: Butterworths.

Northup, D. E. 1988. Community Structure of Arthropods of Carlsbad Cavern. Unpublished Masters thesis. Biology Department, University of New Mexico.

Poindexter, J. S. 1964. Biological properties and classification of the Caulobacter group. *Bacteriological Reviews* 28: 231-295.

Robaux, P., Webb, J. P. and G. D. Campbell. 1976. Une forme nouvelle de Thrombidiidae (Acari) parasite sur plusieurs espèces d'Orthoptères cavernicoles du genre Ceuthophilus (Orthopters, Rhaphidophoridae). *Annales de Speleologie* 31: 213-218.

Rutherford, J. M. and L. H. Huang. 1994. A study of fungi of remote sediments in West Virginia caves and a comparison with reported species in the literature. *Bulletin of the National Speleological Society* 56(1): in press.

Shear, W. A. 1974. North American cave millipedes. II. An unusual new species (Dorypetalidae) from Southern California, and new records of *Speodesmus tuganbius* (Trichopolydesmidae) from New Mexico. *Occasional Papers of the California Academy of Sciences* no. 112: 1-9.

Starr, M. P. (ed.) 1981. The prokaryotes: a handbook of habitats, isolation and identification of bacteria. 2 v. New York: Springer-Verlag.

Viles, H. A. 1984. Biokarst: review and prospect. *Progress in Physical Geography* 8(4): 523-542.

Webb, J. P., Robaux, P. and G. D. Campbell. 1977. Notes on the biology of *Ceuthothrombium cavaticum* (Acari: Thrombidiidae), a parasite of cave crickets (Rhaphidophoridae: *Ceuthophilus*). *Bulletin of the Southern California Academy* 76: 135-137.

Welbourn, W. C. 1978. Biology of Ogle Cave with a list of cave fauna of Slaughter Canyon. *NSS Bulletin* 40: 27-34.

Went, F. W. 1969. Fungi associated with stalactite growth. *Science* 166: 385-386.

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Appendix A: Invertebrates Found in the Entrance/Twilight Zones

The following invertebrates were obtained from the bottom of the entrance drop or its extension, in Lechuguilla Cave. Each organism is coded as to whether it is a troglobite (TB), trogloxene (TX), troglophile (TP), guanophile (GP) or accidental (A).

Class: Myriapoda: Subclass: Diplopoda
- Order: Polydesmida
  - Polydesmidae: *Speodesmus tuganbius* (TB)

Class: Arachnida
- Order: Acari
  - Erythraeidae: *Leptus* sp. (A)
  - Eupodidae: *Eupodes* sp. (A)
  - Oppiidae: *Multioppia* sp. (A)
  - Rosensteiniidae: *Nycteriglyphus* sp. (GP)
  - Thyrisomidae: *Oribella* sp. (TP)
  - Tydeidae: (A)
- Order: Araneae
  - Agelenidae: *Cicurina* sp. (TX)
  - Agelenidae: *Cryphoeca* sp. (TX)
  - Clubionidae: *Costioneira* sp. (A)
  - Dictynidae: *Dictyna* sp. (A)
  - Gnaphosidae: *Drassyllus* sp. (A)
  - Linyphiidae: (TX)
  - Nesticidae: *Nesticus* sp. (A)
  - Salticidae: *Salticus* sp. (A)
- Order: Solpugida
  - Eremobatidae (immature) (A)

Class: Insecta
- Order: Coleoptera
  - Carabidae
    - *Amara* sp. (A)
    - *Rhadine longicollis* Benedict (TP)
    - *Thalassotrechus* sp. (A)
  - Cerambycidae
    - *Moneilema* sp. (A)
  - Chrysomelidae
    - Alticinae: *Chaetocnema denticulata* (A)
  - Phalacridae
    - larvae and pre-pupae (A)
  - Ptilodactylidae (A)
  - Staphylinidae
    - *Thinobius* sp. (A)
  - Tenebrionidae
    - *Eleodes* sp. (A)
    - *Embaphion* sp. (TX)
- Order: Collembola
  - Entomobryidae: (TP)
- Order: Diptera
  - Bombyliidae (A)
  - Mycetophitidae (A)
  - Phoridae (A)
  - Sciaridae (A)
- Order: Hemiptera
  - Nabidae (A)
- Order: Homoptera
  - Cicadellidae (A)
- Order: Hymenoptera
  - Formicidae (A)
  - Ponerinae (A)
  - *Aphaenogaster* sp. (A)
- Order: Lepidoptera
  - Pyralidae (A)
- Order: Microcoryphia
  - Machicidae (A)
- Order: Orthoptera
  - Acrididae
    - *Heliastus* sp. (A)
    - Undetermined genus (Romaleinae) (A)
  - Rhaphidophoridae
    - *Ceuthophilus carlsbadensis* (TX)
    - *Ceuthophilus conicaudus* (TX)
    - *Ceuthophilus longipes* Caudell (TX)
- Order: Pseudoscorpionida: (TP)

Trapasso, L. Michael and Kaletsky, Kelly—Food Preparation Activities and the Microclimate within Mammoth Cave, Kentucky: *NSS Bulletin* 56: 64-69.

FOOD PREPARATION ACTIVITIES AND THE MICROCLIMATE WITHIN MAMMOTH CAVE, KENTUCKY

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Numerous studies have claimed that the microclimate of a cave system remains constant through time and is approximately equivalent to the mean annual temperature of the surrounding region. Mammoth Cave is not only the largest mapped cave system in the world, but also the only one that operates both a kitchen and restaurant deep inside. This situation offers uniqueness to this research. The stability of the microclimate of Mammoth Cave has never undergone extensive investigation. The Snowball Dining Room area was chosen to measure the microclimate of the cave in relation to food preparation and human presence. Three portable weather stations containing a temperature/humidity probe and a datalogger were placed in various locations along three passageways intersecting the dining room. A randomization process was used to determine when and where the data were collected in each passageway. Hourly temperature and relative humidity readings were taken everyday for five months. Both graphic and statistical analyses show relationships between the data and distance from the dining room.

INTRODUCTION

Publications concerning the constant microclimate and airflow patterns of Mammoth Cave data back over a century. An old guide's manual from the late 1800's tells of the difference in summer and winter airflow patterns, which depend upon the surface air temperature (Guide Manual of Mammoth Cave, ca. 1875). This early document states that the whole of Mammoth Cave (which contained fewer known passageways then than now) experienced a uniform, year-around temperature. However, the document failed to explain how this temperature was derived. Most texts concerning karst features and speleology state that caves have a constant temperature and humidity, but fail to go into detail. It is as if this information has been passed down from person to person, and writers have accepted this information without question. For example, Palmer (1981) states that the air temperature in Mammoth Cave is "cool, about 12.8 to 13.9 degrees Celsius (55-57 degrees Fahrenheit) year-round." In addition, the above-mentioned guide's manual quotes 15 degrees Celsius (59 degrees Fahrenheit) but describes no fluctuation in this temperature.

Through the years, these original assumptions, gathered from writings on the question of Mammoth Cave's microclimate, have never undergone an in-depth investigation. Over time, the number of visitors to the cave has increased dramatically, and many new kilometers of passageways have been opened to the public. With this increased tourism, physical changes have taken place within the cave. Tourist trails have been paved, restrooms built, stairways constructed, an elevator installed, and even an underground dining area established; the latter is the major focus of this research.

This work coincides with a revival of official National Park Service policy, both nationwide and at Mammoth Cave National Park, which is to ". . . conserve the scenery, the natural and historic objects, and the wildlife therein. . ." (Albright, et al., 1987). Questions regarding the microclimate of Mammoth Cave, its stability, and the effects of increased human presence on this microclimate have not yet been answered and provide the impetus for this research. During the summer of 1990, we began to monitor the microclimate of the Snowball Dining Room area of Mammoth Cave. This dining room accommodates up to 500 visitors per day every day of the week during the summer and approximately 15 visitors per day during winter weekdays and 75-100 on winter weekends. Spring and fall seasons accommodate numbers of visitors which fall between these numbers. Hot meals are prepared in the dining room on a daily basis without ventilation. The factors of food preparation (e.g., heat from steam tables) and the presence of visitors have brought about concerns regarding the microclimate of this section of cave passageways. It is hypothesized that these food preparation activities alter the microclimate of this area of the cave.

STUDY AREA

Mammoth Cave National Park contains over 21,000 surface hectares and over 530 kilometers of surveyed cave passageways. The park is located in south-central Kentucky in Edmonson, Barren, and Hart counties, approximately 145 kilometers from both Nashville and Lousiville via Interstate 65. Most major points within the Park appear on the Mammoth Cave and Rhoda 7 1/2 minute series topographic quadrangles, published by the United States Geological Survey.

Within the park, the Snowball Dining Room can be accessed easily by an elevator located approximately 3.2 kilometers from the Visitors Center. The dining room, almost directly under Highway 255, is located 81.7 meters (267 feet) below the surface. It can also be reached by walking approximately 1.5 kilometers down Cleaveland Avenue from the Cleaveland Entrance (White and White, 1989). The dining room is used by visitors on the Half-Day and Wild Cave tours, as well as the Cleaveland Avenue Tour for the disabled. Both the Wild Cave and Half Day tours reach the Snowball area from Cleaveland and proceed down Boone Avenue. The Tour for the Disabled enters from the elevator located in Marion Avenue, passes through the dining room, proceeds down Cleaveland Avenue, and doubles back to the elevator (Fig. 1).

BACKGROUND LITERATURE

Since the 1940's, much as been written about cave meteorology. For a comprehensive bibliography see Wefer (1991). For an article of this size, a selected number of references are presented below.

Considerable work has been done investigating the use of the constancy of cave climates for food storage. According to Cox (1981), Beatrice Foods Co. stores almost 10% of all the frozen foods consumed in the U.S. in a cave near Kansas City, Kansas. This revival in underground storage is a result of increased costs associated with refrigeration and warehouse storage. The article also states that many other cities and countries throughout the

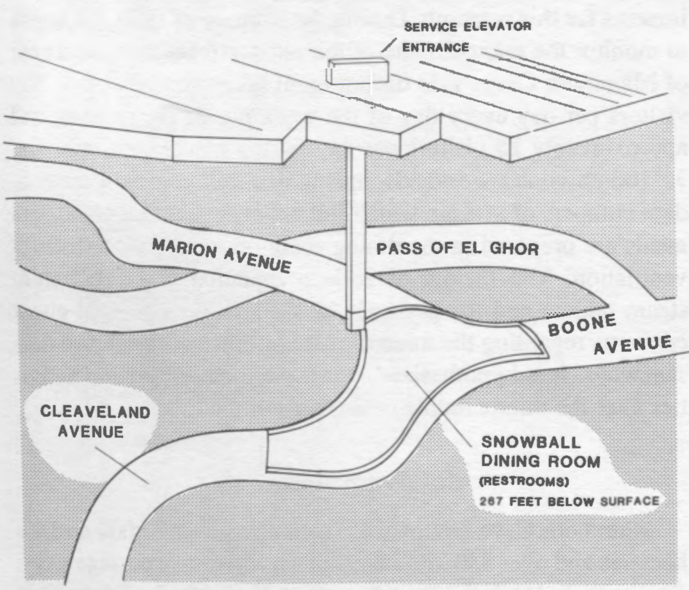

Figure 1. Study Area Layout.

world are using caves and underground structures for storage, business, and entertainment.

With 13.0 degrees Celsius (55.4 degrees Fahrenheit) being most desirable storage temperature for rice, Mitsuda et al., (1972), conducted research on the storage of large quantities of rice in caves and underground facilities. The rice was placed where the temperature was 9-11.5 degrees Celsius (48.2-52.7 degrees Fahrenheit) and the relative humidity was greater than 94%. The researchers found that the rice was well preserved while stored inside the cave.

Research concerning Mammoth Cave is relatively scarce. Lewis and Hale (1982) conducted a temperature and humidity profile in the Historic section of the cave. The validity of their findings are questionable because temperatures were taken only on two occasions. Using a Cole Parmer Psychro-dyne battery operated fan psychrometer, the pair recorded varying temperatures ranging from 7.8 to 14.4 degrees Celsius, varying with distance from the Historic Entrance. However, with the sparcity of data it is impossible to conclude that these are representative of the temperatures of this section of Mammoth Cave.

Most cave climate studies were conducted elsewhere. Ashton (1967) examined the climates of Swansea Cave and Worthy Park I Cave. The location of either of these caves is not known from the information presented. After a series of empirical formulas, the researcher indicated that cave readings were taken by a sling psychrometer, but no explanation regarding time, frequencies, and locations of measurements were given.

Atkinson et al. (1983), as part of their research into cave radon levels, performed a limited investigation into the microclimate of Castlegard Cave in Columbia Icefields of Alberta. In 1979 and 1980, they obtained temperature readings as far as 4200 and 8100 meters from the cave's entrance. Readings were taken with sling-mounted mercury thermometers with wet and dry bulbs; no digital or automatic readings were taken. Their findings support the theory that near the entrance of the cave temperatures vary greatly and stabilize further down the passageways. Central sections of the cave appear to have a very stable temperature (Atkinson et al., 1983).

Davies (1960), in his meteorological study of Martens Cave in West Virginia, stated that temperatures in the cave varied with location. The study took place during a discontinuous 11-year period, thus limiting the accuracy and credibility of his results. Davies discovered that there was a wide variation in temperature just inside of each of Martens' two natural entrances, but after proceeding further into the cave and moving into smaller passageways, temperatures stabilized. He explained further that the main passageways were heated and cooled by outside winds passing through the small cave and that the temperature was controlled also by several streams flowing throughout the cave.

Several studies were carried out in caves that receive a high number of visitors. The climate of the Sterkfontein Cave in South Africa is one example (Niven and Hood, 1978). They discovered that there is a variation in the Sterkfontein Cave climate near the natural entrances of the cave, but found "negligible temporal variations in the deep cave areas." The authors also admitted that the variations throughout the majority of the tourist cave were due to the number of entrances. It is likely that the small size of a cave in relation to the number of openings would also play a major role in the stability of the cave's microclimate, a point Niven and Hood failed to mention.

Unlike the work of Wefer (1989) who clearly outlined precise procedures for obtaining meteorological measurements in cave systems, many cave climate studies left us with many questions concerning equipment use, sampling methodologies, and the number of observations.

Another study involving a tourist cave was undertaken during 1979-1980 in Glowworm Cave, New Zealand (De Freitas, et al. 1982). Due to heavy visitor use and delicate fauna that live within the cave, the researchers elected to investigate this microclimate. Like Mammoth Cave, tourism began in Glowworm in the 1800's, and the facility is managed by the national government. The Glowworm study, however, describes the rate and direction of air circulation within the cave. The researchers theorize varying wind speeds enter the cave from the surface, and change the circulation patterns and offset the equilibrium of the cave microclimate.

Research that addresses directly when cave temperatures are consistent was undertaken by Cropley (1965). His findings indicate that cave temperatures are not nearly as stable as people are led to believe and that cave climates can be affected by outside weather conditions for thousands of meters inside a cave system. The study took place between February and November 1963, in two large cave systems located in Greenbrier County, West Virginia. The data collection consisted of 86 temperature readings at distances varying from 0 to 1,830 meters from the cave entrances. Cropley found that a 1,520 meter-distance had to be traveled before a state of temperature equilibrium was reached.

Human influence in cave microsystems is the topic of research performed by Stark (1969). The study, conducted at Lehman Cave in eastern Nevada, addressed the effect of lights upon plant and animal life inside the cave. Stark reports that although the cave environment is quite stable, the use of lights could result in extremes of temperatures, humidity, air movement, and the drying effects of air.

Research by Nepstad and Pisarowicz (1989) analyzed temperature and humidity variations at Wind Cave National Park in Hot Springs, South Dakota. The findings of the study show that there are varying temperatures within Wind Cave depending on the location. Mean temperatures within the cave ranged from 9.14 degrees to 11.27 degrees Celsius (48.4 to 52.2 degrees Fahrenheit). Humidity also varied, ranging from 86.61 to 94.07 percent.

In research concerning Mammoth Cave's Snowball Dining Room, Aley (1988) attempted to determine the cause of the black coating on the cave walls and ceilings in the Dining Room, and found that the black material was a combination of fungus and algae. According to Aley, daily increases in temperature ranged from 0.5 to 1.0 degrees Celsius. Relative humidity also underwent a daily cycle, rising throughout the morning and early afternoon, then subsiding. Aley hypothesized that this heating was caused by electric lights, cooking, and human presence within the cave.

METHODS AND MATERIALS

For this research, three small portable weather stations were placed in three passageways intersecting the Snowball Dining Room. The equipment was placed approximately 1.5 meters above the cave floor and out of the reach of passing visitors. Instrument placement was determined by stratified sampling technique. Under ideal conditions, the cave microclimate would be monitored simultaneously at numerous locations within each passageway. In practice only three monitors, one for each passageway, were available. Therefore, a random sampling scheme was used.

To accomplish this, a randomization chart was created. A computer-produced list of distances between 0 and 140 meters was generated to determine how far down each passageway the station was to be placed. A 140 meter limit was set because of the presence of an elevator shaft in one passage and junctions with differing passageways. The proximity of these disruptions could alter airflow patterns in the immediate area, thus not allowing the heat plume to travel past these areas to the instruments. Every Thursday and Saturday, the three stations were relocated to a randomly chosen distance from the dining room. The stations would remain at the designated locations for a few days to adjust to the microclimate. A weekday and a weekend day were chosen to allow the stations to experience the varying amounts of visitor traffic.

The air temperature and relative humidity probe was Model 207, manufactured by Campbell Scientific, Inc. The probe contained a Phys-Chemical Research Corporation PCRC-11 RH sensor and a Fenwal Electronics UUT51J1 thermistor. The accuracy of the temperature probe is ± -0.4 degrees Celsius. The accuracy of the relative humidity sensor is ± -5%. Both sensors were capable of recording changes down to one-hundredth of a degree or percentage.

The probe was connected to a 21X Micrologger manufactured by Campbell Scientific, Inc. The datalogger was used to convert the sensor signal into a digital value, to process the measurements over a given time period, and to store the data until retrieved. The battery-operated computer was programmed to obtain sensor readings each hour.

The study was conducted from 1 November 1990 through 31 March 1991. These five months were chosen by agreement with the Mammoth Cave Park Administration and by the amount of Western Kentucky University research grant funding. Though this time period does not include the peak visitation period of summer, it does include Christmas Day. This is the only day of

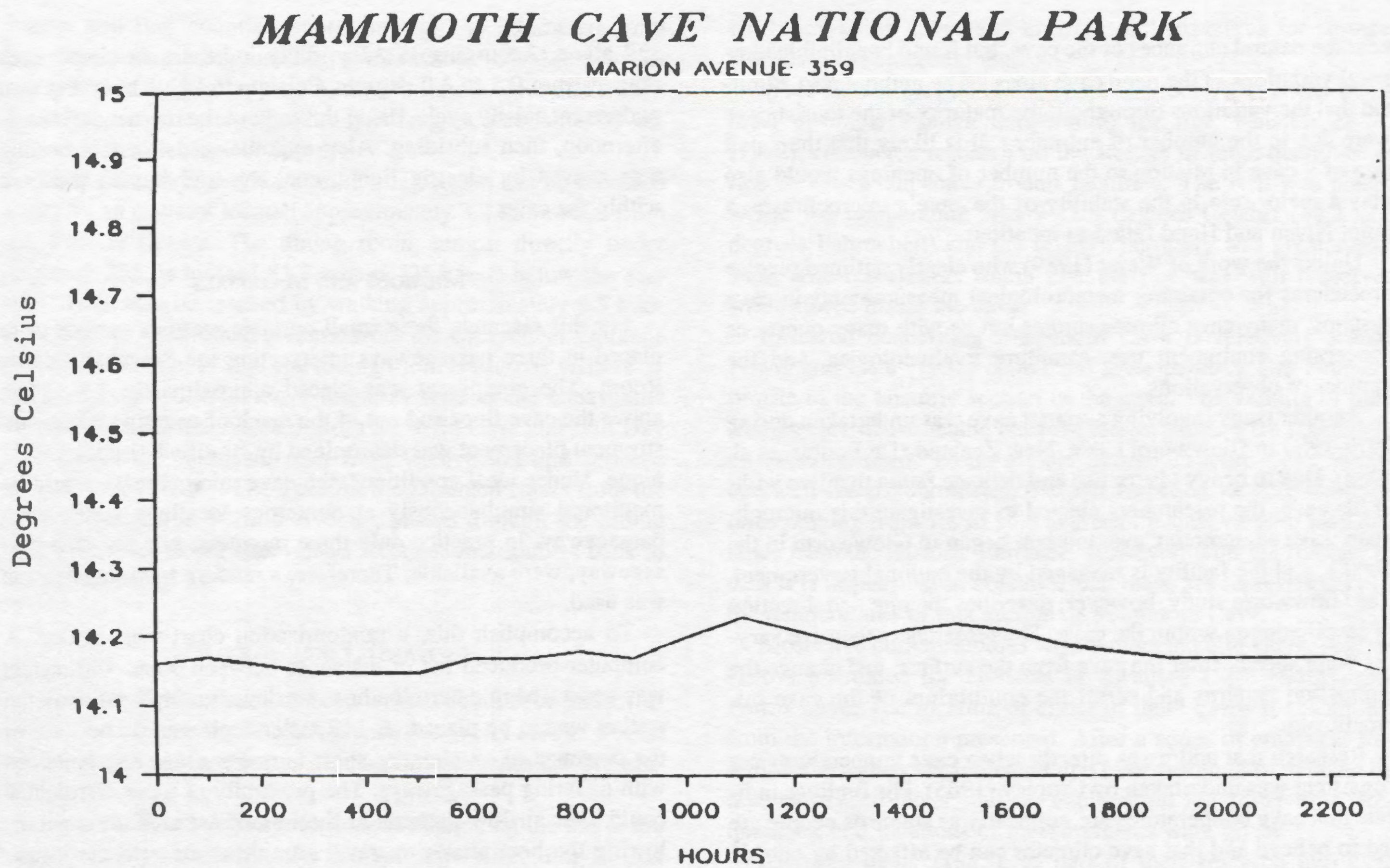

Figure 2. Temperature graph for 25 December 1991.

the year when no tours are granted and, as such, the only control period available for the Mammoth Cave system (Fig. 2).

Correlation and regression analyses were used to determine if there was a systematic relationship between the variable distance from Snowball Dining Room and the meteorological variables of temperature and relative humidity (Table 1). Separate analyses were performed for each passageway and for readings taken at different hours of the day. For example, a 1200 Carmichael Passageway scatterplot and correlation would consist of all the readings taken in Carmichael Passageway at 1200 hours, local time.

The analyses were carried out as follows. Scatterplots were generated for visual examination of the distance relationships using the variables of temperature and humidity with distance from the dining room. The purpose of the scatterplots was to determine the presence or absence of a regression line (Fig. 3). Each scatterplot was accompanied by a corresponding correlation coefficient and regression equation. The correlation and regression analyses provided an objective representation of the data, while the scatterplot provided visual information regarding the general behavior of the relationship.

Analysis of the data resulted from a visual examination of the scatterplots and the accompanying correlation coefficient, con-

Table 1. Correlation Coefficients

	Carmichael		Boone		Marion	
	Humidity	Temp.	Humidity	Temp.	Humidity	Temp.
0100	.23	.34**	.19	.43	–.71	.75
0200	–.26	–.31	.22	.47	–.72	.74
0300	–.25	–.32	.22	.47	**–.70	.69
0400	–.24	–.29	.26	.44	–.72	.70
0500	–.24	–.34	.25	.42	–.72	.70
0600	**–.24	–.35	**.26	.41	**–.72	.71
0700	–.25	–.31	.25	.42	–.71	.70
0800	–.26	–.36	.20	.41	–.71	.71
0900	–.31	–.35	.16	.42	–.69	.70
1000	–.31	–.35	.18	.39	–.69	.71
1100	–.31	–.35	.15	.40	–.70	.72
1200	**–.29	–.25	**.05	.44	**–.68	.69
1300	–.31	–.33	**.05	.51	–.72	.69
1400	–.32	–.33	**–.32	–.33	**–.68	.74
1500	–.30	–.31	.12	.48	–.70	.69
1600	–.30	–.35	.14	.51	–.70	.72
1700	**–.32	–.38	.17	.51	–.71	.71
1800	–.32	–.33	**.17	.53	–.72	.72
1900	–.32	–.35	.18	.50	–.73	.71
2000	–.32	–.34	.19	.50	–.73	.71
2100	**–.34	–.32	.18	.48	**–.73	.71
2200	–.32	–.34	.23	.41	–.72	.70
2300	–.32	–.32	.20	–.39	–.71	.71
2400	–.24	–.31	.20	–.45	–.71	.71

**Indicates correlations used for visual analysis.

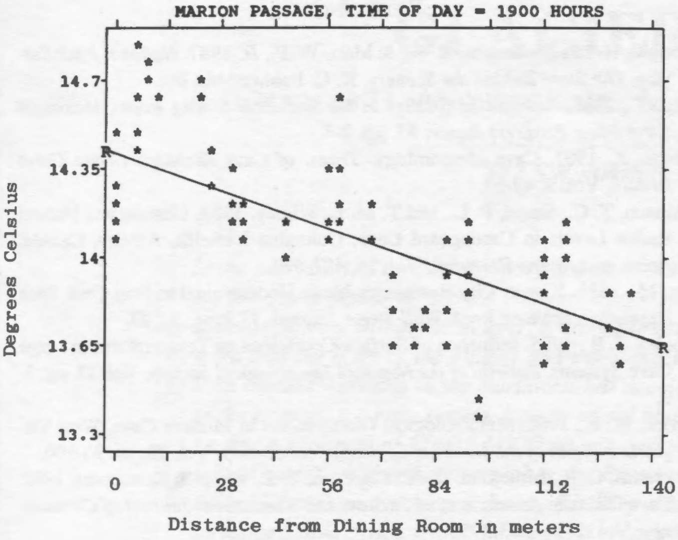

Figure 3. Scatterplot.

stant, slope, and R-Squared value of the regression. One hundred and forty-four scatterplots and correlation coefficients were generated, each broken down by hour and passageway. In addition to this information, regression equations were generated by using an SPSS/PC program.

Correlation coefficients for temperature and humidity with distance were recorded in chart form for each passageway, resulting in 24 sets of data for each corridor. In addition, regression charts were generated, including the regression variables of constant, slope and R-Squared.

RESULTS

On the basis of chart analysis of the correlation coefficients, Marion Avenue had the strongest relationship among all variables, while Boone Avenue showed stronger humidity/distance correlations and weaker temperature/distance correlations (Table 1). Carmichael passageway had slightly weaker correlations between humidity/distance and stronger correlations between temperature/distance.

Marion Avenue, which lies closest to the dining room food preparation equipment, experienced significant correlation coefficients in both temperature and humidity for every 24-hour period (Fig. 4.) A visual analysis of the scatterplots confirmed a linear relationship for each of the charts. Therefore, given that this corridor contains the dining room and kitchen equipment, as with Aley (1988), we assume that daily activity does affect the microclimate in this section of the cave.

Regression slopes for Boone and Carmichael passageways confirm the weaker relationship. The slopes for Boone Avenue were positive, but nearly horizontal, while the slopes for Carmichael were negative and nearly horizontal. The regression slopes for Marion Avenue were the strongest, with a mixture of positive slopes for humidity and negative slopes for temperature.

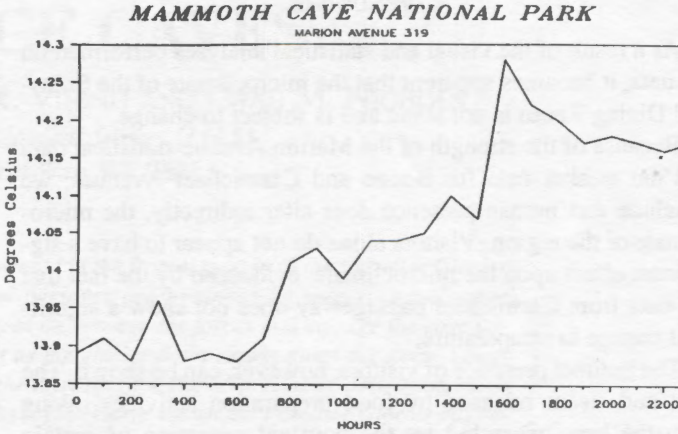

Figure 4. Temperature graph for 15 November 1991.

DISCUSSION

A possible cause for the continuously high correlations and regressions in Marion Avenue could be due to the constant operation of certain equipment in the dining room area some of which extends down Marion Avenue. Refrigeration units and beverage equipment run continuously, giving off heat that can be detected by the sensors.

The difference in correlations and regressions in Carmichael and Boone passageways could be explained by the autumn/winter wind flow patterns. Both variables of temperature and humidity, although low, remained at a constant level during our study in Carmichael because winds blew from the passageway to the dining room, preventing any possible increases in temperature and humidity from entering the area. Altered air from Snowball would move in the direction of Boone Avenue. Although the temperature correlations and regressions in Boone were lower than the other passageways, they were more variable. Temperature correlations increased during the night-time hours, reaching a peak correlation of 0.26 at 0400 hours. There was, however, a pronounced correlation "spike" to 0.32 at 1400 hours, the time that cooking equipment is active and that tours pass through the area. This "spike" marked an increase from a 0.05 correlation of the previous two hours. After this hour, the correlations returned to a lower level.

The humidity correlations and regressions are much stronger than temperature, with a peak correlation of 0.53. There are six hourly correlations which reached a significant level, ranging from 1300 hours to 2000 hours. Although the temperature correlations may not remain high due to the dilution from the cool cave air, it is possible that the humidity correlations are not reduced because the cave air is very humid and allows the increased humidity from the steam tables to travel down Boone Avenue. Since the air is already laden with water vapor, the cave air will not dissipate the steam and allow the air to "dry out."

CONCLUSIONS

As a result of the visual and statistical analyses performed on the data, it becomes apparent that the microclimate of the Snowball Dining Room is not static and is subject to change.

Because of the strength of the Marion Avenue statistical data and the weaker data for Boone and Carmichael Avenues, we conclude that human presence does alter indirectly, the microclimate of the region. Visitors alone do not appear to have a significant effect upon the microclimate, evidenced by the fact that the data from Carmichael passageway does not show a significant change in temperature.

The indirect presence of visitors, however, can be shown. The heat and steam released by food preparation activities, along with the heat generated by the constant operation of certain equipment is evident in the visual and statistical analysis of the Marion and Boone Avenue data. The presence of a statistical "spike" that appeared at the time a tour passed through Boone Avenue and the consistently significant readings in Marion Avenue support this fact. The most pronounced effect was in Marion Avenue, where the majority of equipment extends.

Although this research attempts to answer fundamental questions concerning the microclimate of the dining room, several questions and avenues of research remain. This research was conducted during wintertime conditions within the cave. Unlike the findings of Lewis (1991) where diurnal barometric pressure changes brought about reversals in cave air flow, the enormity and complexity of the Mammoth Cave system translates into a seasonal air flow reversal. Research conducted utilizing a longer study period could include both summer and winter air flow patterns and visitor loads. These additional long-term data could perhaps pinpoint further causes of unnatural temperature and humidity variations.

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Authors' Note—Too numerous to publish in this article, copies of regression charts are available. To obtain copies contact L. Michael Trapasso.

REFERENCES

Albright, H. M., Dickenson, R. E., & Mott, W. P., Jr. 1987. *National Park Service, The Story Behind the Scenery*. K. C. Publications, Inc.

Aley, T., 1988. *Restoration Studies in the Snowball Dining Room. Mammoth Cave Files, Progress Report #1*, pp. 2-4.

Ashton, K. 1967. Cave Meteorology. *Trans. of Cave Research Group Great Britain*, Vol. 9, 47-51.

Atkinson, T. C., Smart, P. L., and T. M. L. Wigley. 1983. Climate and Natural Radon Levels in Castleguard Cave, Columbia Icefields, Alberta, Canada. *Arctic and Alpine Research*, Vol. 15, 487-502.

Cox, M., 1981. Kansas City Businesses Move Underground to Stay Cool, Ease Expansion, Save on Rent. *Wall Street Journal*, 17 June, pg. 27.

Cropley, J. B., 1965. Influence of Surface Conditions on Temperatures in Large Cave Systems. *Bulletin of the National Speleological Society*, Vol. 27, pp. 1-9.

Davies, W. E., 1960. Meteorological Observations in Martens Cave, West Virginia. *Bulletin of the National Speleological Society*, Vol. 22, pp. 93-100.

De Freitas, C. R., Littlejohn, R. N., Clarkson, T. S., and I. S. Kristament, 1982. Cave Climate: Assessment of Airflow and Ventilation. *Journal of Climatology*, Vol. 2, pp. 383-397.

Guide Manual of the Mammoth Cave of Kentucky. (circa 1875). Charles Le Roi Printers, Nashville.

Lewis, J. and M. Hale, 1982. *A Temperature of Humidity Profile Through the Historic Section of Mammoth Cave*. Vertical file, Mammoth Cave National Park.

Lewis, W. C., 1991. Atmospheric Pressure Changes and Cave Airflow: A Review. *Bulletin of the National Speleological Society*, Vol. 53, pp. 1-12.

Mitsuda, H., Kawia, F., and A. Yamamoto, 1972. Underground and Underwater Storage of Cereal Grains. Food Technology, Vol. 26, pp. 50-56.

Nepstad, J. and J. Pisarowicz, 1989. Wind Cave, South Dakota: Temperature and Humidity Variations. *Bulletin of the National Speleological Society*, Vol. 41, pp. 125-128.

Niven, F. M., and G. M. Hood, 1978. Diurnal Atmospheric Characteristics of the Sterkfontein Tourist Cave. *South African Journal of Science*, Vol. 74, pp. 134-136.

Palmer, A. N., 1981. *A Geological Guide to Mammoth Cave National Park*. Zephyrus Press, Teaneck, New Jersey.

Stark, N., 1969. Microecosystems in Lehman Cave, Nevada. *Bulletin of the National Speleological Society*, Vol. 31, pp. 73-83.

Wefer, F., 1989. On the Measurement of Relative Humidity in Cave Meteorology Projects. *Nittany Grotto News*, Vol. 36, pp. 6-14.

Wefer, F., 1991. An Annotated Bibliography of Cave Meterology. *Cave Geology*, Vol. 2, No. 2, pp. 84-119.

White, W. B., and E. L. White (eds.), 1989. *Karst Hydrology. Concepts from the Mammoth Cave Area*. Van Nostrand Reinhold, New York.

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EVOLUTION OF THE PARADISE/STEVENS GLACIER ICE CAVES

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In the early part of the 20th Century, ice caves were discovered in the frontal margin of the Paradise Glacier on the south flanks of Mount Rainier. These subglacial passages are produced by numerous meltwater streams flowing within the glacier. A constant struggle goes on between the forces that enlarge the cave upward into the body of the glacier and those shortening it as the glacier flows slowly down the slope. Long-term climate warming in the Northwest has accelerated the retreat of the Paradise Glacier destroying much of the original ice cave system. Review of old photographs (c1936) have shown the Paradise Glacier has retreated a minimum of 4,000 ft (1220 m) in a period of less than 50 years. The approximately 2-mile-long Paradise Glacier consisted of three lobes, the Paradise, Stevens and the Williwakas. The Stevens lobe (of the Paradise Glacier) once extended down off a steep headwall and covered the entire floor of Stevens Basin. A subtle topographic divide under the ice mass separated the headwaters of the Paradise River and Stevens Creek. As a result, the Paradise River flows westerly off Mount Rainier to Puget Sound. Stevens Creek flows southward into the Columbia River and on to the Pacific Ocean.

A renewed interest in ice cave exploration began in 1967, when only 1.5 miles (2.4 km) of the actual cave area had been mapped. By 1978, Charles Anderson had accomplished mapping the remaining cave systems which totaled over 8.23 miles. The caves featured a complex maze of passages, always in a constant state of change. Falling flakes (long slivers or chunks of ice separating away from walls and ceilings), continuously collapsed inward as a result of interglacial pressures made mapping of the caves a difficult project.

By 1993, accelerated degradation of the glacial toe has resulted in the ice retreat above the Stevens Basin headwall and the destruction of virtually all of the previously mapped ice caves.

INTRODUCTION

This paper will discuss the evolution of Paradise/Stevens Glacier Ice Cave system based on historical documentation, observations and recent mapping surveys between 1960 through 1993. To date, no one has investigated the evolution of the cave system in detail. William Halliday documented several years of observations and data collection in his book *Depths of the Earth* (1976), but very little other historical information was compiled and interpreted.

In addition to an historical approach, we will examine the short term behavior of the cave system by documenting in detail the observed development (and destruction) of the Paradise/Stevens Glacier Caves that has occurred over the past 32 years.

The cave system has been a popular attraction in the Mount Rainier National Park for decades and has accrued a colorful history of exploration. Numerous glaciologists have made mention of the Paradise Glacier caves while visiting and exploring other aspects of Mount Rainier. Two climbers, V. B. Van Trump and Hazard Stevens ascended Mount Rainier in 1870 and weathered a miserable night in an ice cavern at the Columbia Crest. This cave, as well as others rediscovered later in the 20th Century, was formed from the steam heat of venting sulfurous fumaroles. Heavy snow during the 1920s prevented access into the Paradise caves until a Park Naturalist, Floyd Schmoe dug an opening with his ice axe. He published his cave observations in *Nature Magazine*. Schmoe described a white water river flowing through a large domed room with numerous waterfalls, bridges, tunnels and dark passageways. By the end of the 1920s, the Mount Rainier Guide Service was conducting regular tours into the mysterious blue caverns. Tours continued through to the mid 40s, until glacial retreat had all but destroyed the downslope reaches of Paradise Glacier and ice caves (Figs. 1, 2). New openings were discovered at the head of the Stevens Lobe of Paradise Glacier in 1946, but most spelunking interest waned until the mid 1960s (Fig. 3).

In 1954, Lou and Jim Whittaker were scaling Mount Rainier in preparation for an eventual assent up Mt. Everest. The Whittakers further investigated the Colombia Crest Ice Caves. Their experience interested many cavers in the Seattle area, particularly that of the Cascade Grotto and the National Speleological Society (N.S.S.). A team of climbers and cavers jelled from these groups and began an ambitious project of mapping the Columbia Summit Caves. Upon completion, Charlie Anderson and members of the Cascade Grotto moved their efforts further downslope to the Remnant Paradise Ice Caves and the newer openings on the Stevens Lobe snout.

Charlie Anderson began his investigative work in 1967 conducting yearly surveys of cave passages, by mapping and documenting with photography. Initially, only one cave was known and it was assumed that all passages funneled into the main

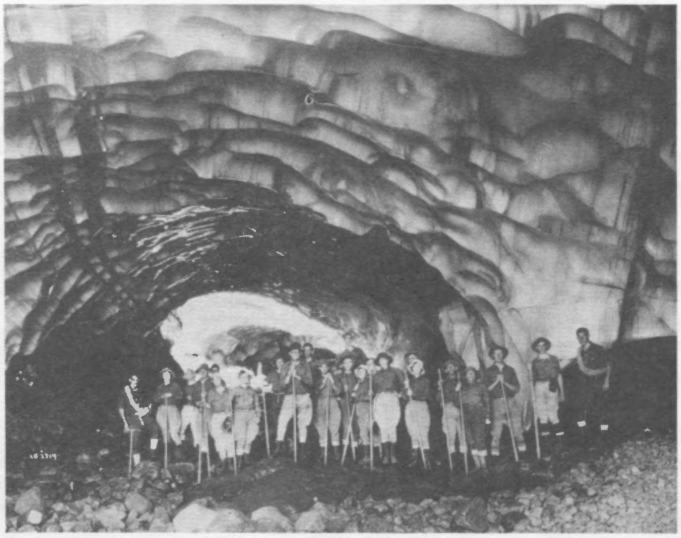


Figure 1. This unidentified group explored the Paradise Glacier Caves sometime in the late 1920's or early 1930's. They were photographed at the original Paradise Ice Cave section which disappeared in 1945. This photo was taken about Avalanche Alley near Surprise Entrance. See Figure 10.

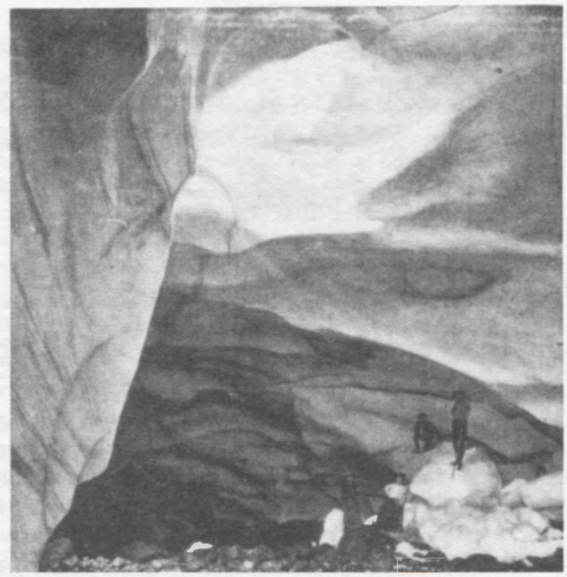
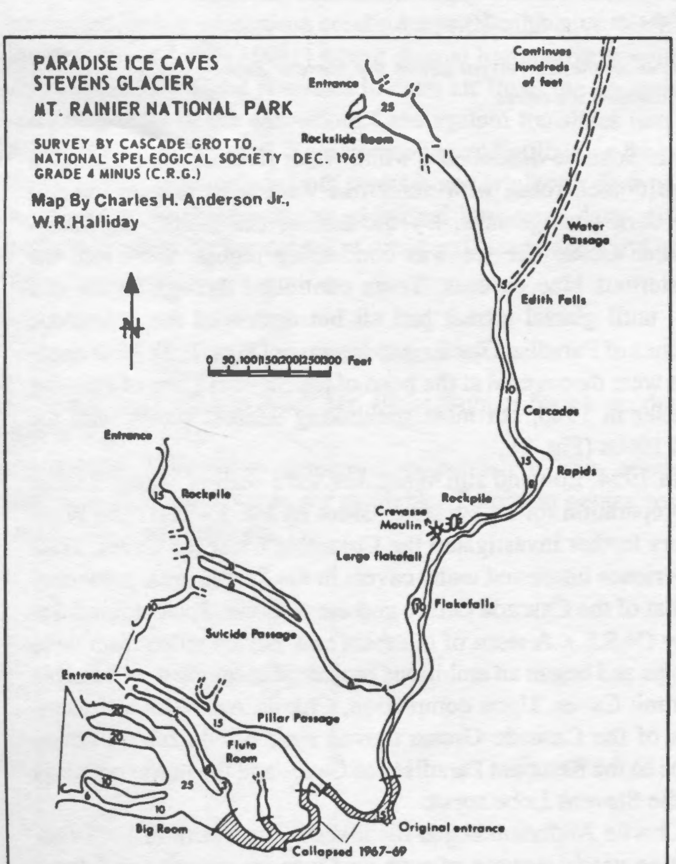


Figure 2. Ice Cave, Paradise Glacier Cave Elevation 6,500 feet. Near Stevens Glacier and Reese's Camp. This passage is the most accessible. This photo was taken near Sluiskin Falls along the Paradise River. See Figure 10.

Photo By H. L. Toles



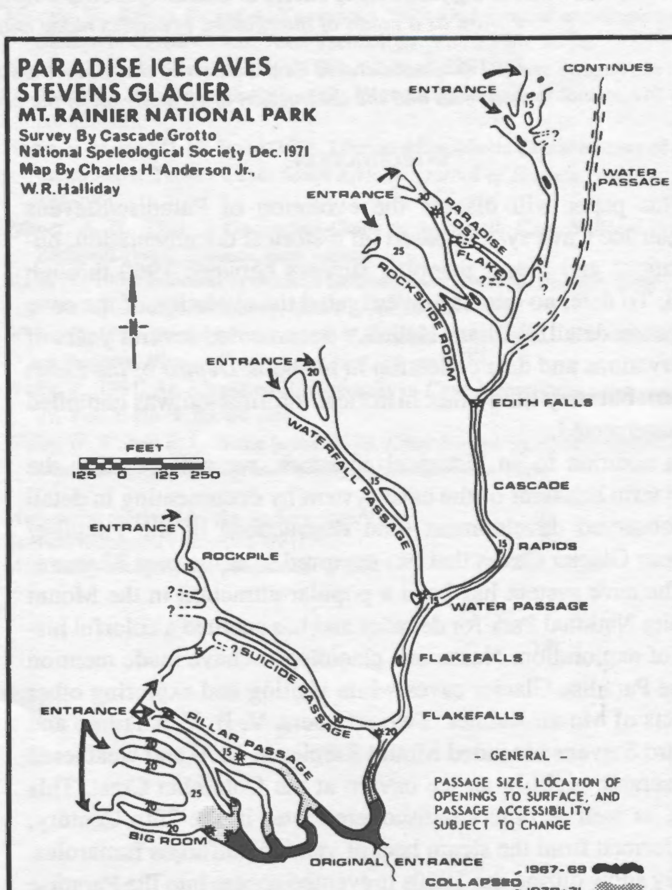


Figure 3. Paradise Glacier Caves System. These maps show the loss of cave area between 1967 and 1971.

Figure 4. Edith Anderson in the Main Entrance on Stevens Creek within Stevens Lobe, July, 1967. This is the main water passage along the Stevens Lobe of the Paradise and Stevens Glacier Caves.

Photo by Charles H. Anderson, Jr.

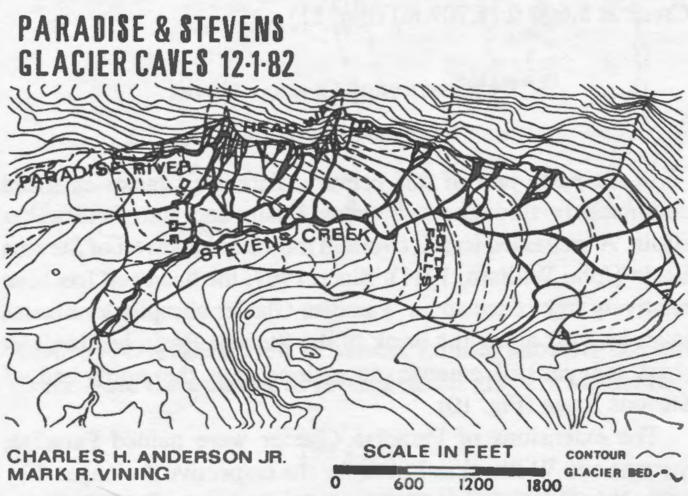


Figure 5. Paradise and Stevens Glacier System as mapped in December 1, 1982, Survey By the International Glaciospeleological Survey (IGS).

stream passage that eventually formed Stevens Creek. By 1970, over 2 miles (1.2 km) of firn cave had been surveyed. Work was interrupted in 1971, due to record snowfalls from 1971 through 1972, but resumed intermittently from 1974 through 1993 (Figs. 3 & 4).

By the end of 1974, over 8 miles (17 km) had been mapped and by May 1978, the length of the system was 8.23 miles (13.25 km). This was the most ever on the map at one time. During the following summer the Paradise River section was segmented at Surprise Entrance and the length dropped to about 7.4 miles (11.9 km), but the ice cave regained the former figure in the winter of 1978-79. More than 15 miles (24 km) of mapping was documented and a great deal remained to be done. This was especially true upslope from the old upper entrance, where compacting snow then linked the ice caves to other remnants of the old Stevens Lobe, as well as to the main body of Paradise Glacier (Fig. 5).

Location

The Paradise Glacier Ice Caves are located in a stagnant lobe of Paradise Glacier on the southeastern flank of Mount Rainier, centrally located in the state of Washington (Fig. 6). Early in the 20th century, the Paradise Glacier spread a wide sheet of ice over a mile (1.6 km) down the slopes of Mount Rainier high above Paradise Valley (Anderson & Halliday, 1969). Northwest of Paradise Valley is Stevens Canyon (named for Hazard Stevens). Ice cascaded off the steep canyon headwall and filled the shallow basin below. Gullies and a subtle ridge down the center of the valley floor divided the ice mass. The northeast side of the glacier drained into Stevens Creek. This portion of the glacier has been named the Stevens Lobe of Paradise Glacier. In the latter 20th century, Stevens lobe eroded and detached itself.

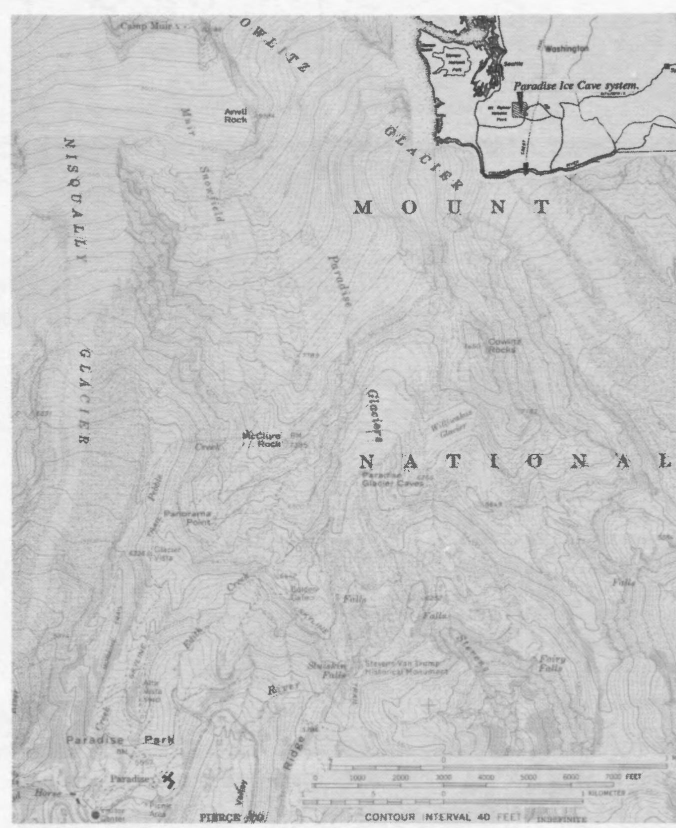


Figure 6. Paradise Glacier Caves, south flanks of Mt. Rainier, Washington, USA. The scale is 1"=2,000 ft. Prepared from the U.S.G.S. 7.5 quadrangle map Mt. Rainier, Wash. (1970, area photo revised 1980).

Figure 7. SUBGLACIAL CAVERNS ON MOUNT RAINIER LURE EXPLORERS. Formal Secretary of the Navy, Curtis D. Wilbur, expressed a wish to tread unbeaten trails when he visited Paradise Valley several years ago about 1908. Guides led him through a labyrinth of passages that had been under the ice for untold ages. This Cave was named for him.

Photo By Ranapar Studio

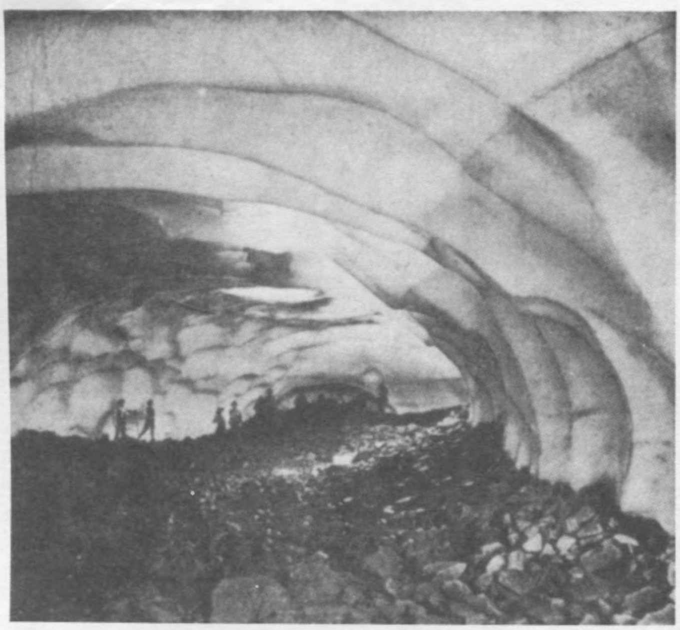


Figure 8. ICE CAVE, STEVENS GLACIER Elevation 7,000 feet. One of the many caves to be found in the smaller glaciers during the months of August and September. This Photo was taken in a side passage along Stevens Lobe and Stevens Creek.

Photo By H. L. Toles

Occasionally, the lobe is erroneously referred to as Stevens Glacier (Figs. 8 & 9).

The original ice caves of the early 20th Century were found at the head of the Paradise River, but these no longer exist (Figs. 1, 7, 8).

Stevens Basin is an elongate, southeast-facing, glacially scored canyon rising steeply to an elevation of 6,400 ft (1,946 m). Paradise Glacier rises above the northwest headwall of Stevens Basin to a maximum elevation of 9,584 ft (2,921 m) near Anvil Rock. To the east, the crater walls rise more gently to a saddle at 7,163 ft (2,183 m). This is immediately adjacent to the Williwakas Glacier, a second detached lobe from Paradise Glacier. Above the headwall, Stevens Basin rises gradually to meet Paradise Glacier at approximately 6,400 ft (1,951 m) with no abrupt changes in slope. Both Paradise Glacier and Stevens Basin truncate near this point due to a deep east-west trending gorge that is occupied by the Cowlitz Glacier. The Cowlitz and adjacent Ingraham Glacier are active alpine glaciers that originate near the Mount Rainier Columbia Summit at 14,410 (4,394 m) (Fig. 9). Stevens Basin terminates at Sluiskin Falls on Paradise River at 6,060 ft (1,847 m) and at Fairy Falls on Stevens Creek at 5,600 ft (1,707 m) (Fig. 11)

DESCRIPTION OF GLACIAL CAVES

Glaciological Setting

In the early part of this century, Paradise Glacier extended continuously throughout Stevens Basin and into Williwakas Basin. A crevassed icefall overlaid the steep headwall of Stevens Basin (John William, 1911). Since 1967, the headwall has been relatively free of ice cover. Paradise Glacier abruptly terminates in an ice cliff along the brink of the Stevens Basin headwall. A short tongue still extends downslope into the north end of Stevens Basin (Fig. 10).

The extensions of Paradise Glacier were named Paradise, Stevens and Williwakas Lobes for the respective drainages they occupied (U.S.G.S. Mt. Rainier 7.5 minute quad, 1955). After the glacier decayed into isolated pieces, the stagnant body occupying Stevens Basin was renamed Stevens Glacier (by this time, the Paradise Lobe had completely disappeared). For consistency, we will refer to the ice body as Stevens lobe of the Paradise Glacier (Fig. 11).

Between 1960 and 1980, Stevens Lobe has undergone subtle fluctuations, but remained relatively stationary. Before 1971, the glaciers yearly snowfall budget tipped the balance to negative. This persisted for a number of years resulting in decay of the ice body. The heavy winters of 1971 through 1976 provided positive budget balances, thereby advancing the glacier by compounded accumulation. Since 1976, the budget balance has remained at zero or slightly negative. These interpretations are not based on snowpack measurements, but by author's observations and by Park Service data collection activities (Fig. 12).

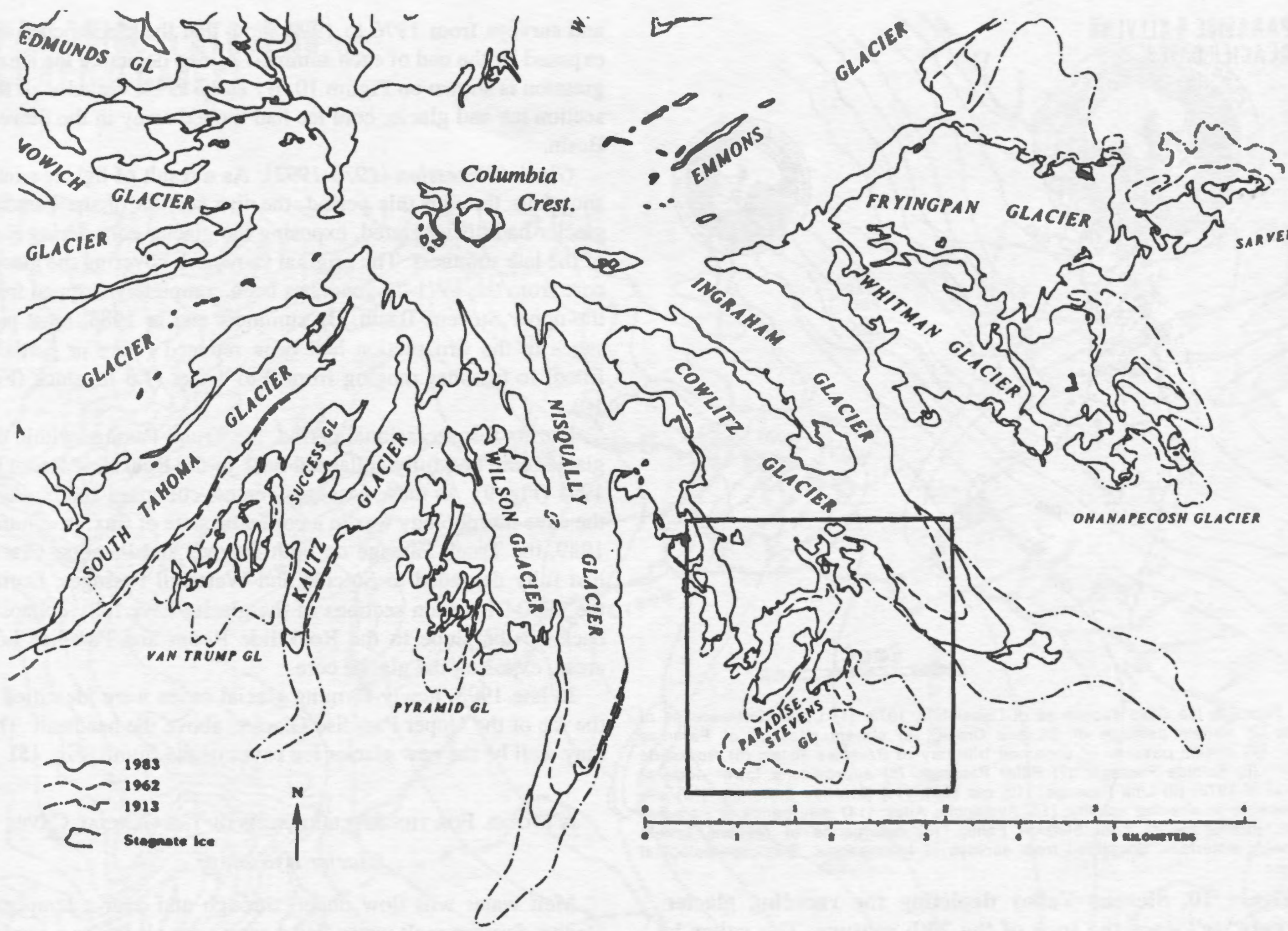


Figure 9. Overhead view of Mount Rainier showing the southerly-facing alpine glacier systems flowing down off the Columbia Crest. Note the amount of retreat on all glaciers snouts (Box denotes both Paradise and Stevens Glaciers).

The Caves

The caves formed under stagnant ablative conditions, have existed in a number of frozen states. First, as glacial ice with a relative density of 0.85 (water = 1.0), second as firn ice with densities varying from 0.65 to 0.85 and as packed snow with a density of 0.65 or less. During the time frame addressed in this paper, the Paradise Glacier has been a stratified mass consisting of all three of these forms. The internal structure of the glacier can be described in a simplified manner. It is composed of core ice that predates the 1970-1974 enlargement due to heavy snow accumulation and a firn section that overlies and extends the lateral and downslope boundaries of the ice field (Fig. 13).

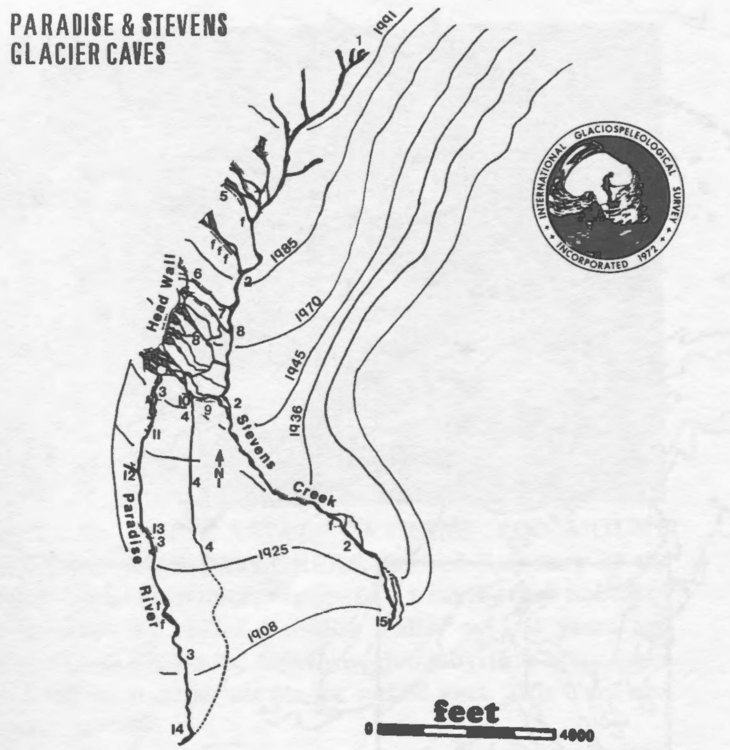
Cave Pattern

The ice cave plan in the firn section tends to be dendritic and complex. Passages are generally low and wide and smaller than those in the glacier core material. Each arm often follows a stream, but due to the thick gravelly nature of the underlying strata, many streams are not exposed on the ground surface. Side passages entering into the main trunk passages are smaller, but also many comprise an extensive complex cave system (Fig. 5).

Ice caves penetrating the glacier core are often symmetrical in cross section (approximately 15 x 20 ft). Streams flowing through the core caves are generally larger in size than those flowing through the firn section. Side passages are few in number, non symmetrical in cross/section and maintain a consistent size throughout their length.

Observations of the Caves Over Time

Glacier Core Decay (1960-1970): Figure 12 shows that snowfall throughout 1960s decade was relatively light. Snowfall totals did not exceed 800 inches (2000 cm) per year until 1970-71. For most of the 1970s, the Stevens Lobe Caves were accessible during summer months to visitors. Photographs taken in



The Paradise Ice Cave system as of December, 1973. (1) Upper Entrance as of 1970; (2) stream passage of Stevens Creek; (3) stream passage of Paradise River; (4) stream passage of unnamed tributary of Paradise River; (5) Rockslide Room; (6) Suicide Passage; (7) Pillar Passage; (8) approximate lower edge of glacier in 1970; (9) Link Passage; (10) old sign; (11) Surprise Entrance; (12) site of possible geothermal activity; (13) Avalanche Alley; (14) resurgence of Paradise River, just upstream from Sluiskin Falls; (15) resurgence of Stevens Creek; (f) major waterfalls. Simplified from surveys of International Glaciospeleological Survey

Figure 10. Stevens Valley depicting the receding glacier "core ice" since the turn of the 20th century. The valley is now virtually clear except for several remnant bodies of firn ice.

1960, 1964 and 1967-70, coupled with ongoing caving surveys between 1967-70, revealed that the glacial core was almost fully exposed by the end of each summer season. Although the glacial core has been receding for decades, between 1967 and 1970, the core front receded over 300 feet (100 m) (Fig. 3).

Cumulative Advancement (1970-1976): As shown in Figure 12, the winters of 1970-1974 were especially heavy with snowfall over 1,100 inches (2800 cm). The winters of 1974-76 also exceeded 800 inches (2000 cm). Throughout this period, snowfall from each winter survived through the following summer and thereby added to the permanent snowpack. The yearly rate of ablation was decreased significantly, suddenly extending the firn snow limit as far as Sluiskin Falls on the Paradise River and nearly to Fairy Falls on Stevens Creek (Fig. 6). The upper Stevens Basin remained ice-covered throughout this period.

Glacier Core Decay (1970-1976): Winters of the late 1970s through 1993 were light without exception. Snowfall did not exceed 800 inches (2000 cm) during this 16 year period. The ice cave entrances remained open for visitor access. Photographs and surveys from 1976 to 1992 show that the glacial core was exposed by the end of each summer. A map depicting the ice regression is shown on Figure 10. By early 1993, virtually all firn section ice and glacier core ice had melted away in the Stevens Basin.

Glacial Recession (1976-1992): As a result of lighter winter snowfalls through this period, the firn section of the Paradise glacier had disintegrated, exposing the glacier core during each of the late summers. The original snowpack covering the glacial core from the 1971-72 years has been completely stripped from the upper Stevens Basin. By summers end in 1985, most passages in the firn section had been reduced (open or partially filled) to trenches ranging from 0 to 4 feet (1.3 m) thick (Fig. 10).

During this recessional period, the Trunk Passage within the glacier core had fully collapsed back to the Rockslide Room by 1991 (Fig. 9). As these passages vented, collapsed and blocked, the cave morphology was in a continual state of flux. In summer 1989, the Trunk Passage on both Stevens and Paradise Creeks had fully degraded to Suicide and Waterfall Passages. During the 1990-91 season sections of the glacier have fully collapsed back up the slope to the Rockslide Room and Paradise Lost areas, exposing the glacial core.

In late 1993, newly-forming glacial caves were identified at the toe of the Upper Paradise Glacier, above the headwall. This may well be the new glacier ice caves of the future (Fig. 15).

A MODEL FOR THE SPELEOGENESIS OF THE GLACIAL CAVES

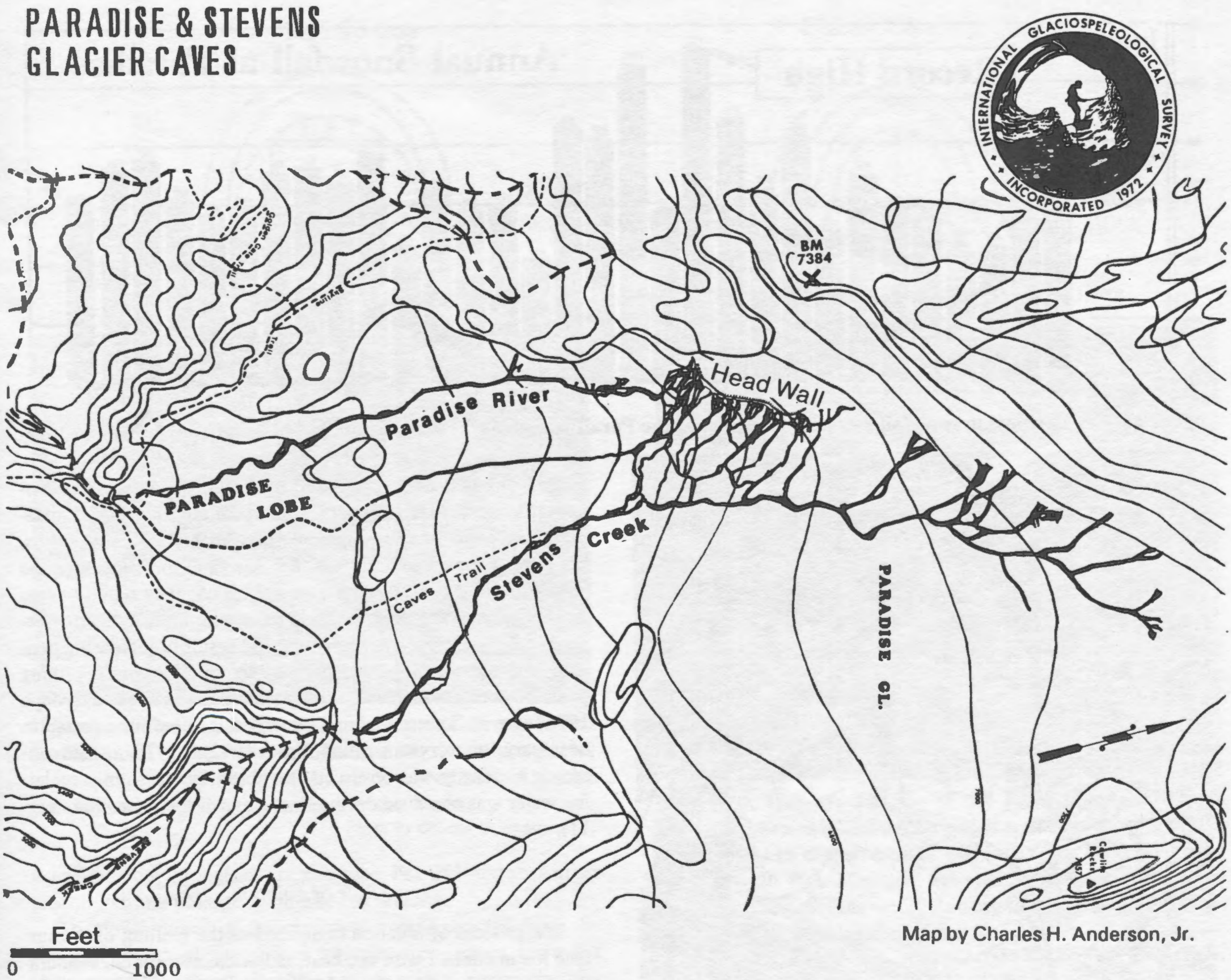
Glacier Hydrology

Melt water will flow under, through and over a temperate glacier. Surface melt water flows across the glacier as a stream, often sinking through crevasses or eventually flowing off the edge of the ice. Surface water can seep through glacial ice by means of a network of intergranular veins. The majority of runoff is subice flow, particularly downslope from the firn limit. The water finally issues from openings in the glacier snout.

Most ice caves follow subice stream courses. Entrances to most ice cave systems are located where flowing melt water either sinks under the ice or emerges. Other entrances occur where surface streams penetrate the ice, but this quite rare (Figs. 4 & 16).

Climate Controls

Each year the shrinkage and growth of a glacier or snowfield repeats a cycle. Ablation operates at a maximum rate during summer months, whereas snow accumulates during the winter and spring. Because of subtle changes in the glacier it may require years to discern whether its in an advancement or retreat stage. Yearly measurements taken at either a fixed time (i.e. 1st of September) or a fixed point in the ablative cycle (first snow of the winter season) will yield preliminary information on the glaciers ongoing changes (Fig. 12).



Map by Charles H. Anderson, Jr.

Figure 11. The Paradise and Stevens Glacier Caves System.

A linear interface exists at the boundary where the surface of the glacier comes in contact with nonglacial snow. This contact is called the firn limit. On a stagnant ice or snow body the firn limit cannot be so easily defined. The lack of bed movement prevents the physical separation of the two zones. Instead, one must study the stratigraphic nature of the body, noting the remnants of each years snowpack to determine whether there is shrinkage or growth.

Light vs. Heavy Winters

Winter snowfall has a primary control on the growth of a stagnant glacier or snowfall. After a heavy winter, the ablative action of the following summer usually will not shrink the body of snow back to its original state. A series of heavy winters with mild summers can significantly extend the margins of the firn snowfield.

A permanent glacial core develops and perpetuates during cooler periods. A record of depositional and accumulation growth is recorded as the ice body grows. Light winters aid in the degradation of the ice body. If there is insufficient snowfall to resist the ablation of summer heating, degradation will accelerate in the older overlying firn material. After a series of mild winters and coupled with warm summers, the firn cover will no longer protect the glacial core. Thereafter, the preserved depositional history will be permanently lost to erosion.

Since the turn of the century, the Paradise Glacier (and associated lobes) has experienced a net recession. All that remains of

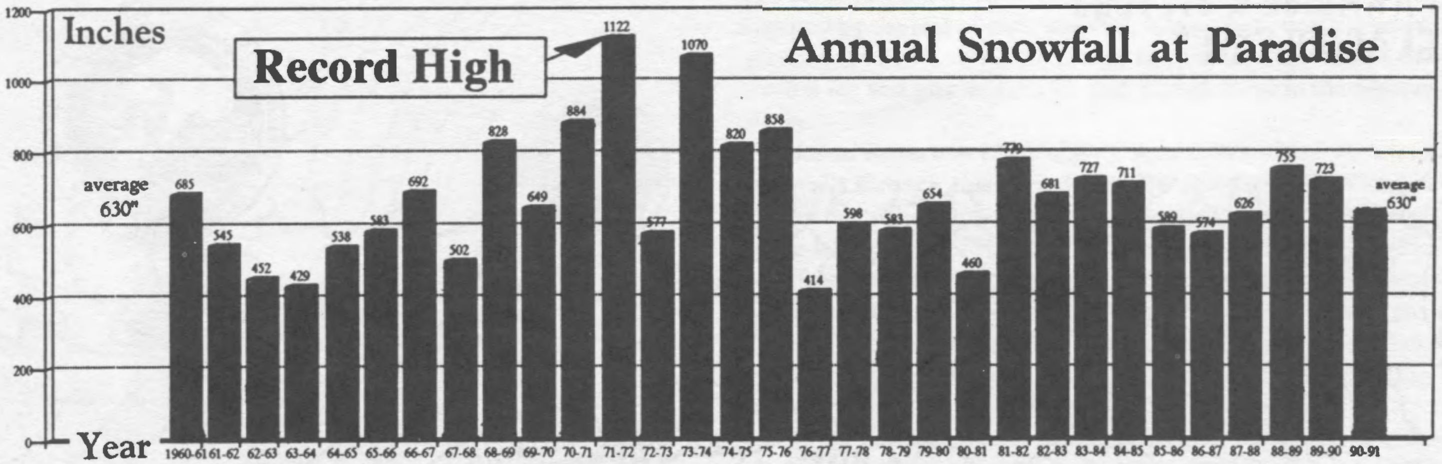


Figure 12. Graph showing snowfall amounts recorded at the Paradise Ranger Station (5,500 ft. ASL) from 1960 through 1991.

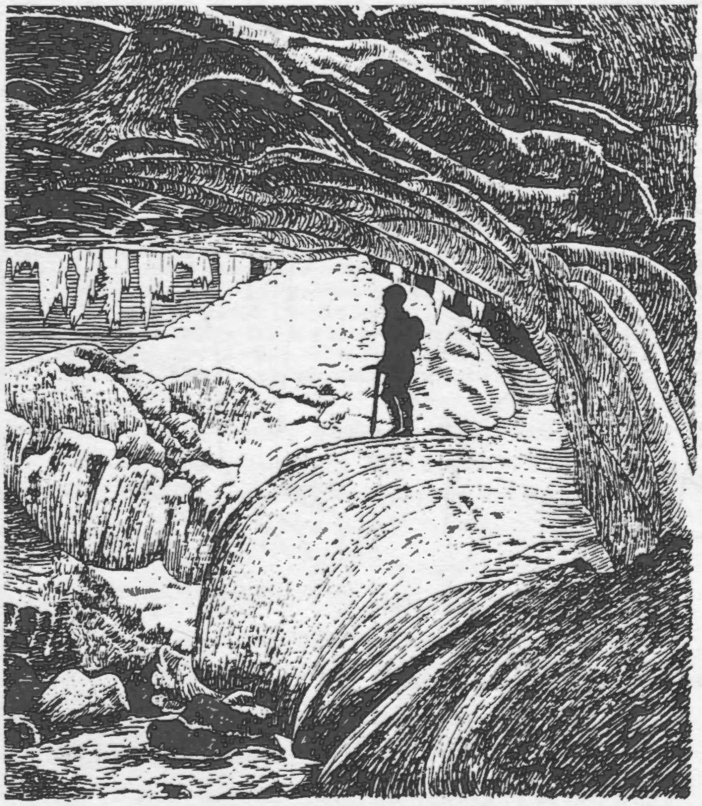


Figure 13. Main Entrance on Stevens Creek in 1969 at a elevation of 7,000 feet. This drawing was done from a photo by Charles H. Anderson Jr. in February 1969.

the old glacier in Stevens Creek Basin are the remnants of glacial core material. (Figs. 11 & 17).

Recrystallization and Modification of Ice Structure

When a winter snowpack survives the following summer and is buried further by the following winter snowpack, the snow layer will begin to compact and recrystallize. As water percolates through the snowpack, daily temperature fluctuations metamorphose snow into subspherical grains that are initially porous, but later compact to solid ice. By this time the density of the snowpack has risen to approximately 0.65, thus qualifying as firn snow. As long as air pockets exist within the firn structure, further recrystallization will occur and result in increasing density. This process is retarded if the overburden and confining pressure does not increase. Winter snowpack from 1970 through 1976 were well preserved and increased the confining pressures necessary for recrystallization. From 1972 to 1978, a steady increase in density was observed. An abrupt decrease in percolating water was observed during final stage of this transition. (Fig. 11).

Role of Ablation

The process of ablation is defined as the melting of the surface ice in contact with air, heat, radiation, absorption, evaporation and sublimation. Glaciers and snowfields undergo ablation at all times during extended periods of little snow. Most ablative mechanisms are in their most active state during the summer period. This is due to the combination of higher temperatures, drier air, less cloud obstruction and extended daylight hours.

Degrading processes acting within the glacial cave include evaporation, sublimation and the conductance of heat. Since the caves are sheltered from direct sunlight, solar radiation is not a contributing factor. In an ideal situation where the length of day, sunlight or cloudiness, temperatures and humidity are constant, the primary control of cave ablation is air flow against and along the walls of the cave.

The ablation rate becomes greatest when there is the least restriction to air flow through the cave. Ablation will also significantly increase where the flow is restricted through narrow passages. The faster growth of the smaller passages results in re-

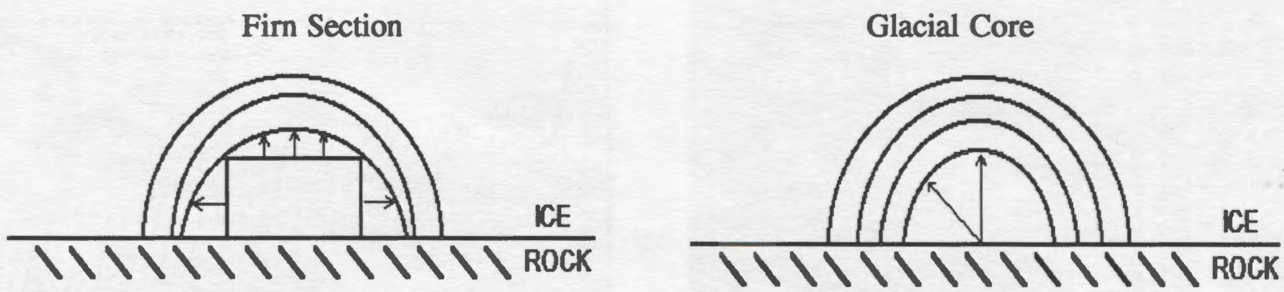


Figure 14. Typical cross section found in firn and in glacial core ice at Paradise and Stevens Glacier Cave.

Figure 15. The Main Entrance on Stevens Creek in the Stevens Lobe of the Paradise Glacier 1991. Note: the glacier regression, in 1992-93, virtually all firn section and glacier core ice had melted away in the Stevens Basin.

Photo By Charles H. Anderson, Jr.

duced air flow through larger passages. For this reason, further growth in trunk passage diminishes to nothing.

The development of the cave system will proceed from the complex pattern observed in a typically firn section, toward a more consolidated and simplified trunk system resembling the pattern exhibited in the glacier core. Firm ice will eventually stabilize and increase in density until it becomes core ice. Continued side-channeling will diminish and trunk systems will evolve. This is consistent with typical glacial processes.

Ideal vs. Non-Ideal Cave Morphology

The regularity of the cross-sectional shape of the cave is influenced by aerodynamic factors affecting air flow. Airflow is the controlling influence on ice cave passage morphology and size, therefore a correlation exists between glacier cave morphology and basic aerodynamic flow principles. The airflow shapes a glacier cave by melting away the internal surfaces. The resulting morphology (cross-section) of an ideal glacial cave can be evaluated by comparing with fluid dynamics theory for the development of flowage conduits in degrading solids.

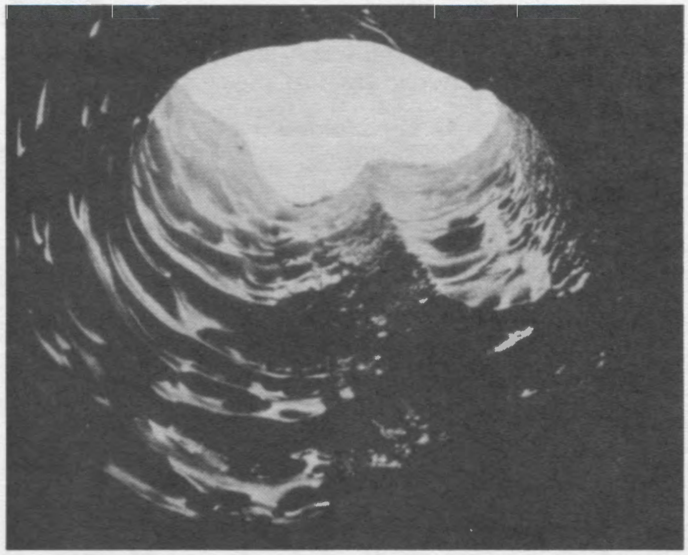


Figure 16. This moulin was in the Pillar Passage in 1968. Looking upward to the surface of the glacier. The moulin is about 8 feet in diameter. The distance from the cave to the surface is 20 feet. Moulins, cylindrical holes in the glacier ice, form from surface water flowing through the ice. Ice Pillars form during winter months.

Photo By Charles H. Anderson, Jr.

The radius of curvature acts as a control of ablative activity. The air flow is less restricted over large-radius curved surfaces so they tend to have an ablation rate which is higher. Where radii are smaller causing areas of restricted air flow, the restricted zones ablate at a retarded rate.

Circular passage morphology allows for maximum airflow with minimum drag. This configuration allows a uniform ablation rate on all surfaces. Air flow (in equilibrium) will produce a scalloped, but overall circular cave entrance. (Figs. 13, 18 & 25).

The relationship between the cave wall and floor is more difficult to analyze. The composition of the floor can differ widely between caves as well as along its course.

The radius of curvature is a valid measurement of structural stability of a cross sectional form. Abrupt changes in the ice cave direction will accelerate erosion, thus smoothing corners and ir-

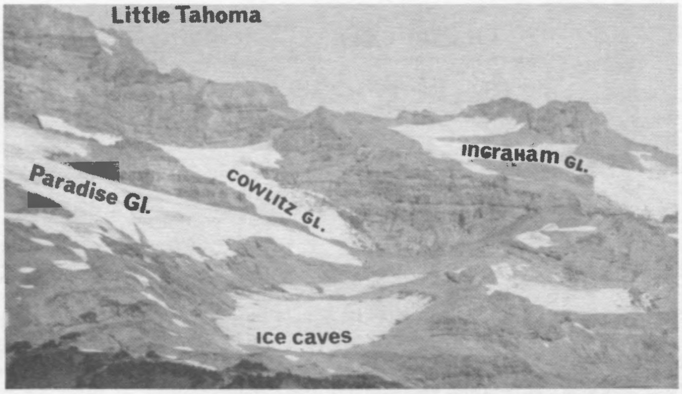


Figure 17. The main entrances of the Paradise and Stevens Glacier Caves System can be seen in the Stevens Glacier. This photo was taken August, 1970, (See Figure 10).

Photo By Dr. William R. Halliday

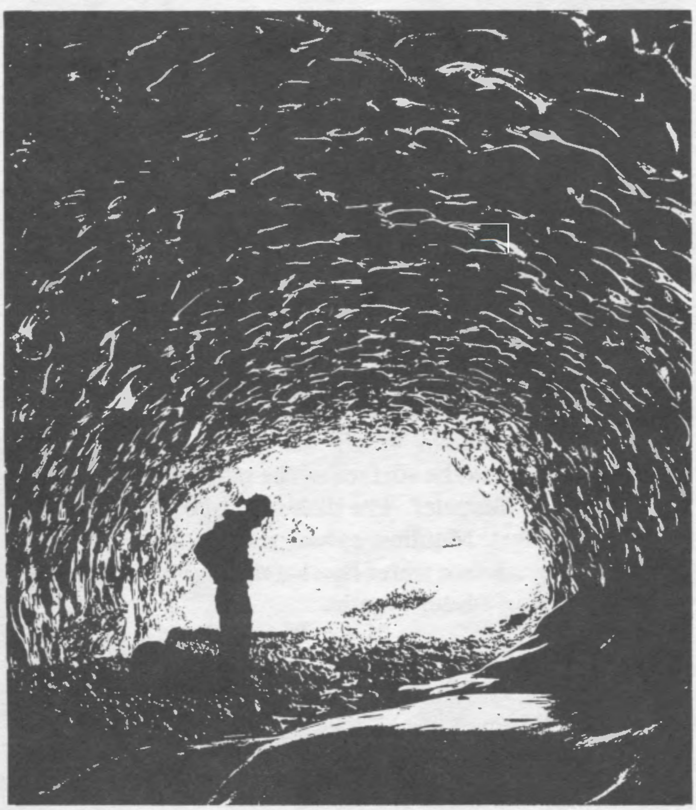


Figure 18. Stevens Glacier Cave entrance in August 1985, at a elevation of 7,000 feet. This circular passage morphology allows for maximum air flow with minimum drag, (Note the scallops on the cave walls).

Photo By Charles H. Anderson, Jr.

regularities. As the trunk passage grows into a mature form it should rise away from the rock or soil floor.

In late 1970, the upper end of Pillar Passage achieved this ideal end-form morphology. Most passages in the glacial core have been mapped as semicircular in shape. However, some pas-

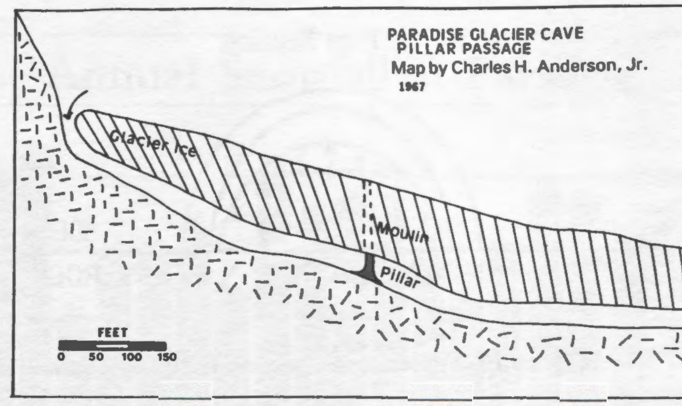


Figure 19. Cross-section of glacier ice mass in contact with underlying volcanic material. Water percolating off the headwalls flows under the ice creating proto-ice caves. Moulins, cylindrical holes in the glacier ice, form from surface water flowing through.

Figure 20. This photo was taken in 1969 showing part of the Paradise and Stevens Glacier Caves system in a collapsed segment during the course. This photo was taken between the Big Room and Stevens Creek entrance, (See Figure 10).

Photo By Charles H. Anderson, Jr.

sages have been modified by glacial flow, flaking, esker or moraine formation. Cross sections of passages within the firn section resemble conduits that are low and broadly arching. The angle between the floor and cave wall is very close to a right angle (Figs. 5 & 19).

Venting and Blocking

As both cave and surface ablation continue through a summer season, often the cave ceiling will erode to the glacier surface. Fracturing and snowfall weight may cause a ceiling collapse. The cave system suddenly gains a vent for outside air The re-

Figure 21. This photo was taken in October 1970, showing part of the collapse that segmented the glacier system during the course of the study. The sign warns of the risk of additional collapse of the cave system.

Photo By Charles H. Anderson, Jr.

Figure 22. This photo, taken in September 1991, shows part of the Paradise and Stevens Glacier Caves System in a collapsed segment. This entrance is in the Stevens Creek in the Paradise Glacier around the upper part of the cave system, (See Figure 10).

Photo By Charles H. Anderson, Jr.

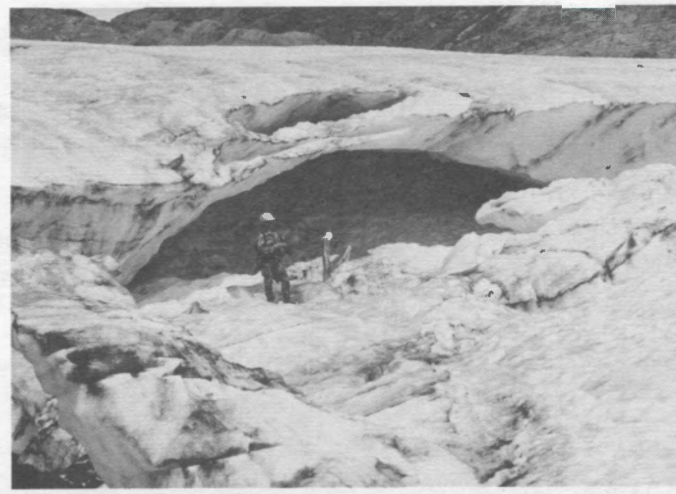


Figure 23. This photo was taken in September 1991 of the Stevens Creek Entrance. Though somewhat closer, the snout of the glacier in late summer shows the crevasse pattern as well as multiple entrances, also note the flake fall at the entrance.

Photo By Charles H. Anderson, Jr.

Figure 24. This September 1, 1991 photo shows the last Big Room just before it collapsed. Mike Anderson is surveying in the Big Room which is on Stevens Creek. One week later this room collapsed.

Photo By Charles H. Anderson, Jr.

sulting increase in air exchange accelerates the ablation rate in certain cave segments that ultimately produces a trunk passage.

When the ceiling does collapse, the debris restricts flow in the passage and retards the ablation rate. The following winter snows can completely block what was a former trunk passage. This venting and blocking process was responsible for most of the observed changes in the trunk pattern between 1977 and 1980 (Figs. 20 & 21).

CONCLUSION

The Paradise Glacier has afforded an unique opportunity for scientists to study the dynamics of an active alpine glacier. Since the discovery of ice caves at the toe of Paradise Glacier in the early 1900s, over 8 miles of mapped cave have now disappeared

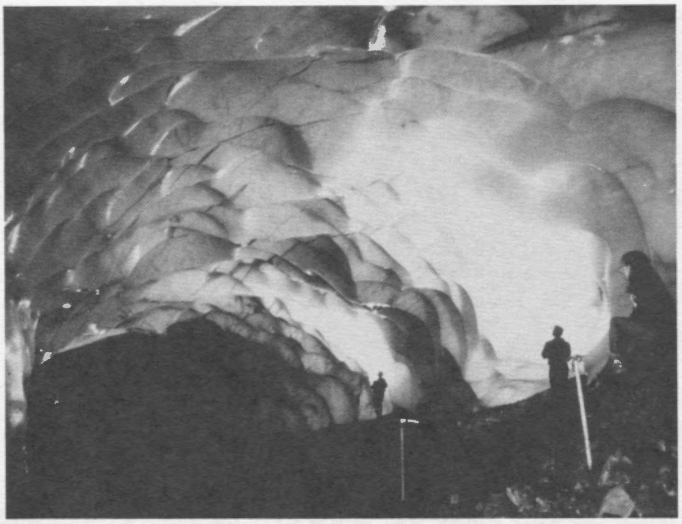


Figure 25. This was the original "Big Room" in the glacier caves system. Edith Anderson and Rick Riggs are surveying the Big Room in July 1967. Note the scallops pattern of the cave walls. The Big Room collapsed in September 1970.
Photo By Charles H. Anderson, Jr.

to the fast-receding glacier. Fortunately, persistent explorers have photographed the beauty of these caves and are methodically documenting the ongoing changes. (Figs. 10, 22, 23, & 24).

Although the Stevens Lobe has now receded to the top of the Stevens Basin headwall, there is new visible evidence that caves are once again forming just above the headwall. There are no plans presently to investigate these new openings, but curiosity will surely bring new explorers in the future (Fig. 15).

ACKNOWLEDGMENTS

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REFERENCES CITED

Anderson, Jr., C. H., and Halliday, W. R. 1969. The Paradise Ice Caves, Washington: An extensive glacier cave system. NSS Bull. 31:55-72.

Halliday, W. R. 1976. Depths of the Earth. 2nd Edition, Harper and Row, New York, Chap. 17, pp. 359-376.

Williams, J. H. 1910. The Mountain That Was God. 1st. Edition, John H. Williams, Tacoma, Washington.

Topographic map, U.S.G.S. Mount Rainier, Washington, East Quadrangle 7.5 minute Series 1955.

Topographic map, U.S.G.S. Mount Rainier, Washington, East Quadrangle 7.5 minute Series 1970.

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MORPHOLOGY AND DEVELOPMENT OF SALT CAVES

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Morphology and origin of salt caves are discussed, based on a study of 105 caves in Mount Sedom salt diapir, Israel. High solubility of rock salt has favoured the development of allogenic caves under arid climate. Caves along the margins of the mountains are integrated systems with open outlets at base level. Central caves lack such an outlet, discharging slowly through narrow fissures to a regional aquifer. Cave profiles are adjusted to base level, allowing reconstruction of the evolutionary history of the region.

INTRODUCTION

Rock Salt, composed mainly of halite (NaCl), is extremely soluble, three orders of magnitude more than limestone. However, salt caves were scarcely studied until recently, and their very existence has been doubted in some scientific literature (e.g. Bögli, 1980, p. 3). The first modern review discussing salt caves is by White (1988, p. 337).

Because of its solubility, rock salt outcrops are rare. Salt layers (which are not uncommon in the subsurface), usually dissolve completely by meteoric water down to depths of several hundred meters. This process, termed interstratal (or intrastratal) karstification is often accompanied by salt aquifers, breccias, subsidence dolines and bedrock collapse structures (DeMille et al., 1964). Such features may originate at depths of more than 1000 meters below surface. However, few true caves in salt were known until recently. Cave explorers have found one example in the Persian Gulf (Shaw, 1979), 31 caves in Rumania (Ponta, 1986), five in former USSR, two in Spain, and eight in Algeria (Chabert, 1989). For a detailed bibliography see Choppy, (1988). No accessible salt caves in the American continent are known to the author, but interstratal salt karst is common (Quinlan et al., 1986).

The largest known assemblage of salt caves is found in Mount Sedom, Israel. During the last decade 105 caves have been surveyed in this rock salt mountain (Frumkin, 1982; Donini et al., 1985; Frumkin, 1986). The range of salt cave types of Mount Sedom seems to include the common morphological types found elsewhere, as well as types unknown from other localities. Each type is represented by enough specimens to allow classification and generalized discussion.

The purpose of this paper is to discuss the morphology and genesis of the major types of salt caves, based on a detailed study of Mount Sedom caves (Frumkin, 1992).

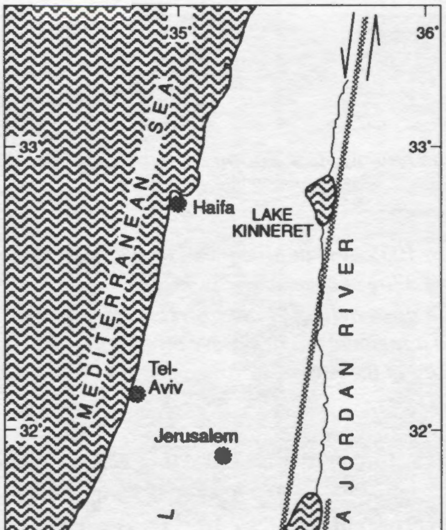
REGIONAL SETTING AND GEOLOGY

Mount Sedom is the exposed head of a salt diapir, forming an elongated ridge 11 by 1.5 km, rising up to 250 m above the 1993 Dead Sea level (Fig. 1) in the sinistral transform fault zone of the Levant (e.g. Garfunkel et al., 1981). In 1993, the elevation of the Dead Sea surface, being the regional base level, was 410 m below MSL (Frumkin, in press, b). The Dead Sea basin is filled by a thick sequence of detrital sediments and evaporites which give rise to subsurface salt diapirs (Neev and Hall, 1979). Of these, Mount Sedom, on the southwestern shore of the lake, is the only one to have broken the surface. It consists of Plio-Pleistocene(?) beds of rock salt, of marine origin, piercing through tilted strata of younger lake evaporites and clastics.

As the diapir rises, lithostatic pressure is released and fissures tend to open in the upper parts of the rock mass, especially near its margins. These are important for initial groundwater flow, since the primary porosity of rock salt is negligible. Borehole evidence indicates that below base level, fissures are annealed (closed) under pressure, due to the plastic properties of salt (Yossi Charrash, Dead Sea Works, personal communication, 1992). Bedding planes are vertical or steeply inclined. They often yield under the shear stress induced by the rising diapir and become minor fault plains (Zak and Freund, 1980). Horizontal fissures are rarely found in Mount Sedom. Before its subaerial extrusion, the top of the rising diapir suffered dissolution by groundwater. Residual, relatively insoluble anhydrite, shales and dolomite accumulated above the salt, forming a cap rock that is up to 50 m thick (Zak and Bentor, 1968). The flat, near-horizontal contact between the steeply inclined salt layers and the cap rock is referred to as the 'salt table' (Vroman, 1950-1). The cap rock is covered by Late Pleistocene Lisan lake sediments ('Lisan Marls'), consisting of aragonite, clays and gypsum (Begin et al., 1980). The Lisan Marls will be included in the term 'cap rock' for most of the present discussion. The top of Mount Sedom is roughly tabular, with many small catchments up to 0.7 km^2 in area. Karst terrain has developed under arid to extremely arid climate during the Holocene; the oldest cave was dated to ~7000 convention ^{14}C years (Frumkin et al., 1991).

HYDROLOGICAL BACKGROUND

The region is extremely arid today, with an average yearly rainfall of 50 mm. Annual precipitation-evaporation deficit ex-



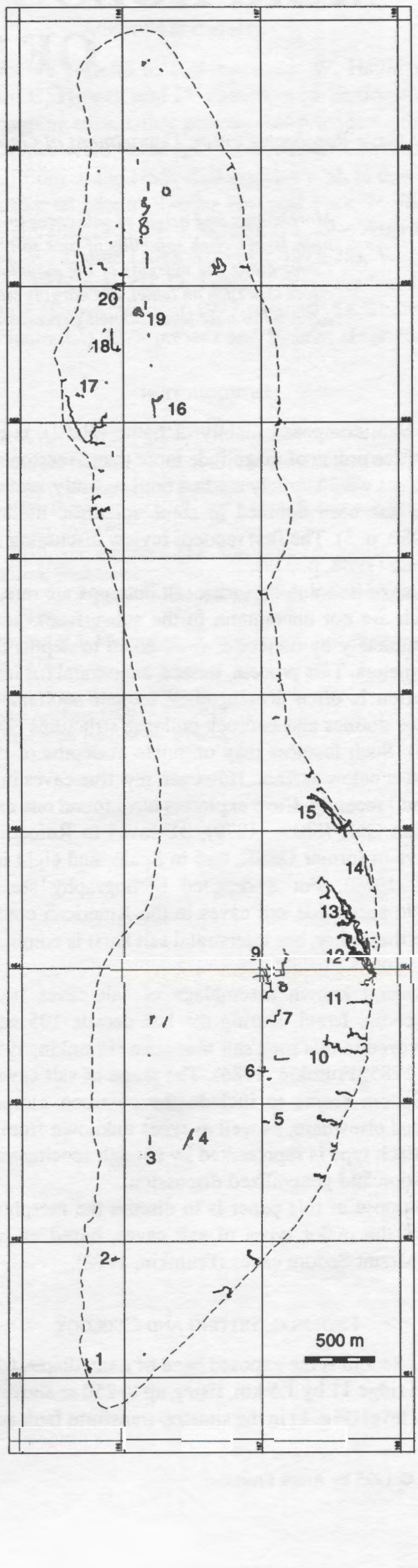


Figure 1. Map showing the location and ground plan of Mount Sedom caves (1) Nahal Melah Cave System, (2) Tupim Cave, (3) Gavish Cave, (4) Karbolot Cave, (5) Prahim Cave, (6) Tsinor Cave, (7) Notsa Cave, (8) Zehuhit Cave, (9) Qupa Cave, (10) Colonel Cave System, (11) Bua Cave System and Karega-Nolda Cave, (12) Malham Cave System, (13) Lashleshet Cave, (14) Lehavim Cave System, (15) Sedom Cave System, (16) Nahash Cave, (17) Sharsheret Cave, (18) Mifrazim Cave, (19) Agam-Yavesh Cave, (20) Mevokhim Cave.

ceeds 2 m. During the infrequent rainstorms, runoff collects on the relatively impervious cap rock and flows into fissures, leading to large cavities in the underlying rock salt. Such a setting may be classified as allogenic karst (Jakucs, 1977), even though the cave catchments are within the boundaries of Mount Sedom.

The eroded cap rocks contribute large amounts of clastic load to flood water, ranging from 10% to 80% by weight (Gerson and Inbar, 1974). Flood flow velocities range from 0.5 to 2m/sec, allowing bedload cobbles to be carried along cave passages. Extreme suspended load concentrations may render the flow dense and highly viscous. Suspended load scarcely changes while the water is flowing through the caves. On the other hand, TDS (total dissolved solids) in flood flow increases dramatically within the caves, from ~10 g/l (gram/liter) at stream sinks up to 200-300 g/l. This consists mainly of halite (Frumkin, in press, a). Most flood waters remain chemically aggressive while flowing rapidly within cave passages. However, if the flow is stopped or slowed down considerably, saturation is approached after few hours or days.

Two types of resurgences are known along Mount Sedom margins, differing from one another chemically and hydrologically (Frumkin, in press, a): (1) Cave outlets where sinking streams reappear. (2) Alluviated resurgences discharging diffuse continuous flows of brine ("exurgences" of Sweeting, 1972). The brine emerges along the foot of the eastern escarpment and in some eastern caves (Fig. 2), apparently discharging from a aquifer (Figs. 3, 4) encountered in boreholes (Petroleum Services, 1979). It is saturated in salts, with high concentrations of Mg^{++}, K^{+} and Br^{-}, in addition to Cl^{-} and Na^{+} (Frumkin, in press, a).

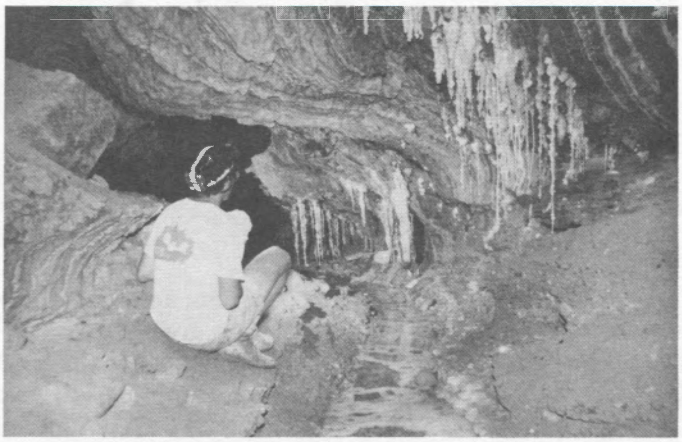


Figure 2. Rock salt passage in Malham Cave. Vertical salt beds are seen in the upper right corner. A saturated brine seeps from the alluviated bottom, forming (salt) rimstone pools. Vadose seepage forms halite stalactites.

METHODS

Some 20 km of cave passages have been surveyed by compass, tape and clinometer. Higher precision elevations with maximum of ±5 mm were measured by a tripod-mounted automatic Wild surveyors' level, for comparing cave levels to one another and to the water table level.The time scale for cave development was obtained by direct measurement of downcutting from 1986 to 1991 (Frumkin and Ford, in press) and by ^{14}C dating of driftwood carried by floods into the caves (Frumkin et al., 1991). This dating method, applicable in caves younger than ~40,000 years, provides the actual age of speleogenesis with error margins of only a few hundred years, compared to carbonate speleothem dating which provides the minimum age of the cave passage with larger error margins.

Hydrological, chemical and isotopic data being published elsewhere (Frumkin, in press, a) are also used to facilitate the present discussion.

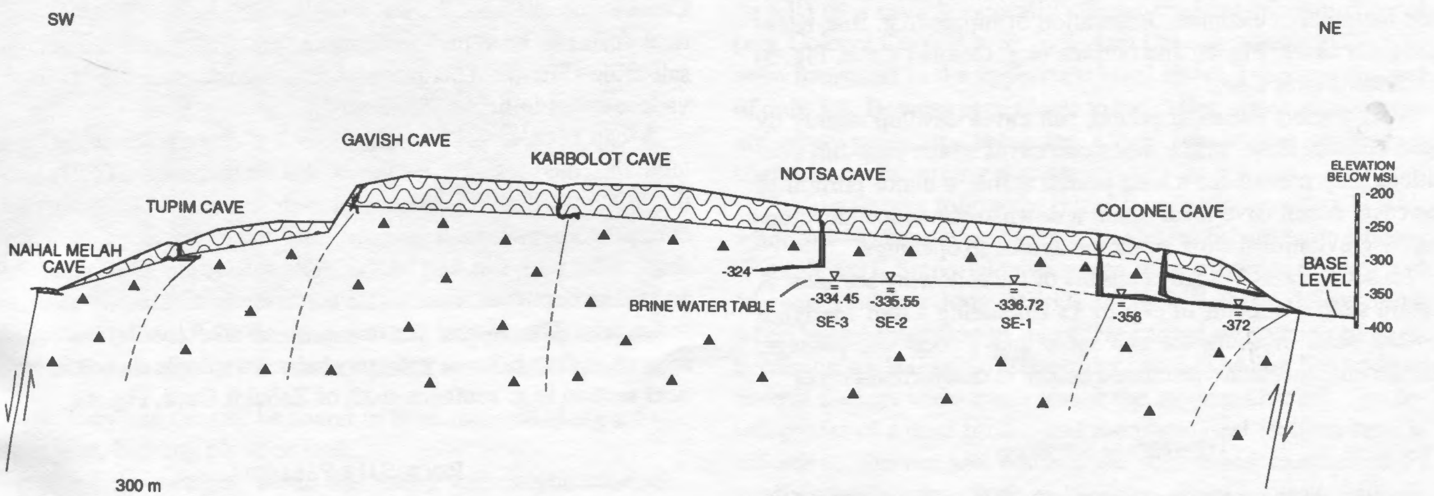


Figure 3. Cross section of southern Mount Sedom. Curly lines indicate cap rocks and black triangles are rock salt. Upper level of Colonel Cave is reconstructed from segments between breakdowns. Salt layers in caves dip subvertically westward.

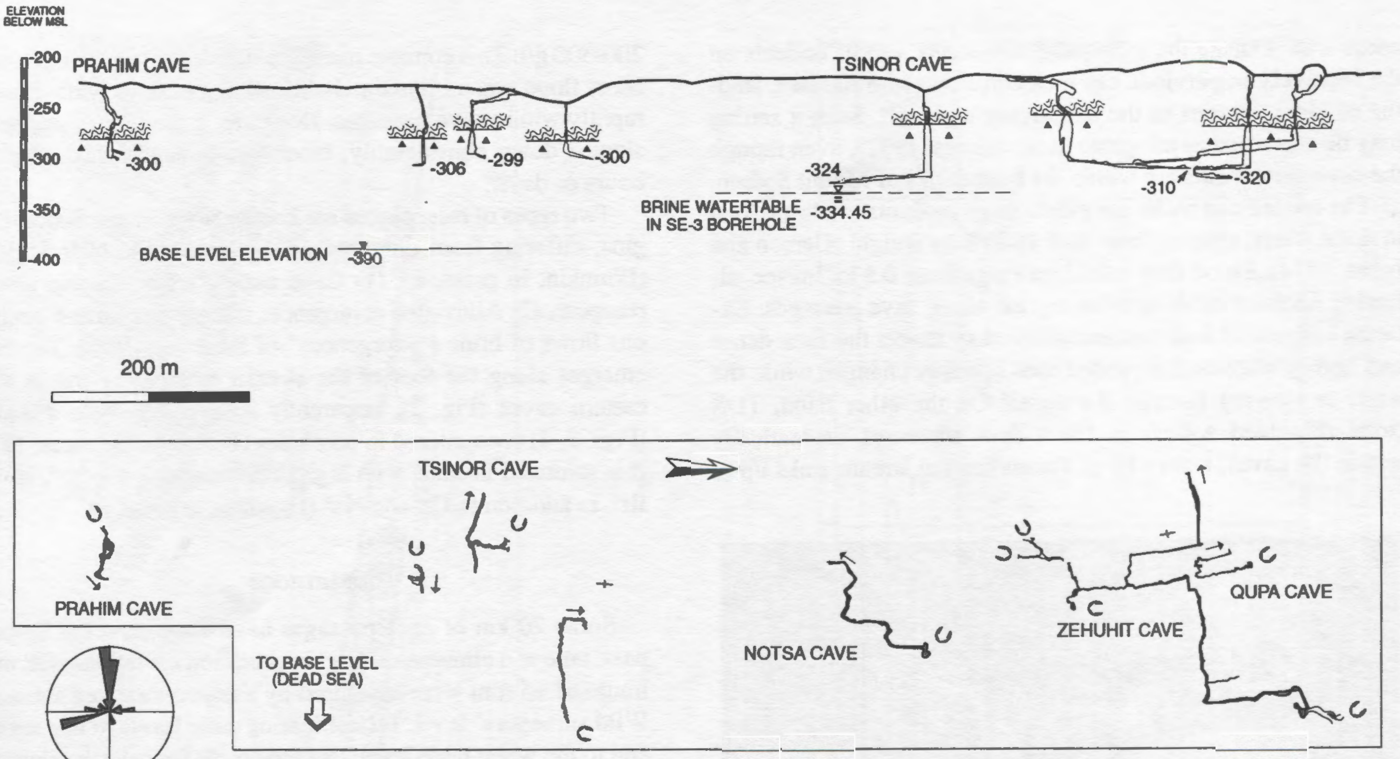


Figure 4. Inlet caves in the central part of southern Mount Sedom. (A) North-south section. (B) Ground plan; arrows indicate sinks and flow direction at the cave bottom. Bedding is vertical, shown by crosses. (C) Rose diagram shows preferred flow directions in salt cave passages. Most conduits developed westwards along joints and southward along bedding plains, although Dead Sea base level is in the east.

COMMON CAVE MORPHOLOGY IN MOUNT SEDOM

Each cave is fed by one or more sinks with a distinct catchment area. Often several conduits join underground to form a branchwork cave (e.g. Zehuhit Cave, Fig. 4). Most of the older caves are multi-phase, possessing inactive conduits above or beside the modern channels. Relocation of inputs (e.g. Bua-Karega-Nolda caves, Fig. 5) and outputs (e.g. Colonel Cave, Fig. 3) is common over time.

After a short initiation period, salt caves develop mainly by open-channel flow, unlike limestone caves where pipe-full conditions may prevail for a long period across a major portion of the cave. A salt cave must retain a downstream slope, developing by gravitational flow along the available openings.

An active cave typically consists of the following sections: A stream sink, a conduit in cap rocks (including Lisan Marls), a vertical shaft crossing the salt table and a rock salt passage. These components are discussed below in downstream order.

UPSTREAM SECTIONS

Subaerial channels are captured into subsurface routes through fissures in the cap rock (Fig. 6) that offer higher gradient flow routes. The sink dimensions vary from impenetrable (few cm), up to 2 m. Some sinks drain directly downwards to shafts crossing the salt table, while others lead first to sub-horizontal passages in cap rock. Most cap rock flow routes are narrow, up to several tens of cm in width. Both piping and dissolution enlarge the channels within these relatively insoluble rocks. Close to the salt table the cap rock channel usually becomes vertical, forming the upper, narrow part of a shaft which crosses the salt table (Fig. 4). This morphology is comparable to invasion vadose caves in limestone (Ford and Ewers, 1978).

A cap rock fissure usually does not extend across the salt table into the rock salt. However, the shaft drops vertically into the salt, regardless of fissures or bedrock dip. Its cross section enlarges downwards below the salt table, having a bell-like shape. The rock salt part of the shaft may reach 15 m diameter and 60 m depth. In most shafts the floor is covered by alluvial sediments. The lower, vertical part of shaft walls are either smooth or fluted. Some younger shafts are spindle shaped in vertical section (e.g. southern shaft of Zehuhit Cave, Fig. 4).

ROCK SALT PASSAGES

The shafts in most of the studied caves are drained by subhorizontal conduits, typically vadose canyons with incised me-

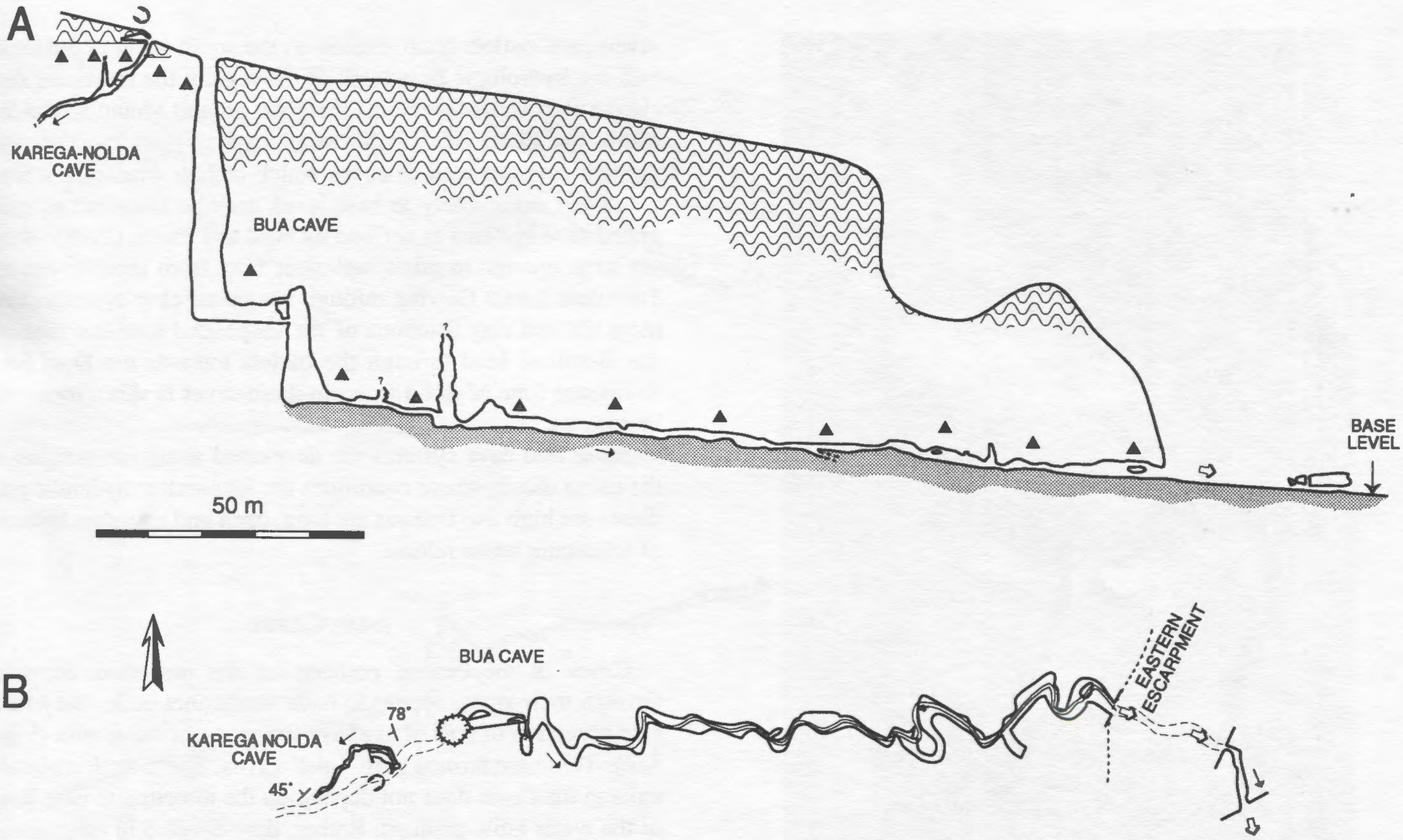


Figure 5. (A) Profile (B) map of Bua Cave system (surveyed by Anan Zeidner) and Karega-Nolda Cave. The catchment of Bua Cave was recently captured upstream, forming the embryonic Karega-Nolda Cave.

Figure 6. The sink of Sharsheret Cave; a typical cave input developed on a cap rock fissure crossing a subaerial channel.

anders. They can usually be found to have initiated along a fissure—joint, bedding plane or fault.

Average downcutting along the young salt canyon channel shown in Figure 7 was 44 mm during 5 years of measurement (Frumkin and Ford, in press). It took place mainly in the course of two major floods. Salt bedrock is exposed along the passage bottom and its mean gradient is 40%. Gradients from 2 to 10% are more common in most active passages, in which case the bed will be alluviated. Alluvial clastic deposits are fine grained to pebbly, including anhydrite, dolomite and quartz, all locally derived from Mount Sedom. The uppermost inactive storey (or 'level') of a cave is typically steeper than the modern channel (e.g. Colonel Cave, Fig. 3). In Sedom Cave, gradients of 27-32% were measured in the uppermost level above a modern channel of only 5%. Downstream, closer to the outlet, upper level storeys are more moderate, becoming either sub-parallel to modern channels or converging with them.

Steep passages follow the initial fissure closely (Figs. 8, 9A), while sub-horizontal passages with aluvial fill are more sinuous (Figs. 5, 9B). Some wide passages with meander notches and 'shelves' indicate long periods of flow without downcutting, when lateral migration of meanders caused destruction of earlier canyon walls (Fig. 10). The older caves in Mount Sedom have several distinct wide levels above the modern channel. The development of a cave profile and morphological features such as meanders, shelves and notches are sometimes constrained by hardly soluble layers, such as dolomite, shales and anhydrite, interbedded within the salt (Fig. 9C).

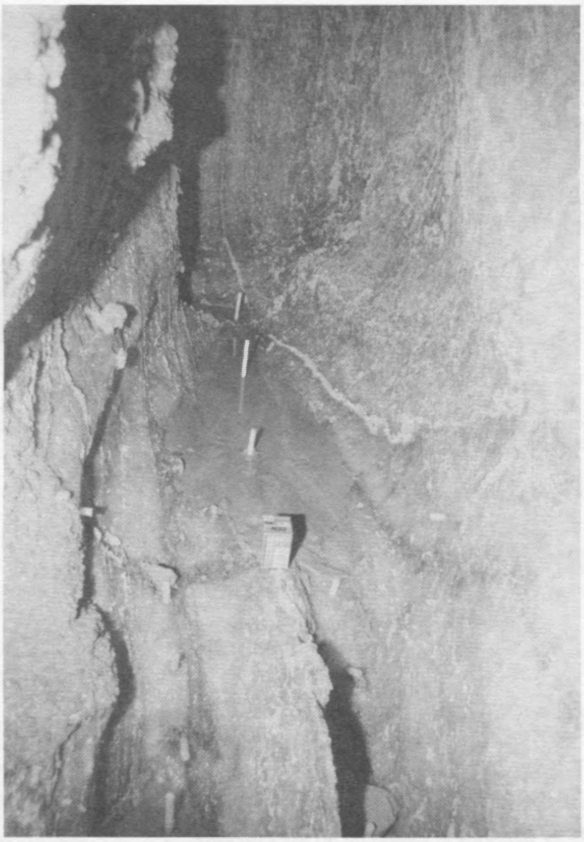


Figure 7. A young passage in Sedom Cave, one day after 9 Feb. 1987 flood. Using the white plastic pegs as benchmarks, 2 cm of downcutting was measured to have occurred during this flood. The film box for scale is 6 cm high.

Solid load may settle on the cave bottom, shielding the floor and favouring upward dissolution of the roof—a form of paragenesis (Renault, 1967). Corrosion bevels—flat roofs regardless of geologic structure (Ford and Williams, 1989, p. 307) develop where flood water touches the ceiling (Fig. 9E). Any salt protruding from the ceiling into the passage is truncated by the water, and upward solution proceeds with the same rate across all the bevel. The resulting flat ceiling is an imprint of the water surface forming it. A vadose canyon is often entrenched in the alluvium under a bevel (Fig. 9F, 11).

Salt caves may be classified into two groups according to the way they terminate: (1) integrated cave systems, having a distinct open outlet; (2) inlet caves, lacking such an outlet.

INTEGRATED CAVE SYSTEMS

In terms of exploration limits, thirty eight of the studied caves are 'through caves' (as classified by Jennings, 1985, p. 137)—they can be traversed along the full distance from sink to outlet (e.g. Colonel Cave, Fig. 3; Bua Cave, Fig. 5). These caves are located along the margins of Mount Sedom (Fig. 1). Twenty-seven cave outlets drain directly to the south basin of the Dead Sea, the hydrologic base level of the region; the remainder discharge westwards into wadis that flow around Mount Sedom towards the Dead Sea. In terms of hydrological function, the through caves as well as caves which include inaccessible segments but drain freely to base level, may be classified as integrated cave systems as defined by Ford and Ewers (1978)—they are large enough to allow turbulent flow from input to output. Turbulent floods flowing through integrated cave systems carry most silt and clay fractions of the suspended load and most of the dissolved load through the outlets towards the Dead Sea. Residence time of flood water in these caves is short, measured in minutes.

Integrated cave systems are developed along the margins of the rising diapir, where conditions are favourable: hydraulic gradients are high and fissures are long, open and abundant because of lithostatic stress release.

INLET CAVES

Caves in the central portions of the mountain, accessed through their sinks, appear to have no distinct outlet but terminate several m or tens of m above the apparent water table (Figs. 3, 4). These are termed here 'inlet' caves. The direction of conduits in the caves does not depend on the direction to base level or the water table gradient. Rather, they develop in orientations dictated only by available open fissures. Some inlet caves such as Zehuhut, Tsinor and Notsa seem to flow away from the Dead Sea base level (Fig. 4B, C). Some inlet caves develop close to one another but do not meet (e.g. Zehuhit Cave and Qupa Cave, Fig. 4).

The downstream parts of Inlet caves often contain steep silt and clay banks with surge marks, similar to those described by Bull (1976) in limestone caves. They indicate occurrence of low energy water pondings with variable residence times (see below), in which sediment load could settle. This further suggests that the limit of exploration is also a hydraulic limit between two sequential modes of water flow: rapid turbulent floods prevailing from input to cave bottom, and diffuse infiltration below the bottom of the explorable passage, down to the output boundary of Mount Sedom. The water infiltrating from inlet caves may recharge the brine aquifer known from boreholes SE1, SE2 and SE3 (Figs. 3, 4). However, chemical and isotopic differences between the ponded water and the aquifer indicates an additional source and a complex origin of the aquifer (Frumkin, in press, a).

A transition between slow and rapid kinetics, known in limestone to coincide approximately with the laminar-turbulent transition (White, 1977), is not known in salt dissolution. Therefore salt fissures are not believed to enlarge in a uniform rate over long distances downstream under phreatic conditions. Rather, dissolution seems to act mainly close to the inputs, forming inlet caves; infiltrating water probably approaches saturation rapidly

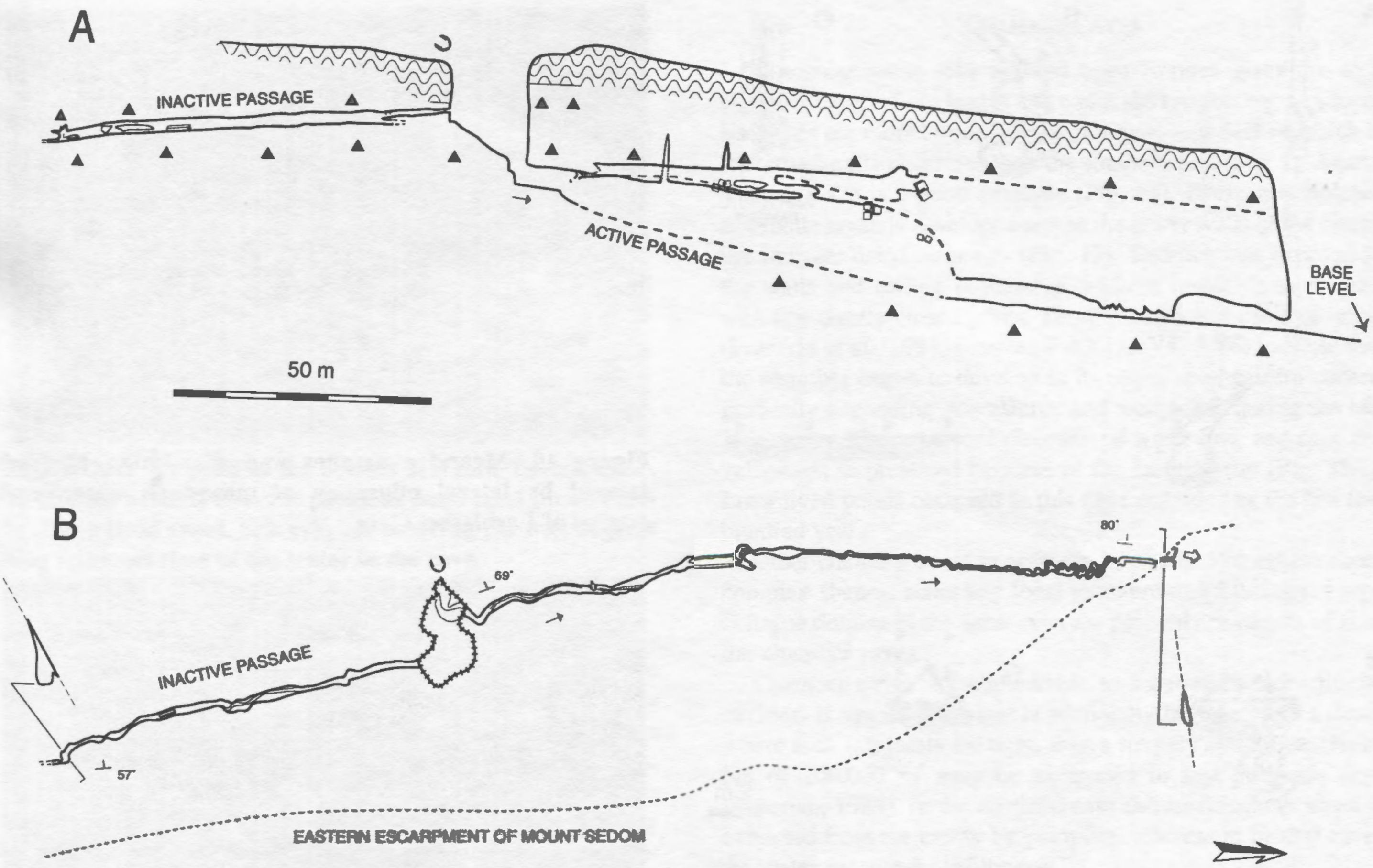


Figure 8. (A) Profile (B) map of Levahim Cave. The passages follow the initial partings, meandering slightly. The inactive southern passage, being sub-parallel to the escarpment, failed to connect to base level. The receding shaft cut across another parting, diverting the flow northward, to the present outlet. The modern channel is steep with no alluvium, indicating active downcutting. Note the initial lenticular cross section (enlarged x2.5), developed along the inclined parting.

below the bottom of the cave. This partly explains why true phreatic conduits are not known in Mount Sedom, apart from paragenetic passages developed under full pipe conditions in the vadose zone. Other arguments discouraging development of salt phreatic caves are: (1) Open fissures are not available below base level. (2) Mixing corrosion (Bögli, 1980, p. 35) is absent. (3) The abundant sediment load settles down in phreatic conditions of low water energies, blocking fissures and conduits. (4) Deep cavities formed in environments sustaining deep ground water circulation tend to collapse or anneal rapidly under lithostatic pressure.

Flood Water Ponds

Silt and clay sediments settling at the bottoms of inlet caves impede infiltration, extending the residence time of pond water. Three of the studied caves in northern Mount Sedom had perennial ponds throughout the study period of 1984-1991. They are perched, without any lithologic control, tens of meters above the nearest potential outlet at the foot of the mountain. Water level in each lake also differs from the others by tens of meters.

Pond waters are highly concentrated with solutes, up to 324 g/l, consisting mainly of halite. This is compatible with flood water chemistry, but not with the brine aquifer mentioned above (Frumkin, in press, a). Both dissolution and precipitation features are observed on walls bordering ponds, as well as on cave walls where ponds have dried out.

Horizontal notches indicate levels of aggressive water temporarily diluting the pond during floods. A horizontal notch is typically 10-20 cm deep (Figs. 12, 13D), consisting of a flat corrosion bevel above a sloping sidewall (facet of Kempe et al., 1975). These features are formed where pond waters develop density gradient stratification. The upper aggressive water layer, originating from the latest flood, dissolves the cave wall. A thin film of heavy, saturated water descends gravitationally along the wall, initiating convection currents in the water. The saturated water is replaced by aggressive water moving from the center of the pond surface towards the walls (Farkas et al., 1951). Densi-

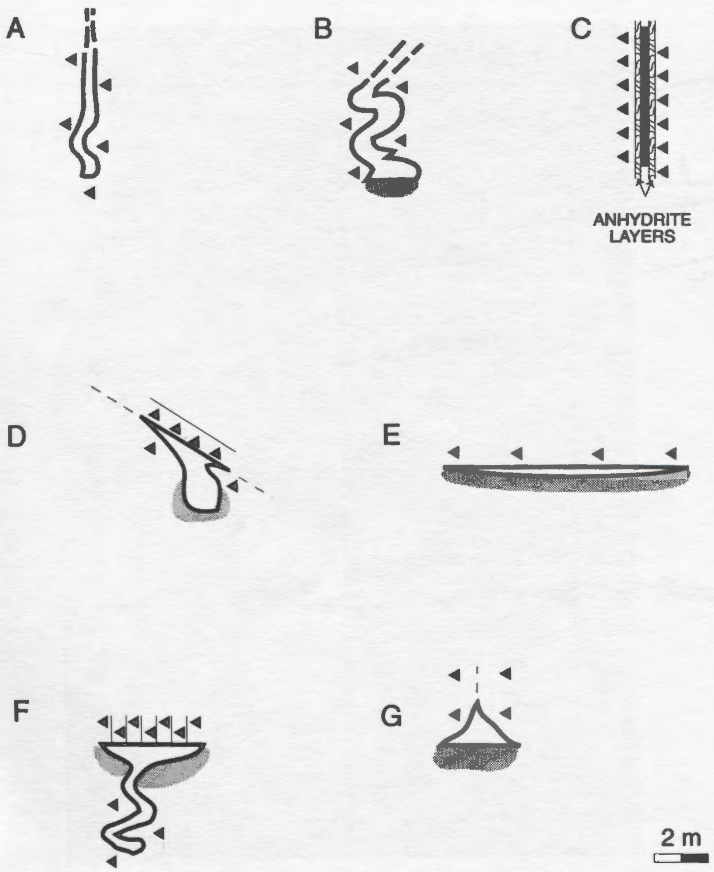


Figure 9. Cross sections of salt cave passages: (A) Young steep canyon, Lehavim Cave. (B) Mature canyon with developed meanders and alluviated channel, Zehuhit Cave. (C) Canyon constrained by anhydrite layers, Malham Cave. (D) Initial fissure widened by full pipe flow, followed by vadose downcutting, alluviation and further downcutting, Lehavim Cave. (E) Corrosion bevel formed by paragenesis is in steeply inclined salt beds, Mevokhim Cave. (F) Paragenetic passage with later vadose entrenchment, Prahim Cave. (G) Triangular cross section tapering upwards, formed under full pipe flow with high hydraulic head in a maze passage, Karbolot Cave.

ty stratification in salt water was also observed in the Dead Sea Works evaporation ponds after floods discharged fresh water into them. Similar notches with bevels and facets are observed in German gypsum caves (Pfeiffer and Hahn, 1972). Notches with bevels appear more rarely in limestone caves, e.g. in water table caves in Australia (Jennings, 1985, p. 148) and in China (Ford and Williams, 1989, p. 307). The density gradient between aggressive and saturated waters may reach ~30% in salt, ~0.2% in gypsum but only ~0.03% in limestone. It favours the development of beveled notches in the more soluble rocks, where water is more likely to reach stable stratification, rather than in limestone.

Figure 10. Meander notches and dissolution 'shelves' formed by lateral migration of meanders; upper level canyon of Lashleshet Cave.

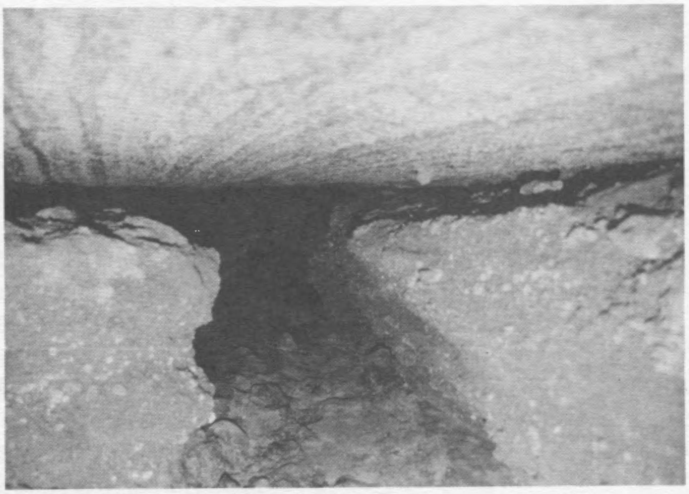


Figure 11. Corrosion bevel and alluvial sediment formed by paragensis, with later vadose entrenchment.

Large secondary halite crystals on some cave's walls indicate supersaturation of the water between successive floods (Fig. 12). The increasing solute concentration is attributed mainly to direct dissolution of rock salt. However, evaporation which is indicated by stable isotope enrichment of ponded water (Frumkin, in press, a) also increases the total dissolved solids. Temperature decrease after summer is a less important factor which may cause supersaturation and precipitation (Cigna, 1986).

Horizontal notches and secondary salt are absent in many inlet caves, indicating that residence time of the ponded water there is too short to produce these features.

Cross sections of some inlet cave passages become smaller downstream, tapering to an impenetrable point (Fig. 14). There is no lithological constraint. The flowing water is still aggressive at the end of the passage, indicating that the taper results from a

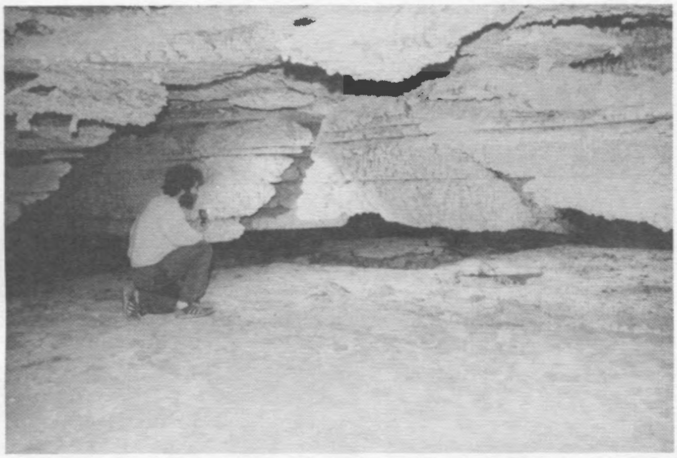


Figure 12. A dry pond at the bottom of Agam-Yavesh Cave. Horizontal notches indicate previous pond level immediately after a flood event. Salt crystals covering the wall suggest long residence time of the water in the cave.

downstream decrease of flood discharge caused by gradual infiltration along the alluviated channel. Ephemeral surface streams in arid environments also display a similar decrease of discharge downstream (Renard and Keppel, 1966). This behavior differs from most caves and fluvial systems in moist envrionments, where discharge and cross section stays constant or increases downstream (e.g. White and Deike, 1989). Limestone caves may however taper downstream during their initial phase of development because of decreasing aggressiveness (Palmer, 1991).

Tapering inlet salt caves which terminate with no signs of water ponding, indicate that all flood water infiltrates along the channel. On the other hand, there are sharp responses where only a fraction of the flood can infiltrate along the passage. Mifrazim Cave is an example. An abrupt change in passage cross section from a narrow vadose canyon (Fig. 13B-C, sections 1-4) to a wide bevelled passage (Fig. 13C, section 5) indicates the maximum level of the pond water there. This is comparable to the morphological change observed in the vadose-phreatic transition of some limestone caves (Palmer, 1984).

ELONGATED INLET CAVES

The ground plans of inlet caves suggest a range that is contained within three end members: elongated conduit, chamber and maze. Some caves display features of two or three of the end members combined. The most common form is an elongated conduit, however, consisting of one or more segments developed along fissures (Figs. 4, 13, 14). Elongation is favoured in fissured rock with low hydraulic head, under gravitational flow. The morphological features of the conduit are similar to those of integrated cave systems (discussed above), down to the uppermost pond level at the downstream end of the conduit.

CHAMBER CAVES

A homogeneous rock without open fissures gives rise to a chamber cave, whose length and width are roughly equal. Chamber caves are more common in northern Mount Sedom which is less structurally deformed than the southern part (Fig. 1), Agam-Yavesh Cave is a good example (Fig. 15). Horizontal notches and halite crystals developed across the lower walls of the chamber indicate dried up ponds (Fig. 12). Bedrock salt exposed in the walls and ceiling is massive, without insoluble layers and with few tightly closed joints. Three radiocarbon dates of wood (Frumkin et al., 1991, samples # AY1, AY4, AY6) indicate that the chamber began to develop in its upper southeastern corner, gradually expanding downwards and westwards during the last 3000 years. The westward direction of water flow and cave development is preferred because of the bedding dip (Fig. 15A). Long lived ponds occurred in this cave only during the last few hundred years.

Other chamber caves in northern Mount Sedom exhibit more complex shapes, reflecting local structure and lithology. Large collapse dolines in the same area are probably remnants of similar chamber caves.

Chamber caves are comparable to solution-mined artificial cavities. If aggressive water is artificially introduced to a depth where rock salt joints are tight, then a roughly cylindrical chamber of 100,000 m^3 may be excavated in few hundreds days (Saberian, 1983). In the artificial case the resulting salt water is extracted from the cavity by pumping, whereas in natural caves the water escapes by infiltration.

FLOOD WATER NETWORK MAZES

High fissure frequency with a considerable hydraulic head applied by flash floods favour the development of network mazes. Karbolot Cave, having the largest catchment among inlet caves and extensive fissure system is an example (Fig.16). Infrequent large floods have submerged most of the cave for short periods during the recent centuries, as indicated by surge marks, clay deposits and wood twigs, dated to 480 (conventional ^{14}C) years BP (Frumkin et al., 1991, sample #Ka1). The maze passages developed mainly along two interconnected dense fissure systems, perpendicular to each other. The fissures probably originated by pressure release of the rising diapir. Passages scarcely developed along the fault plains as these are sealed by clay. The passage cross section is typically triangular, with a ceiling tapering upwards into a fissure, and a floor covered with alluvium (Fig. 9G). The salt network maze is similar to flood water mazes described in limestone caves (Palmer, 1975).

LONGITUDINAL PROFILE

Thirty-six alluviated salt cave systems slope asymptotically towards base level. Perching on an insoluble bed near the cave

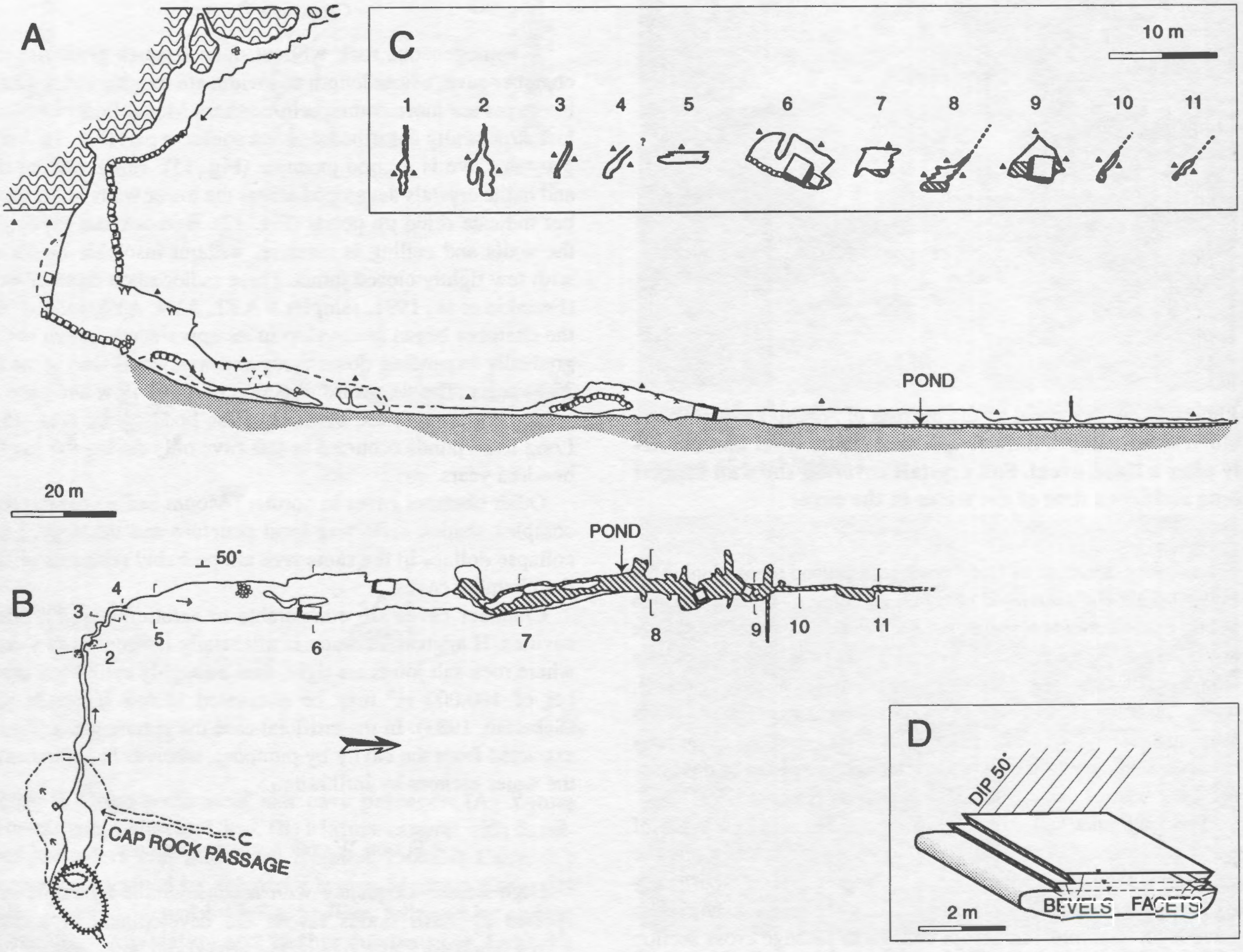


Figure 13. Mifrazim Cave. (A) Profile with 1987 level of flood water pond. (B) Map. (C) Cross sections. (D) Isometric view of the passage at section 5, showing dissolution features with correspondent water levels. The rock salt passage may be divided to three segments: sections 1-4—vadose canyon; sections 5-9—passage widened by pond water; section 10-1—passage tapers where aggressive water hardly arrives.

outlet was observed in five caves. It is readily recognized by an abrupt change in gradient because the beds are sub-vertical. Young unequilibrated passages downcut in the salt until they reach the minimal gradient allowing transportation of their coarse sediment load. The active alluviated channels are apparently adjusted to the present base level of erosion with a profile below which the channel cannot degrade and at which neither net erosion nor deposition occurs (Barrel, 1917). The downcutting process prior to reaching equilibrium may take some hundred years up to few thousand years for the measured downcutting rates of ~1cm/year (Frumkin and Ford, in press). The equilibrium profile is a time-independent configuration, maintained as long as boundary conditions do not change. However, Mount Sedom boundary conditions such as base level elevation do change rapidly. The adjustments of cave profiles to such changes result in multi-phase cave systems in which each storey may have reached an equilibrium state while active. The inactive storeys may be used to reconstruct base level changes. Palmer (1987) suggested using limestone cave levels in a similar way for cases where the piezometric limit can be observed. The high modification rate of salt cave systems suggests that they can yield a much higher temporal resolution. Figure 17 presents a model for profile evolution in a multi-phase salt cave system. For simplification, a cap rock passage was omitted and conduits are represented by straight lines instead of exponential lines. Most integrated cave systems originate as inlet caves, created by a capture of subaerial channel into a cap rock fissure (Fig. 17A).

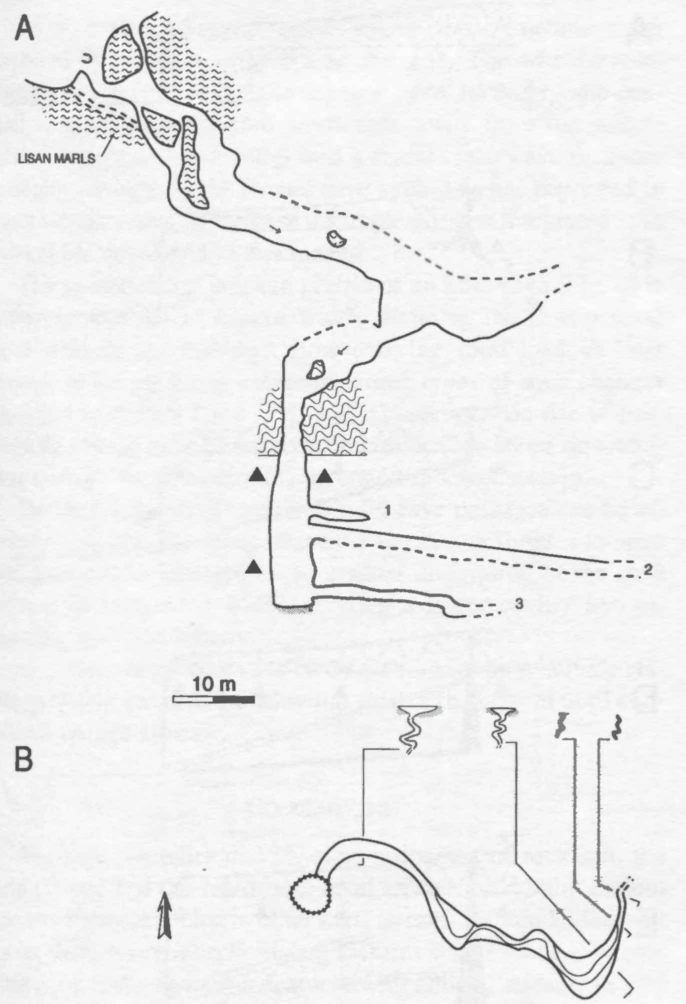


Figure 14. Prahim Cave. (A) Profile showing upper levels in Lisan Marls and cap rock, and three stories of salt passages extending from the shaft. (B) Map and cross sections of salt passage #2.

Diversionary routes are common where earlier conduits are blocked by alluvium, until a conduit connects to an output point and a stable condition is achieved in ground plan (Figs. 8, 17B). If a connection to the output boundary is not established, the cave continues to evolve as an inlet cave. The earliest integrated flow route can be traced along the highest level of some caves in the form of a fissure widened by dissolution (Fig. 9D). Early conduits often follow the shortest route available along the vertical fissure from input to output (Fig. 17C). Consequent downcutting adjusts the profile to base level (Fig. 17D). A change of boundary conditions such as Dead Sea level or diapir uplift is followed by downcutting (Fig. 17E) or paragenesis (Fig. 17F), maintaining grade with the changing base level. This model is comparable to the vadose theories for the development of limestone caves (Warwick, 1953).

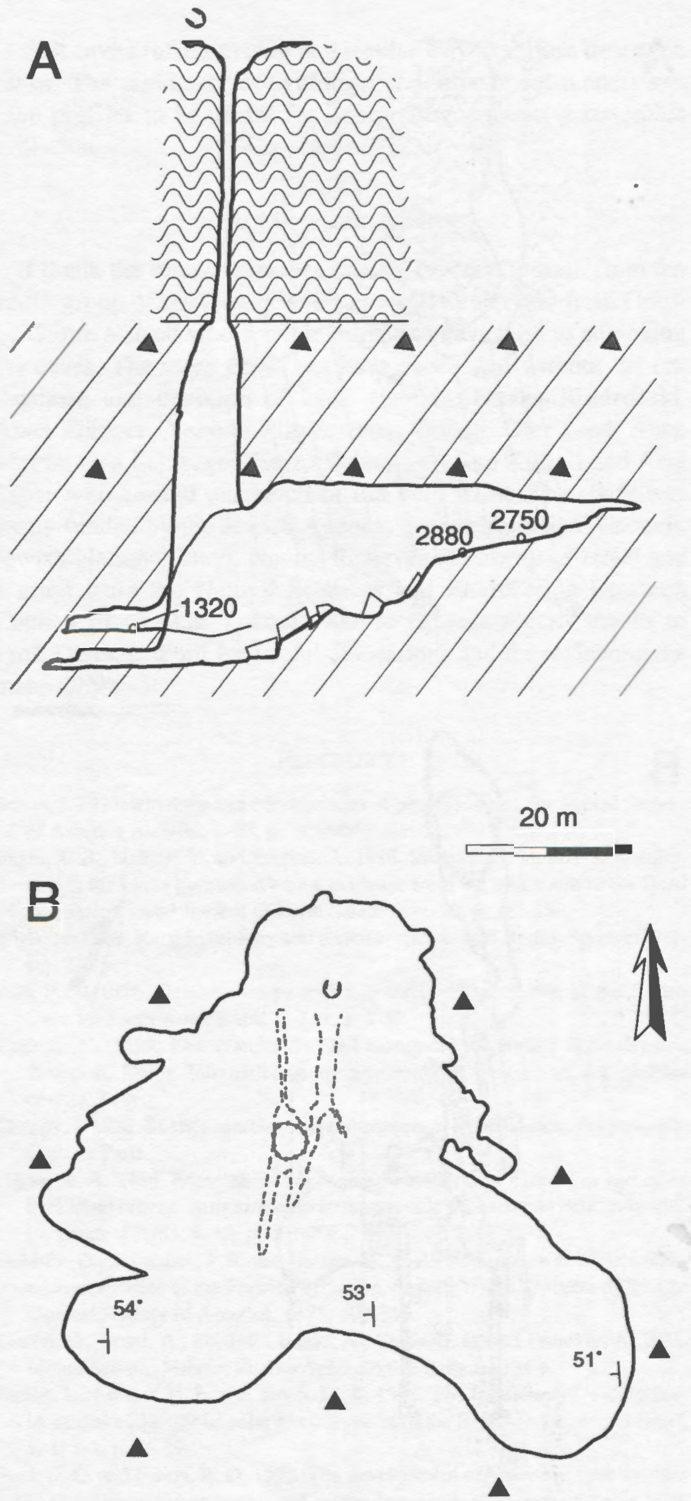
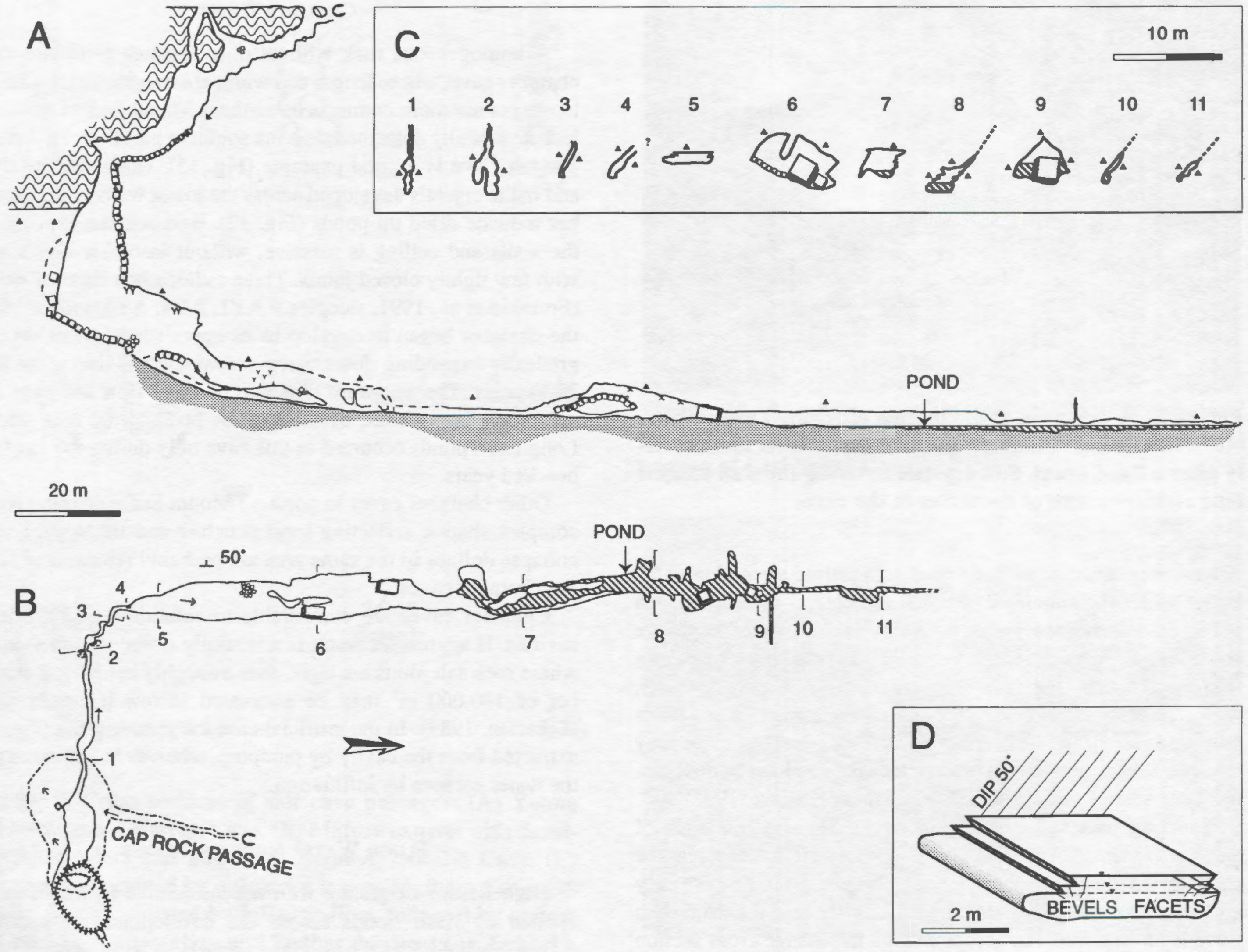


Figure 15. Agam-Yavesh Cave—a typical chamber cave. (A) Vertical section (B) Map. Conventional radiocarbon dates (years BP) of wood fragments are given. The lower western portion contains dry pond features (Fig. 12).



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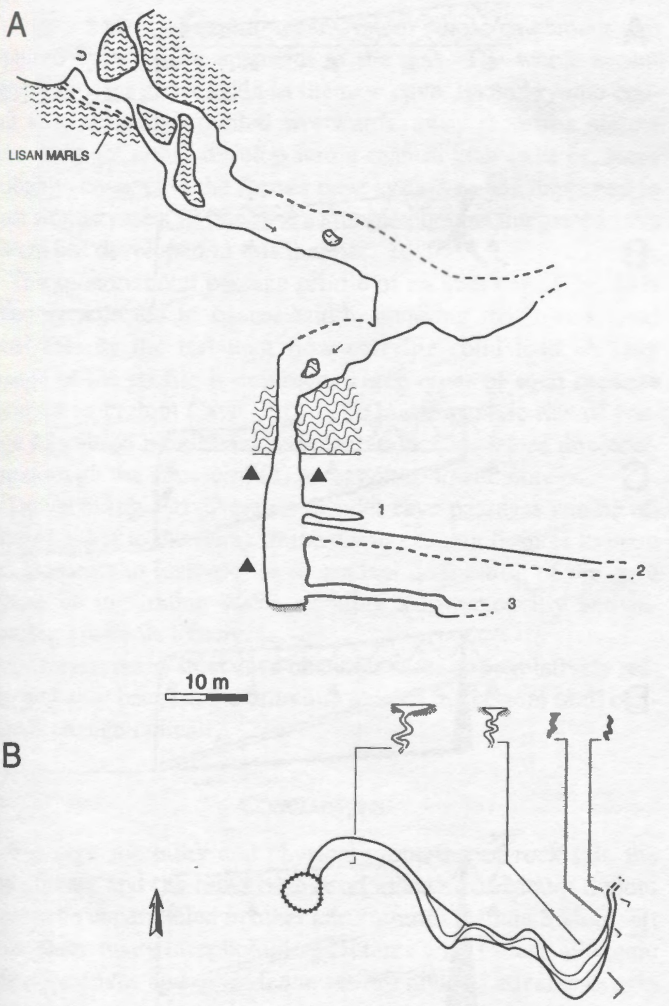

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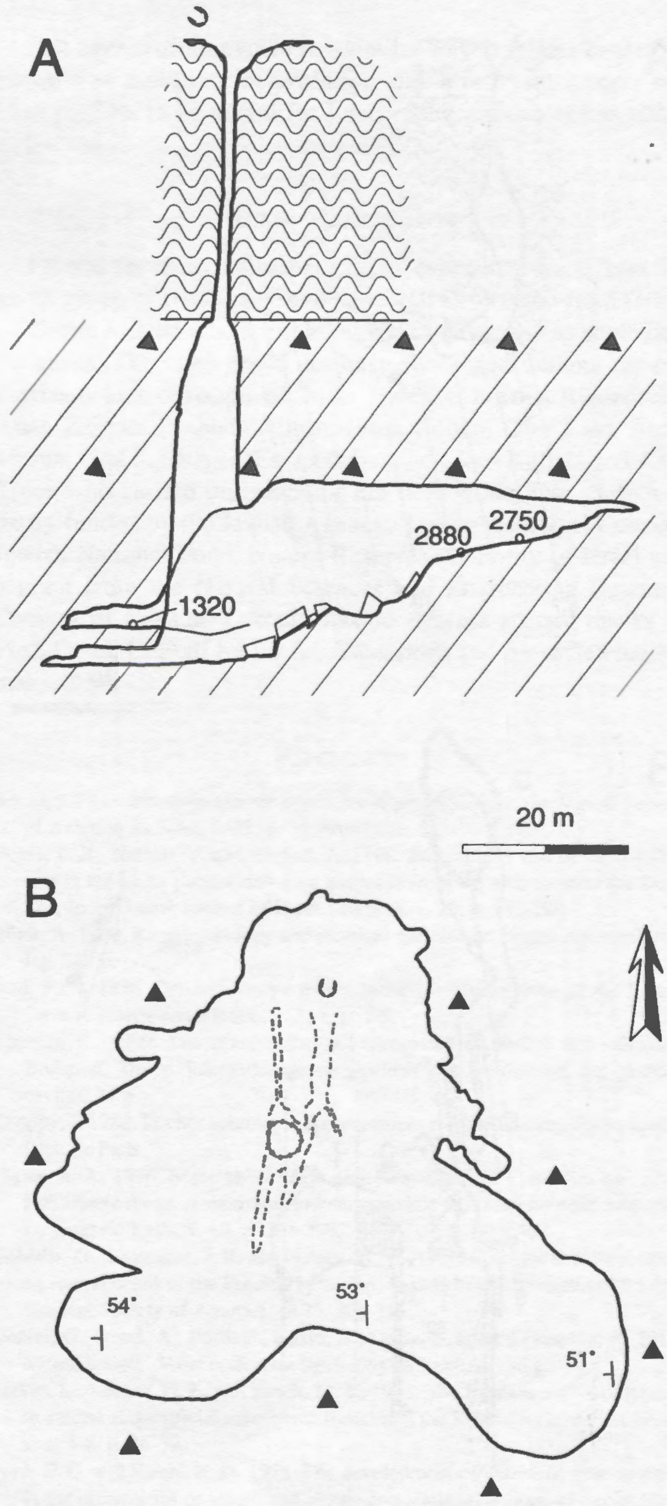

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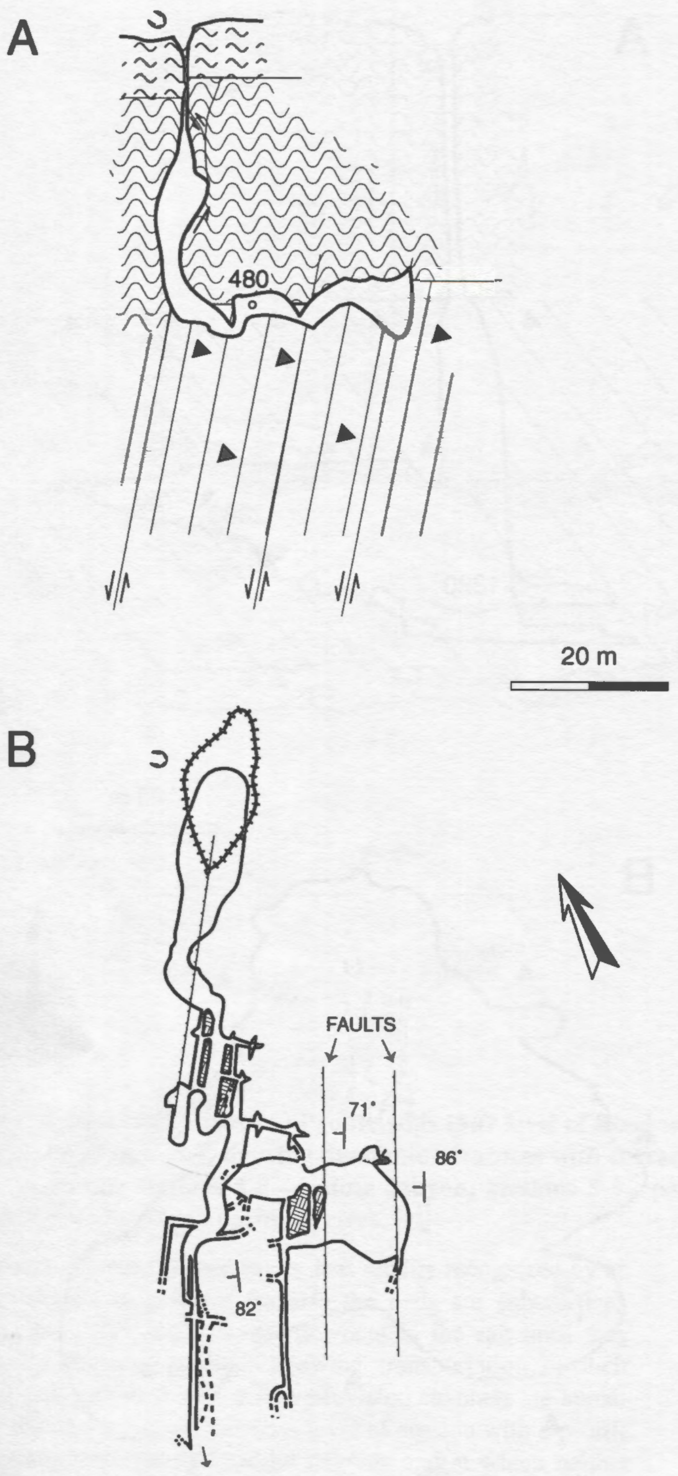

Figure 16. A network maze at the northern end of Karbolot Cave. (A) Vertical section; (B) Map. Radiocarbon dated twig (480 years BP) indicates development during recent centuries.

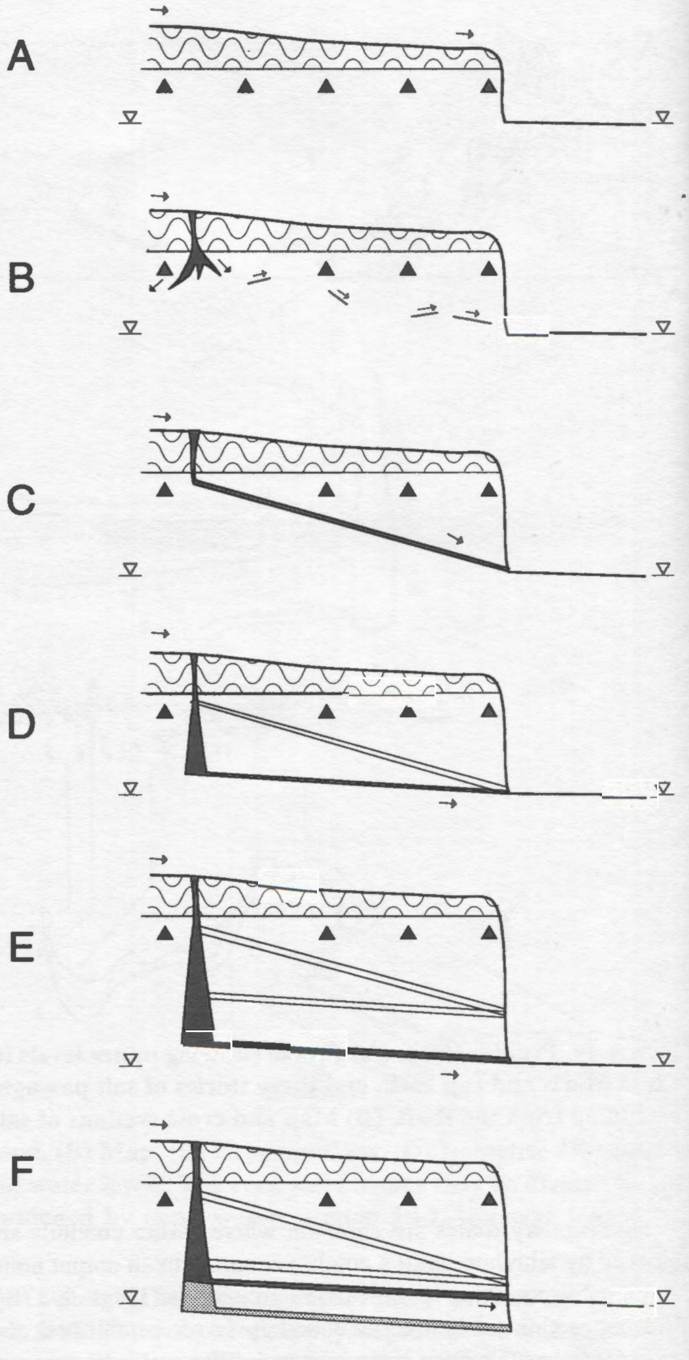

Figure 17. A model for the evolution of a cave system profile. (A) Subaerial channel. (B) A capture into cap rock fissure forms an inlet cave. (C) Input-output connection established. (D) Profile graded to base level. (E) Lowering of base level invokes further downcutting. (F) Base level rising causes paragenesis.

Figure 5 shows a mature cave system whose catchment was captured by a fissure upstream of the sink. The whole evolutionary process starts again in the new cave. Its embryonic conduit is structurally oriented westwards, away from the mature cave. It might either develop into a mature inlet cave or, more probably, connect to the former cave system as has happened in most similar cases. In one case a completely new integrated cave system has developed in this manner.

The subhorizontal passage profile of an inlet cave (Fig. 4) is probably adjusted to fissure width, attaining the lowest level penetrable by the turbulent flow carrying solid load. A later change of the profile is common. Three types of such changes occurred in Prahim Cave (Fig. 14): (1) paragenetic rise of passage #2 caused by alluvial sedimentation; (2) vadose downcutting through the alluvium; (3) diversion to lower storeys.

Downcutting and diversion of inlet cave passages can be attributed either to the rising of the diapir causing fissures to open and gradients to increase, or to gradual dissolution of the cave bottom by infiltrating water, creating a lower cavitiy and increasing gradients locally.

However, many inlet cave channels seem to be relatively stable, probably because the alluvium shields the bottom until conditions change radically.

CONCLUSIONS

The high solubility and physical properites of rock salt, the arid climate and the rapid base level changes of Mount Sedom seem to be unparalleled in other karst terrains. Mount Sedom salt caves share many morphological features with vadose allogenic limestone caves and other features with alluvial streams in arid terrains.

The salt caves of Mount Sedom formed under seemingly contradictory conditions. The arid climate has favoured the rising of a large salt mass above base level without its being dissolved completely. The high solubility and dissolution rate of salt, together with the allogenic nature of recharge and the sporadic intense rains focus an immense dissolution energy along the flood routes. One result is the development of large inlet caves without being integrated to an output. The long interval between successive floods is important, allowing the water enough time to seep slowly to base level. Local rock structure determines the cave patterns, ranging from chamber caves in homogeneous, nonfissured rock, to elongated conduits and mazes in fissured rocks. Hydraulic conductivity and head determine the residence time of flood water in caves and whether interlinked fissures are widened to form a maze. Integrated cave systems are the common end member under high conductivity conditions.

Salt caves appear to be the fastest evolving karst caves (excluding ice cavities). Radiocarbon dates show that a salt cave or a single cave level develops to accessible dimensions in a mere few hundred years (Frumkin and Ford, in press), compared to ≥10,000 years in limestone (Mylroie and Carew, 1987).

Salt cave profiles evolve in a similar way to vadose limestone caves. The rapid rate of evolution and adjustment renders salt cave profiles to be useful for interpreting regional geomorphic evolution.

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REFERENCES

Barrel, J. 1917. Rhythms and measurement of geologic time: Geological Society of America Bulletin, v. 28, p. 745-904.

Begin, Z. B., Nathan, Y. and Ehrlich, A. 1980. Stratigraphy and facies distribution in the Lisan Formation—new evidence from the area south of the Dead Sea, Israel: Israel Journal of Earth Sciences, v. 29, p. 182-189.

Bögli, A. 1980. Karst hydrology and physical speleology: Berlin, Springer-Verlag, 284 p.

Bull, P. A. 1976. Dendritic surge marks in caves: Transactions of the British Cave Research Association, v. 3, 1, p. 1-5.

Chabert, C. 1989. Les grandes cavites mondiales en roches non-calcaires: Badapest, Union Internationale de Speleologie-Commission des grandes cavites, 34 p.

Choppy, J. 1988. Roches solubles non carbonatees et karstification: Paris, Spéléo Club de Paris.

Cigna, A. A. 1986. Some remarks on phase equilibria of evaporites and other karstifiable rocks: Attis simposio internazionale sul carsismo nelle evaporiti; Le Grotte d'Italia, v. 12, p. 201-208.

DeMille, G., Shouldice, J. R. and Nelson, H. W. 1964. Collapse structures related to evaporites of the Prairie Formation, Saskatchewan: Bulletin of the Geological Society of America, v. 75, 307-316.

Donini, G., Rossi, A., Forti, P., Buzio, A., Calandri, G. and Frumkin, A. 1985. Monte Sedom: Milano, Societa Speleologica Italiana, 135 p.

Farkas, L., Litman, H. L. and Bloch, M. R. 1951. The formation of "salt tables" in natural and artificial solar pans: Bulletin of the Research Council of Israel, v. 1, 1-2, p. 36-39.

Ford, D. C. and Ewers, R. O. 1978. The development of limestone cave systems in the dimensions of length and depth: International Journal of Speleology, v. 10, p. 213-244.

Ford, D. C. and Williams, P. W. 1989. Karst geomorphology and hydrology: London, Unwin Hyman, 601 p.

Frumkin, A. 1982. Formation of potholes and caves in rock salt, Mount Sedom (in Hebrew, English abstract): Niqrot Zurim, Journal of the Israel Cave Research Center, v. 6, p. 15-38.

Frumkin, A. 1986. The cave survey of Mont Sedom, Israel: Atti simposio internazionale sul carsismo nelle evaporiti; Le Grotte d'Italia, v. 12, p. 305-308.

Frumkin, A. 1992. The karst system of the Mount Sedom salt diapir: PhD dissertation (in Hebrew, English abstract), Jerusalem, The Hebrew University, 135 p.

Frumkin, A. in press a. Hydrology and solutional denudation rates of halite karst: Journal of Hydrology, in press.

Frumkin, A. in press b. The Holocene history of the Dead Sea levels in Ben-Avraham, Z., Gat, Y. and Niemi, T. M. eds., The Dead Sea—a summary of recent research. In press: Tel Aviv, Oxford University Press and Tel Aviv University.

Frumkin, A. and Ford, D. C. in press. Rapid entrenchment of stream profiles in the salt caves of Mount Sedom, Israel: Earth Surface Processes and Landforms, in press.

Frumkin, A., Magaritz, M., Carmi, I. and Zak, I. 1991. The Holocene climatic record of the salt caves of Mount Sedom, Israel: The Holocene, v. 1, 3, p. 191-200.

Garfunkel, Z., Zak, I. and Freund, R. 1981. Active faulting in the Dead Sea rift: Tectonophysics, v. 80, 1, p. 81-108.

Gerson, R. and Inbar, M. 1974. The field study program of the Jerusalem-Elat symposium, 1974. Reviews and summaries of Israeli research projects: Zeitschrift für Geomorphologie Supplementband, v. 20, p. 7-11.

Jakucs, L. 1977. Morphogenetics of karst regions: Budapest, Akademiai Kiado, 284 p.

Jennings, J. N. 1985. Karst geomorphology: Oxford, Basil Blackwell, 292 p.

Kempe, S., Brandt, A., Seeger, M. and Vladi, F. 1975. "Facetten" and "Laugdecken," the typical morphological elements of caves developing in standing water: Annales de Spéléologie, v. 30, 4, p. 705-708.

Mylroie, J. E. and Carew, J. L. 1987. Field evidence of the minimum time for speleogenesis: NSS Bulletin, v. 49, p. 67-72.

Neev, D. and Hall, J. K. 1979. Geophysical investigations in the Dead Sea: Sedimentary Geology, v. 23, p. 209-238.

Palmer, A. N. 1975. The origin of maze caves: NSS Bulletin, v. 37, 3, p. 56-76.

Palmer, A. N. 1984. Geomorphic interpretation of karst features, in LaFleur, R. G., eds., Groundwater as a geomorphic agent: Boston, Allen & Unwin, p. 173-209.

Palmer, A. N. 1987. Cave levels and their interpretation: NSS Bulletin, v. 49, p. 50-66.

Palmer, A. N. 1991. Origin and morphology of limestone caves: Geological Society of America Bulletin, v. 103, p. 1-21.

Petroleum Services. 1979. Solution mined liquid hydrocarbon storage caverns, Mount Sedom, Progress Report 2: Tel Aviv, Petroleum Services Ltd., 12 p.

Pfeiffer, D. and Hahn, J. 1972. Karst of Germany, in Herak, M. and Stringfield, V. T., eds., Karst—important karst regions of the northern hemisphere: Amsterdam, Elsevier, p. 189-223.

Ponta, G. 1986. The evaporite karst of Romania: Atti simposio internazionale sul carsismo nelle evaporiti; Le Grotte d'Italia, v. 12, p. 407-415.

Quinlan, J. F., Smith, A. R. and Johnson, K. S. 1986. Gypsum karst and salt karst of the United States: Atti simposio internazionale sul carsismo nelle evaporiti; Le Grotte d'Italia, v. 12, p. 419-420.

Renard, K. G. and Keppel, R. V. 1966. Hydrographs of ephemeral streams in the Southwest: Proceedings of the American Society of Civil Engineers, v. 92, p. 33-52.

Renault, P. 1967. Le problem de las speleogenese: Annales de Speleologie, v. 22, p. 5-21.

Saberian, A. 1983. Utilization of leaching models in the design of large crude oil storage cavities, in Schreiber, B. C. and Harner, H. L., eds., Sixth International Symposium on Salt, v. 2: Alexandria, Virginia, The Salt Institute, p. 235-348.

Shaw, T. R. 1979. History of cave science: Crymych, Oldham, 490 p.

Sweeting, M. M. 1972. Karst Landforms: London, Macmillan.

Vroman, J. 1950-1. The movement and solution of salt bodies as applied to Mount Sedom: Israel Exploration Journal, v. 14, p. 185-193.

Warwick, G. T. 1953. The origin of limestone caves, in Cullingford, C. H. D., eds., British caving: London, Routledge & Kegan Paul, p. 41-61.

White, W. B. 1977. Role of solution kinetics in the development of karst aquifers, in Tolson, J. S. and Doyle, F. L., eds., Karst hydrogeology: 12th congress of the International Association of Hydrogeologists, p. 503-517.

White, W. B. 1988. Geomorphology and hydrology of karst terrains: New York, Oxford University Press, 464 p.

White, W. B. and Deike, G. H. 1989. Hydraulic geometry of cave passages, in White, W. B. and White, E. L., eds., Karst hydrology, concepts from the Mammoth Cave area: New York, Van Nostrand Renhold, p. 223-258.

Zak, I. and Bentor, Y. K. 1968. Some new data on the salt deposits of the Dead Sea area, Israel, Symposium on the Geology of Saline Deposits, v. Earth sciences, 7: Hannover, Unesco, p. 137-146.

Zak, I. and Freund, R. 1980. Strain measurements in eastern marginal shear zone of Mount Sedom salt diapir, Israel: The American Association of Petroleum Geologists Bulletin, v. 64, p. 568-581.

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COMPARISON OF CAVE PASSAGEWAYS WITH FRACTURE TRACES AND JOINTS IN THE BLACK HILLS REGION OF SOUTH DAKOTA

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More than a dozen major caves, including Jewel Cave and Wind Cave, are present in the Madison Limestone of the Black Hills region of South Dakota. Collectively, the Black Hills caves consist of hundreds of kilometers of cave passageways. In general, cave passageways are believed to show more or less the same orientation as that of fracture traces and joints. Keeping in mind the complex geological processes and tectonic events involved in the formation of the Black Hills and its caves, the problem of correlating caves passageways with the fracture traces, lineaments, and joints becomes a challenging task. This analysis will help to understand the structural control involved in the creation and the development of the Black Hills caves.

The study area hosts Crystal Cave and Black Hills Caverns and is flanked by Boxelder Creek to the north and Rapid Creek to the south, in the vicinity of Rapid City. Fracture trace and lineament mapping, done on aerial photographs and SPOT images, resulted in the creation of rose diagrams. Similarly, cave passageways for Crystal Cave and Black Hills Caverns were also plotted on a rose diagram. Joints were measured in the field and plotted on rosettes with 10° intervals. Because rose diagrams are good only for visual comparisons, a modified Kolmogorov-Smirnov (K-S) test was performed to statistically compare the rose diagrams. The results were then compared with other cave passageways in the Black Hills.

The degree of correlation with cave passageways was found to be the highest for fracture traces, followed by a somewhat lower degree of correlation for lineaments, and no correlation for joints. The cave passageways, fracture traces, and lineaments showed north-eastern (NE) and north-western (NW) preferred orientations, NE being more prominent. The joints showed a strong NE trend in their orientation but did not pass the statistical test of correlation. The most likely reason is that fracture traces and lineaments represent not only underlying fractures but also solution cavities formed along bedding planes, while fracture data do not include solution cavities. This observation is confirmed by a rose diagram of borehole fractures of the Madison Formation.

INTRODUCTION

"Caves are where you find them" is an expression that has often been used to rationalize the apparently anomalous location of a particular cave (Wilson, 1977). However, a combination of geologic, lithologic, hydrologic, and structural factors determine which particular zone in a mass of a soluble rock will be dissolved to form a cave.

It is a well-known phenomenon that many caves have passageways consisting of straight segments representing places where groundwater has dissolved carbonate rocks along joints or bedding planes. In the folded limestone of the Appalachian region, Davies (1960) found that most cave passageways were largely oriented along the joints. Howard (1964) found that "... only those original fractures in limestone which are widest and which have high hydraulic gradient will have enlarged cave passageways." For the caves located in the gently dipping rocks of the central Kentucky area, Deike (1968) observed that the majority of the cave passageways are not fracture-controlled. Barlow and Ogden (1982) did not find any correlation between the cave passageways and the joints for caves in Benton County, Arkansas.

Prominent joints and fractures can be mapped accurately on the terrain only if bare rock is exposed. Moreover, joints are well developed only in massive, competent strata. Fracture traces are believed to be the surface expression of underground jointed zones of rocks and are defined as "natural linear traces, consisting of topographic (including straight stream segments), vegetation, or soil tonal alignments, visible primarily on aerial photographs." While fracture traces are less than a mile long, lineaments are more than one mile, and can extend continuously or discontinuously to many miles (Lattman, 1958). Fracture traces and lineaments have been successfully mapped on aerial photographs and Landsat images. The correlation of fracture traces with cave passageways, and interpretation of results, however, needs prior knowledge of the geologic history of the area.

GEOLOGIC SETTING

The major caves of the Black Hills are located in the Madison Formation of early Mississippian age, which varies in thickness from 90 m at Wind Cave in the south to more than 180 m in the northern part of the Black Hills (Rahn and Gries, 1973). The Madison is underlain by 10 to 20 m of shaly, dolomitic Englewood Limestone and overlain by 110 to 260 m thick Minnelusa Formation. The Minnelusa is mainly sandstone and shale with interbeds of limestone and dolomite (Rahn, 1987) and forms a moderately permeable cap that transmits groundwater recharge to, and discharge from, the underlying Madison (Palmer and Palmer, 1989). The overlaying detrital sedimentary rocks present elsewhere have been removed from the area of the caves by erosion.

Figure 1 is the stratigraphic column of the Paleozoic and Mesozoic strata in the Black Hills. In the area of Jewel and Wind caves, the Madison Formation consists of three distinct units of nearly equal thickness. The upper unit is a massive, fossiliferous limestone containing local breccia. The upper contact of this limestone is a highly irregular karst surface of Late Mississippian age, with paleo-caves and fissures. Many of these paleo-caves have narrow, irregular tubes going upwards to the base of the Minnelusa. The middle unit is dominated by dolomitic limestone and dolomite with less common karstification. The lowest unit consists of massive, fractured dolomite without any significant signs of paleo-karstification.

The Madison Formation was deposited under shallow water conditions that prevailed in the area during Mississippian time. Shoaling conditions, reef building, and low lying islands were common. The lagoonal areas acted as an evaporating basin in which gypsum and anhydrite formed and became incorporated into the limy sediments (Back et al., 1983).

Before the Madison was buried under Pennsylvanian sediment, it experienced a change from salt water to fresh water conditions as the area gradually and intermittently emerged above sea level (Palmer and Palmer, 1989). Saline groundwater was slowly displaced by fresh water. This change undermined the stability of gypsum and anhydrite, formed caves, and disrupted the surrounding rock. The hydration of anhydrite to gypsum results in a volume increase of as much as 30%. This increase in volume might have resulted in the fracturing and brecciation of upper and lower units of the Madison Formation.

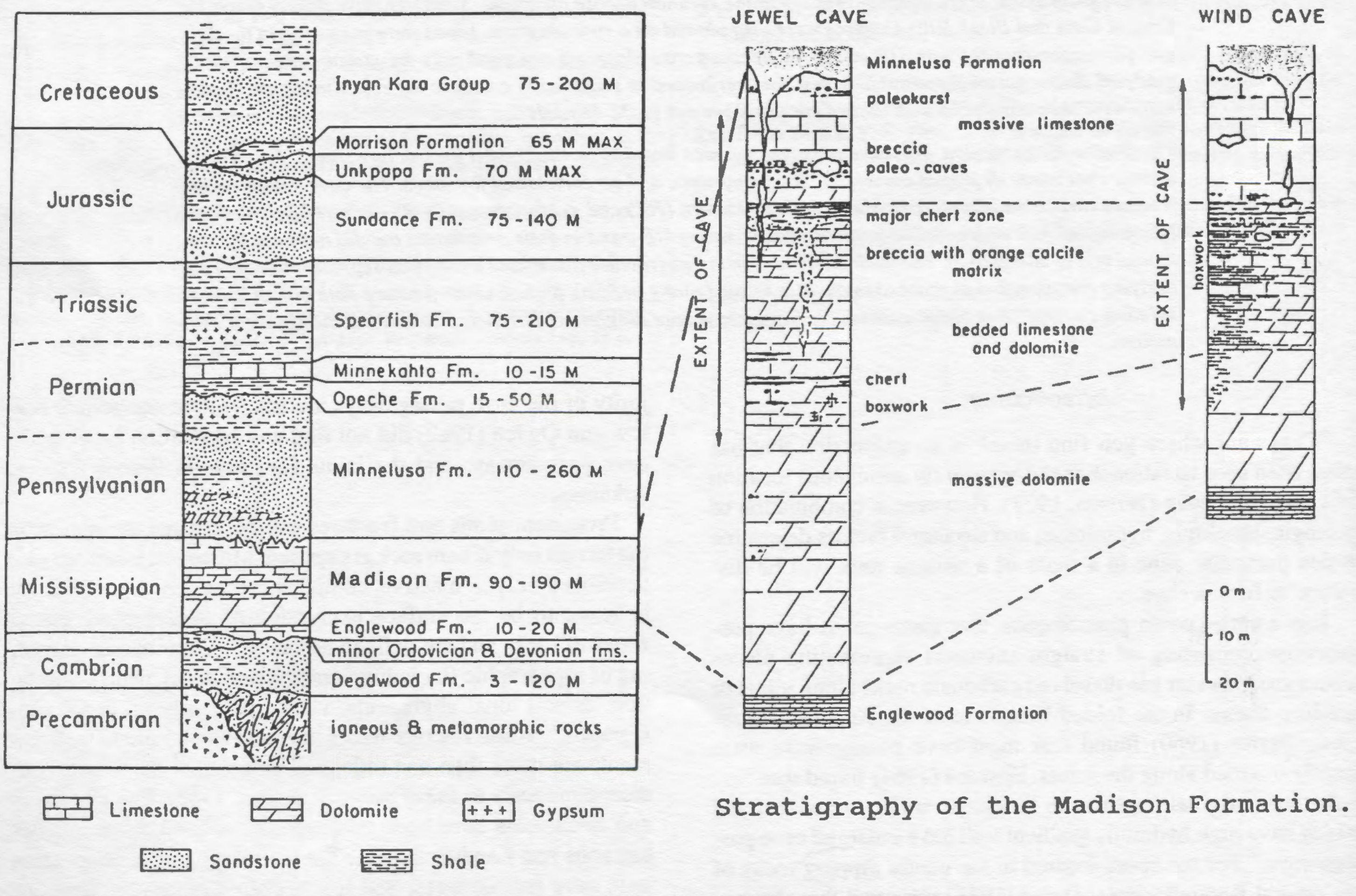

Figure 1. Paleozoic and Mesozoic strata exposed in the Black Hills (Modified from Palmer and Palmer, 1989).

The Black Hills were formed by a block-like, domal uplift during the Laramide orogeny about 60-70 million years ago. The uplift is asymmetrical, dipping steeply (20°-30°) to the east and gently (5°) to the west. The uplift breached the Opeche Formation and allowed meteoric groundwater to enter the Minnelusa and the underlying Madison for the first time in 250 million years (Deal, 1962). The circulation of solutionally aggressive water in the exposed Madison resulted in the major phase of cave development. The shape of the present cave passageways indicates that water dissolved limestone and dolomite at comparable rates. Prominent chert layers in the Madison served as dissolution barriers and resulted in the multi-story structure of the Black Hills caves (Ford, 1989).

Location of the Study Area

The study area is located in the Black Hills and is bounded by Boxelder Creek to the north and by Rapid Creek to the south, in the vicinity of Rapid City, South Dakota (Fig. 2). The area is underlain by the Madison and Minnelusa Formations. Almost all the known caves of the Black Hills region are located in the Madison. The overlying Minnelusa Formation is hydraulically connected to the Madison. Black Hills Caverns and Crystal Caves are present within the study area. The geological map of the study area does not show any major faults, but two anticlinal structures are present north of the area. The strata dip gently (<15°) towards east, which is also, more or less, the present groundwater flow direction (Rahn, 1992). The study area covers an area of 96 km^2.

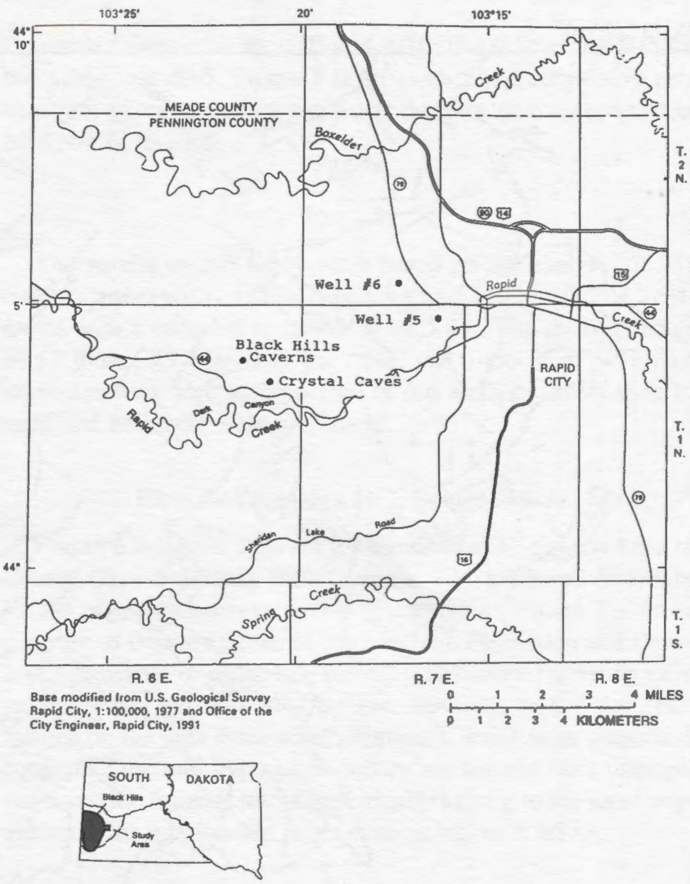

Figure 2. Location of the Study Area.

Procedures

The length and orientation of each passageway for Crystal Cave and Black Hills Caverns was measured directly on cave passageways maps. Keeping in mind the asymmetrical nature of the Black Hills uplift, it was thought prudent to consider the passageways orientation of only Crystal Cave and Black Hills Caverns. The study area is considered to be structurally homogenous. The orientation of cave passageways was then grouped into 18 classes of 10° each.

The fracture trace map (Fig. 3) was prepared by first delineating the study area on topographic sheets (Rapid City West and Pactola Dam) at 1:24,000 scale. The geological boundaries for the Minnelusa as well as Madison formations were then transferred from published geological maps. A preliminary geological map prepared by Dr. Jack Redden, of South Dakota School of Mines, was used to delineate the western boundaries of the study area. Aerial photographs at 1:24,000 scale were then used to trace fractures for the study area. This scale of aerial photography was preferred to other scales because of the ease of transferring the fracture traces to the geological map of the same scale. Fracture trace mapping was performed with the technique developed by Lattman (1958). The fractures were traced on mylar overlays after carefully examining stereo-pairs one by one using 2.5 power lens pocket stereoscope, under reflected light. To prevent bias in tracing of fractures in the area adjacent to the area already traced, the tracing was done intermittently and the locations for tracing fractures were constantly changed. In order to remove the effect of photogrammetric error, an effort was made to confine the fracture tracing to the central part of the photograph.

Different images of the project area were studied in order to trace lineaments. They included black and white aerial photographs, a color aerial photo-mosaic, infra-red Landsat images, and black and white SPOT images. Because lineaments were defined as the fracture traces which are longer than one mile, it was thought necessary to use an aerial photo-mosaic instead of individual photographs for tracing the lineaments A color aerial photo mosaic, mounted on cardboard, was obtained from Horizons Surveying Inc. of Rapid City. Lineaments were first traced on a mylar overlay and then transferred to a base map of the project area. However, it was soon realized that the scale of the photo-mosaic (1:24,000) might show a bias towards already traced fractures vs. lineaments; hence this exercise was abandoned. As compared to infra-red Landsat, black and white SPOT images were selected because of their high resolution and clari-

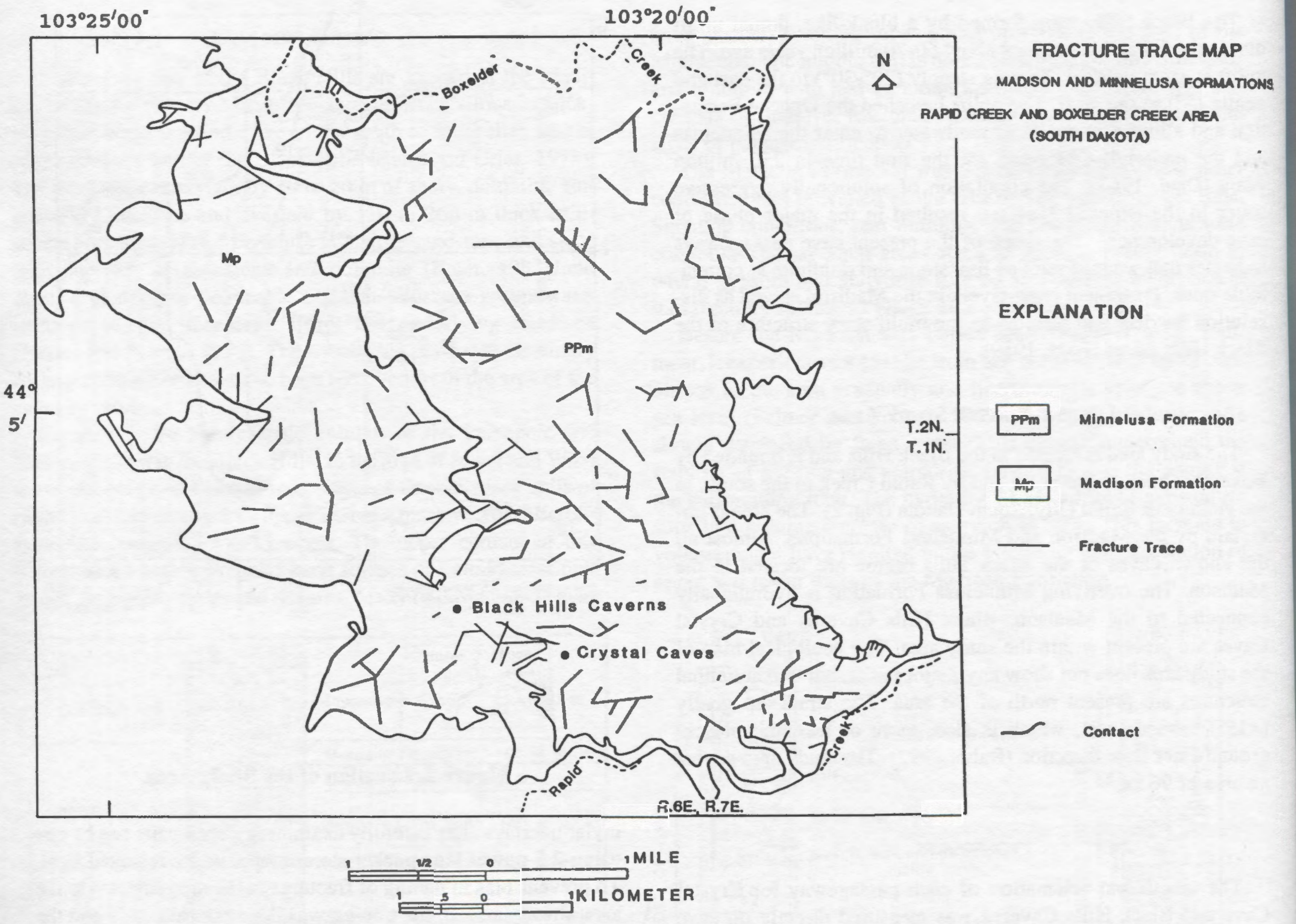

Figure 3.

ty. A stereo-pair of the SPOT images was obtained from the EROS Data Center, Sioux Falls, South Dakota. The look angle for these images was 2.9° to the left and 25.1° to the right. The scale of the SPOT images is 1:300,000. Figure 4 is an enlarged lineament map for the study area based on the SPOT images.

A detailed joint survey was conducted in the Madison Formation during which joints orientations were measured with a Brunton compass at selected locations. Natural exposures along Boxelder Creek and Rapid Creek were selected for this purpose. The joints were also measured along road cuts (State Route 44 and 79), passing through the study area. All joints were vertical or nearly vertical.

STATISTICAL METHODS

For the statistical comparison of the rose diagrams, a comparative study was made to select the proper statistical test for the collected data. The tests considered for this purpose were:

1) Chi-square test, and
2) Kolmogorov-Smirnov (K-S) test.

The Chi-square test and the K-S test have been used to compare rose diagrams (Rueb, 1984; Barlow and Ogden, 1982). The K-S test treats individual observations separately and thus, unlike the Chi-square test, does not lose information through the combining of categories. Moreover, for very small samples, a Chi-square test is not applicable but the K-S test is. Based on this, Siegel (1956) suggested that the K-S test is more powerful than its alternative, the Chi-square test.

Kolmogorov-Smirnov (K-S) Test

The K-S two-sample test is a test of whether two independent samples were dawn from the same population (or from a population with the same distribution). The two-tailed K-S test is sensitive to any kind of difference in distributions from which the

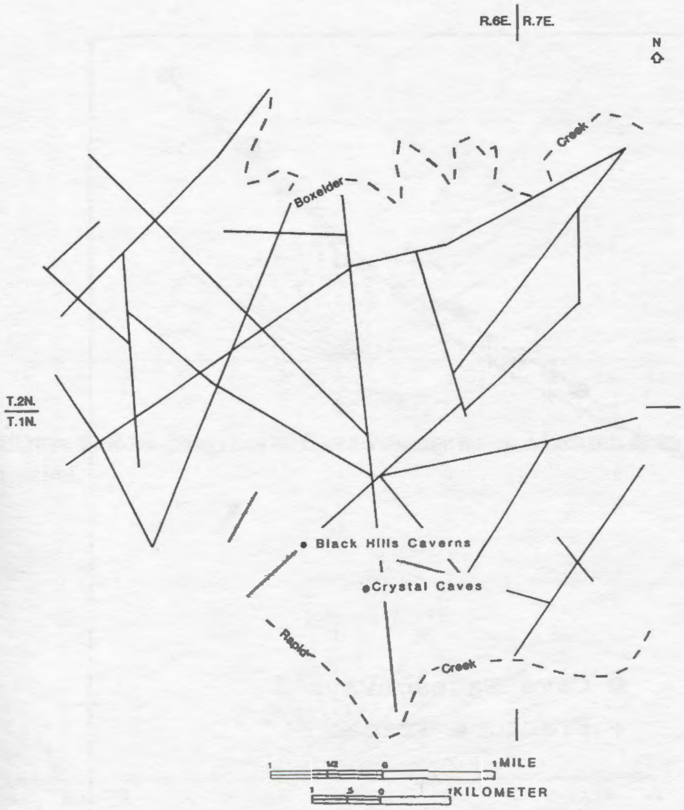

Figure 4. Lineament Map of the Study Area.

two samples were drawn. The test is concerned with the agreement between two cumulative distributions of two sets of sample values.

If the two samples have in fact been drawn from the same population, then the cumulative distributions of both samples may be expected to be fairly close to each other. If the cumulative distributions are too far apart at any point, then there is an evidence for rejecting the null hypothesis. The null hypothesis states that the sets of data being compared are from the same population.

For statistical comparison, a modified (Kuiper, 1960) version of the K-S test was used. This modified version was also used for the caves and lineament data of the Arkansas area by Barlow and Ogden (1982). The modified version of the test is useful for the circular nature of data for which no true base line exists. Graphs of the cumulative percent data were constructed to compare the difference, D, between values in any two classes, i.e., 0-10° to 0-10°, etc. Because it is totally arbitrary to compare the 180° range clockwise from west to the east, it is necessary to search for the maximum D of any 180° range. This was done by repeating the 180° cumulative percent plot to include the full 360° range. The maximum D value was then compared to table values at a chosen alpha (α) level. The α level is known as significance level. If the calculated maximum D was greater than or equal to the table D value, then the null hypothesis was rejected. Common values of α are 0.05 and 0.01. The α level selected for this study was 0.05. Figure 5 is an example of cumulative percent plot of cave passageways and fracture traces observed in Madison Formation.

RESULTS

The results of this study were based on the analysis of 351 fracture traces with a cumulative length of 110 km and 24 lineaments with a cumulative length of 67.5 km. The measurements of 51 joints, 43 bore-hole fractures, and 1056 m of cave passageways were also incorporated in this analysis. More than 10 modified K-S tests were performed.

Cave Passageways vs. Fracture Traces

Figure 6 is a rose diagram for trends of cave passageways of Crystal Cave and Black Hills Caverns. Two preferred directions for the cave passageways are N40E and N60E. Figure 7 is a rose diagram of fracture traces of the Madison Formation and shows many preferred orientations, including the ones shown by cave passageways, but with slightly less intensity. A K-S test, performed on the data from which Figures 6 and 7 were generated, confirmed the null hypothesis, indicating that the cave passageways and the fracture traces statistically belong to the same population. This relationship holds even at higher α levels.

Cave Passageways vs. Lineaments

Many preferred orientations are evident on Figure 8, which is a rose diagram for the lineaments in the Madison Formation. A visual comparison with Figure 6 shows that the N60E trend is common in the two figures. The K-S test confirms the null hypothesis but the strength of the relationship is somewhat less than the cave passageways-fracture traces relationship. The relationship significantly increases by plotting the lineament data on number-weighted rose diagram rather than length-weighted. For fracture traces, the relationship remains almost the same. This behavior was due to the difference in lengths of the lineaments, which varied from as short as 1 mile to as long as 5 miles.

The fracture trace and lineament data for the Minnelusa Formation were also plotted on rose diagrams and statistically compared with the Madison Formation. Although the fracture traces and lineaments of the Minnelusa were more strongly oriented toward the NE direction than the Madison, the K-S test confirmed the null hypothesis. The strong NE trend was also observed for the joints in the Minnelusa Formation. The strong correlation between the fracture traces and the joints indicates that fracture traces are more joint-controlled in the Minnelusa Formation.

Cave Passageways vs. Joints

The preferred orientation for joints in the Madison Formation is N50E (Fig. 9), similar to the orientations of cave passageways

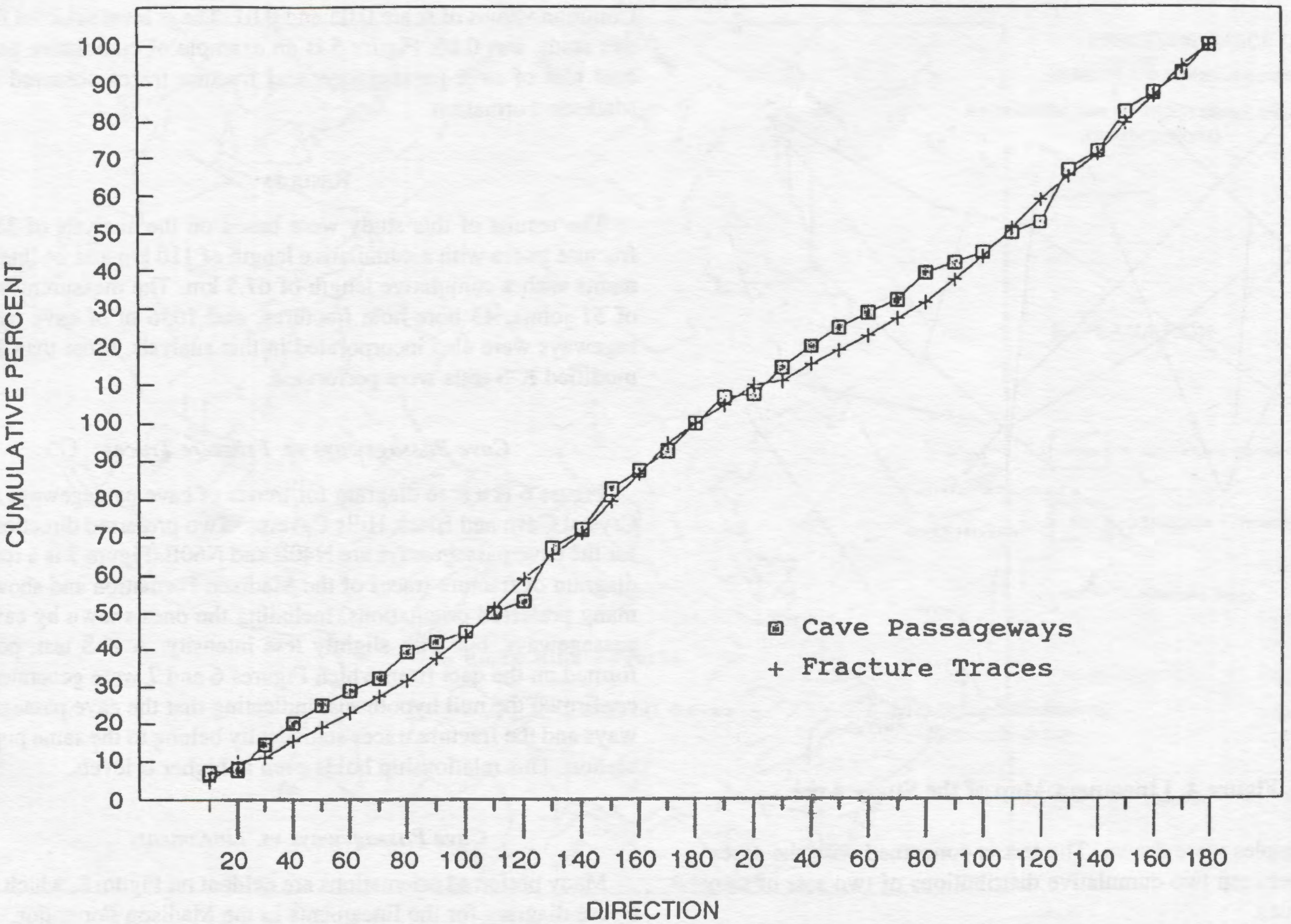

Figure 5. Cumulative Percent Plot of Cave Passageways and Fracture Traces, Madison Formation.

and the fracture traces. K-S tests performed on these data, however, do not confirm the null hypothesis. The lack of correlation of joints with cave passageways or fracture traces can be attributed to a number of reasons. Preferential solution of joints in the groundwater flow direction, difficulty in the measurement of joints, and shadows on the aerial photographs because of the high relief are considered to be the key factors for the lack of correlation for the caves passageways, present in the Rockerville quadrangle of the Black Hills area (Rahn, 1993). The clarity of aerial photographs and SPOT images, and number of exposures (man-made and natural) of the Madison Formation in the study area, rule out the possibility of error in the collected data. The formation of caves by preferential dissolution of joints is appealing but hard to verify in light of available data. We believe that Crystal Cave and Black Hills Caverns are not only oriented in the direction of joints but also along bedding planes. The fracture traces are the surficial expressions of planes of weakness and incorporate not only joints but also bedding planes, while the measured joints do not represent the bedding planes. The dissolution of the bedding planes of the Madison Formation can be seen along Boxelder Creek and borehole fracture logs.

Borehole Fractures and the Black Hills Caves

Borehole fracture data were obtained by acoustic televiewer (ATV) logs for two wells (Well #5&6) drilled in the Madison Formation. The location of those wells is shown in Figure 1. The ATV logs are used in well logging to provide an oriented image of the borehole walls. An acoustic signal is sent out from a rapidly rotating tool and the return signal is recorded on Polaroid film. The image is not a photograph but is an accurate depiction of the borehole walls based on the rate of return of the acoustic signal. A rapid return time gives a lighter image than a slow return time. The tool is magnetically oriented to record compass directions of these images. Fractures and bedding planes appear as dark sinusoidal features on the televiewer logs from which strikes and dips can be calculated.

Figure 10 is a rose diagram for borehole fractures which were observed in Well #5 and #6. The vuggy nature of most of the fractures encountered in the Madison wells made it difficult to differentiate joints from bedding planes. However, the majority of bedding planes show low dip angles that strike NE. The magnetic orientation used to measure fracture orientation was small,

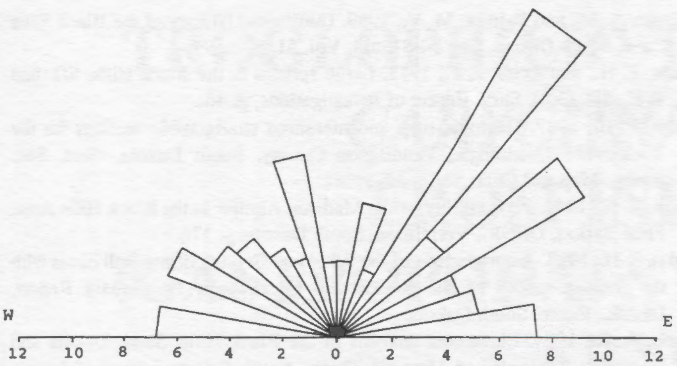

Figure 6. Rose Diagram of Cave Passageways, Madison Formation.

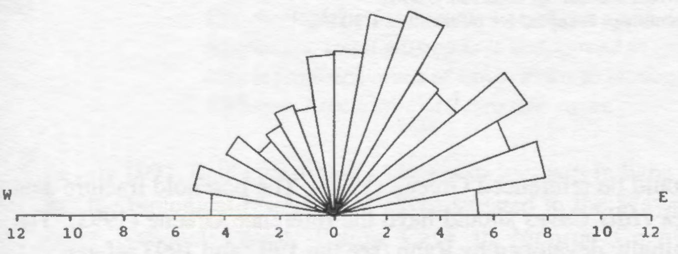

Figure 7. Rose Diagram of Fracture Traces, Madison Formation.

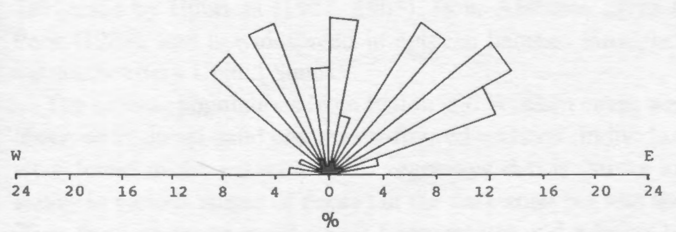

Figure 8. Rose Diagram of Lineaments, Madison Formation.

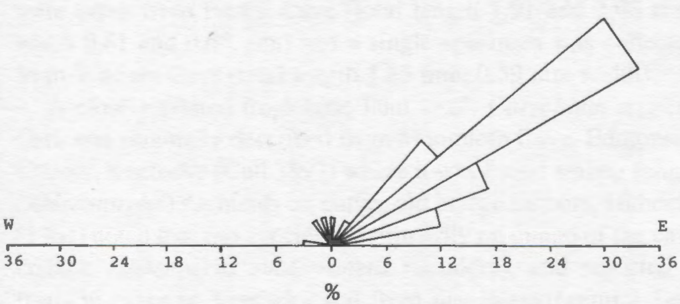

Figure 9. Rose Diagram of Joints, Madison Formation.

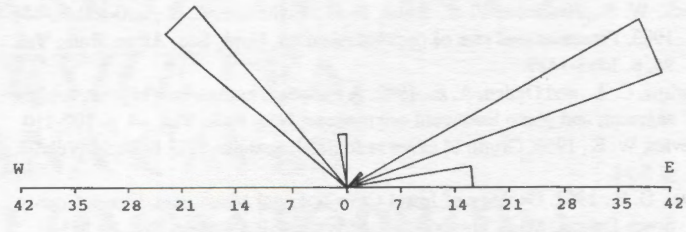

Figure 10. Rose Diagram of Bore-Hole Fractures, Madison Formation.

hence the orientation of fractures could not be measured precisely. For that reason, the orientation of fractures was calculated in 45° intervals (N, NE, E, etc.) and the data for 43 fractures were grouped into 5 classes. Bedding planes, solution openings, and vuggy zones were all considered as fractures. The angle of the dip of those fractures, as revealed by ATV logs, varied from 10° to 60°. As seen in Figure 10, two trends are prominent. We believe that the NW trend corresponds to the strike of the bedding planes whereas the NE trend represents fractures of the Madison Formation. These trends are consistent with the cave passageways and joints orientation.

CONCLUSIONS

Cave passageways are oriented along preferred orientations. Generally, this orientation is along planes of weakness of structural origin, such as joints. In case of Black Hills caves, however, the study of the cave passageways must be done with reference to the geologic events involved in the formation and the development of joints. The present study, done on a structurally homogeneous area of the Black Hills, shows that the orientation of cave passageways of Crystal Cave and Black Hills Caverns mimics the fracture traces and lineaments orientation measured at the surface. However, the joint orientation did not compare statistically with the cave passageways. The most likely reason is that fracture traces and lineaments represent not only underlying fractures, but also the solution cavities formed along bedding planes, while fracture data do not include solution cavities. This observation was confirmed by the rose diagram of borehole fractures of the Madison Formation.

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REFERENCES

Back, W. B., Hanshaw, P. N., Rahn, P. H., Rightmire, C. T., and Rubin, M., 1983. Processes and rate of dedolomitization, Geol. Soc. Amer. Bull., Vol. 94, p. 1415-1429.

Barlow, C. A., and Ogden, A. E., 1982. A statistical comparison of joint, straight segment, and photo lineament orientations, NSS Bull., Vol. 44, p. 107-110.

Davies, W. E., 1960, Origin of caves in folded limestone, NSS Bulletin, Vol. 22, p. 5-18.

Deal, D. E., 1962. Geology of Jewel Cave National Monument, Custer County, South Dakota, M. S. Thesis, Univ. of Wyoming, Laramie, WY, p. 183.

Deike, G. H., 1968. Limited influence of fractures on the cave passages in the Central Kentucky Karst (Abs)., NSS Bulletin, Vol. 30, p. 37.

Ford, D. C., 1989. Feature of the genesis of Jewel Cave and Wind Cave, Black Hills, South Dakota, The NSS Bull., v. 51, p. 100-110.

Greene, E., 1993. Hydraulic properties of the Madison Aquifier System in the western Rapid City area, South Dakota. U.S. Geological Survey, Report No. 93-4008, p. 56.

Howard, A. D., 1964. Process of Limestone cave development, Inter. Jour. Speleology, Vol. 1. p. 47-60.

Kuiper, N. H., 1960. Tests concerning random points on a circle, Royal Nederland Academie of Arts and Sciences, Proceed. A63.

Lattman, L. H., 1958. Technique of mapping geologic fracture traces and lineament on aerial photographs, Photogrammetric Engineering. Vol. 24, p. 568-576.

Palmer, A. N., and Palmer, M. V., 1989. Geological History of the Black Hills Cave, South Dakota, The NSS Bull., Vol. 51, p. 72-99.

Rahn, P. H., and Gries, J. P., 1973. Large springs in the Black Hills, SD. and WY., SD. Geol. Surv. Report of Investigations, p. 46.

Rahn, P. H., 1987. Geologic map and measured stratigraphic sections for the Rockerville Quadrangle, Pennington County, South Dakota, Geol. Soc. Amer., Map and Chart Series MCH062.

Rahn, P. H., 1992. Permeability of the Madison Aquifer in the Black Hills Area, Final Report, DENR., Vermillion, South Dakota, p. 176.

Rahn, P. H., 1993. A comparison of the Wind and Crystal Sitting Bull caves with the fracture traces of the Rockerville Quadrangle, Preliminary Report, DENR., Pierre, South Dakota.

Rueb, A. R., 1984. Lineament analysis of the Black Hills, South Dakota and Wyoming, Unpublished Master's Thesis, South Dakota School of Mines, Rapid City, South Dakota. 89 pages.

Siegel, S., 1956. Nonparametric Statistics, McGraw-Hill, New York.

Wilson, J. R., 1977. Lineaments and the origin of caves in the Cumberland Plateau of Alabama, The NSS Bull., Vol. 39, p. 9-12.

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Note added in proof: The caption of Figure 2 (the location map) should be referenced Greene (1993). The borehold fracture data (Page 100, first line of the paragraph: *Borehole Fractures and the Black Hills Caves* should have the reference Greene (1993). The fracture trace, joint orientation and cave passageway correlation was originally developed by Rahn (see the 1992 and 1993 references). His contribution is gratefully acknowledged.

Hobbs, H. H., III; First Record of the Troglophilic Terrestrial Snail *Carychium exile* Lea, From Indiana Caves:: *NSS Bulletin* **56: 104-105.**

FIRST RECORD OF THE TROGLOPHILIC TERRESTRIAL SNAIL, *CARYCHIUM EXILE* LEA, FROM INDIANA CAVES (GASTROPODA: STYLOMMATOPHORA: CARYCHIIDAE)

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The troglophilic land snail, Carychium exile *Lea, is reported from two caves in southern Indiana. This translucent, small gastropod is widespread in epigean habitats of the southeastern United States but is found also in food-rich areas of caves. Prior to its discovery in Indiana caves this small snail was known only from Alabama, Kentucky, and Tennessee caves.*

In July 1992, field investigations began in southern Indiana to assess the biological resources of caves situated in the Wayne-Hoosier National Forest. Patton Cave in Monroe County, William Cave in Lawrence County, and others were entered on separate trips in October. Physicochemical and biological data were collected from each cave and procurement of the tiny, translucent gastropod, *Carychium exile* Lea was made with the aid of a small wet paintbrush and an aspirator. This troglophilic terrestrial snail had been reported from caves in Kentucky and Tennessee by Hubricht (1964, 1965), from Alabama caves by Peck (1989), and is widespread in epigean habitats throughout the southeastern United States.

The Indiana populations from Patton and William caves were observed in damp, sand and gravel-floored sections. Individuals were found in the gravel and on vegetative debris (sticks and leaves in various stages of decay) in the dark zone but less than 30 m from an entrance where air temperatures and relative humidity were 14.3°C and 94% (Patton Cave, 24 October) and 13.9°C and 100% (William Cave, 31 October). Two individuals were taken from Patton Cave (total length 1.91 and 2.03 mm, width 0.61 and 0.65 mm) and a single specimen was collected from William Cave (total length 1.85 mm, 0.59 mm width).

A closely related troglobitic land snail, *Carychium stygium* Call, was originally described from Mammoth Cave, Edmonson County, Kentucky (Call 1897) where it was found among fungal (*Rhizomorpha*) filaments on damp, old bridge timbers. Hubricht (1964) noted that this species fed primarily on guano of the cave cricket, *Hadenoecus subterraneus* (Scudder), and reported it from 36 caves in Kentucky and from one in northcentral Tennessee. Barr (1967) indicated that populations were usually found in food-rich areas typically near entrances.

All Indiana cave specimens of *C. exile* demonstrate the typical narrow, tapering, conical shell with five whorls, and the columellar tooth is quite small (Fig. 1). The outer shell surface striations are pronounced and specimens generally have well developed upper and columelar lamellae. While alive, individuals were translucent and shiny; soft tissues of preserved specimens are opaque and white. Collections are housed in the Department of Biology, Wittenberg University, Springfield, Ohio.

This represents the first report of the troglophilic land snail *Carychium exile* from an Indiana cave and extends the species' geographical range significantly to the north. This species is probably widespread in the karst regions of southern Indiana and because this snail is very small and difficult to observe in the field, biospeleologists are urged to use magnifying lenses when searching substrates and/or fine-meshed strainers for sifting silt and sand. A wet paintbrush or an aspirator are useful collecting tools. Also, Berlese extractions have proven to be a useful technique for collecting snails and numerous other small invertebrates from allochthonous materials in caves in the southeastern United States.

Acknowledgments

Appreciation is extended to Howard Kronk of Springfield, Ohio, to Kristie Liebhaber of Bloomington, Indiana, and to Jeffrey P. Lapp and Chris Frost of Wittenberg University for their help in the caves. A special thanks is made to Larry Mullins of the U.S. Forest Service for suggesting this project and for his assistance in the field. I am grateful to David A. Smith for identifying the snail. Funds were supplied by the U.S. Forest Service and the Wittenberg University Faculty Research Fund Board.

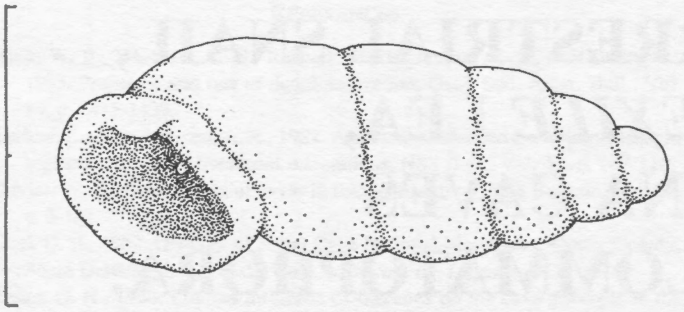

Figure 1. The troglophilic terrestrial snail, *Carychium exile* Lea, from Patton Cave, Monroe County, Indiana (scale, 1 mm).

LITERATURE CITED

Barr, Thomas C., Jr. 1967. Ecological studies in the Mammoth Cave System of Kentucky I: The biota. Internat. J. Speleol., 3: 147-204.

Call, R. Ellsworth. 1897. Some notes on the flora and fauna of Mammoth Cave, Kentucky. Amer. Nat., 31 (365): 377-392.

Hubricht, Leslie. 1964. Land snails from the caves of Kentucky, Tennessee and Alabama. Bull. Natl. Speleol. Soc., 26(1): 33-36.

Hubricht, Leslie. 1965. The land snails of Alabama. Sterkiana, 17: 1-5.

Peck, Stewart B. 1989. The cave fauna of Alabama: Part I: The terrestrial invertebrates (excluding insects). Bull. Natl. Speleol. Soc., 51 (1): 11-33.

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ABSTRACTS OF THE NATIONAL SPELEOLOGICAL SOCIETY

Annual Meeting, August 2 - 6, 1993
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Norma Dee Peacock, Editor

BIOLOGY

CAVERNICOLOUS SCULPINS OF THE COTTUS CAROLINAE SPECIES GROUP (Pisces: Cottidae) FROM PERRY COUNTY, MISSOURI

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Sculpins discovered in caves, springs and associated surface drainages in Perry County, Missouri, show remarkable morphological differences when compared to specimens of the banded sculpin, Cottus carolinae, from southeastern Missouri. Sculpins frequently inhabit cave entrances, burt are encountered less frequently deep in caves. Sculpin populations with apparent cave adaptations such as those from Perry County Missouri, have not been reported from any other area. The description of these sculpins is in progress, and determination of their taxonomic status awaits completion of the research. Specific questions being addressed deal principally with morphological and genetic characteristics, reproductive biology, specific habitat, food sources and availability, distribution, and population estimates. Analysis of 10 meristic and 2 morphometric characters within Perry County Cottus and those from southeastern Missouri revealed consistent differences in several features. In addition, there remains a great deal of variation within the Perry County specimens themselves, particularly those from caves. Some characteristics the cave populations exhibited include: reduced pigment, reduced eye size, reduced number of pelvic rays, a gap between the dorsal fins, and a longer caudal peduncle. Surface seining and in-cave observations continue to yield information regarding specific habitat, food sources and availability, distribution, and population estimates. The large, base level cave streams of this area provide suitable habitat, generally with an abundance of troglobitic, intermediate, and surface food sources. At present, sculpins are found in waters of four large cave systems of the county, and seem to be limited on the surface to the streams (and their tributaries) into which these cave discharge.

VARIATION IN HELEOMYZID FLIES FROM CAVES

Edward A. Lisowski Center for Biodiversity - Illinois Natural History Survey, 172 Natural Resources Building, 607 E. Peabody Drive, Champagain, IL 61820

Measurement of gene flow between and differentiation of geographic populations contribute useful information pertinent to investigations of evolutionary processes. This study is an analysis of genetic and morphological variation within and among populations of five species of heleomyzid flies from caves in Illinois, Indiana and Kentucky. Starch-gel eletrophoreisis of enzymes was used to detect allozyme variation and assess genetic variability. Measurements of wing veins were used to assess morphological variability. Several questions are addressed: Is the variability related to degree of cave-adaptation? Is morphometric variability correlated with allozyme variability? Are cave populations differentiated in terms of genetic and morphological characters?

PRELIMINARY REPORT ON A BIOLOGICAL INVENTORY AND WATER QUALITY ANALYSIS OF ILLINOIS CAVES, SPRINGS AND MINES

Taylor, Steven J. and Krejca, Jean K. - Center for Biodiversity, Illinois Natural History Survey, 172 Natural Resources Building, 607 East Peabody Drive, Champaign, IL 61820

Throughout our two year biological inventory approximately 100 of the over 390 known caves in Illinois are being examined. Giving priority to caves not previously inventoried, this project expands on earlier studies, providing valuable baseline data on Illinois cave fauna. In addition, a variety of water quality parameters are being measured, with emphasis on pesticides and fertilizers. Creating a detailed cave database for the state is another important product of this study. About half of the sites to be inventoried have been visited. While vertebrates were identified on sight, specific identification of many invertebrates awaits determination by taxonomic specialists. Thus far the water quality analysis has not revealed any caves or springs with contaminant concentrations which exceed state or federal maximum contaminant levels. We have detected the presence of the persistent breakdown products of DDT and Aldrin in both water samples and aquatic cavernicolous invertebrate tissues, demonstrating that the use of these agricultural chemicals can be detected in cave systems many years after they are no longer in use. Because of the increasing human impact on the karst regions of the state - from farming chemicals and sedimentation to expanding urbanization - the main goal of this project is to serve as a management tool. The inventory will be useful for future monitoring the health of Illinois' cave life and karst groundwater, and will aid in understanding human impact on karst areas of the state.

COMMUNICATION AND ELECTRONICS

COMPARISON OF LORAN AND GPS FOR PINPOINTING CAVE ENTRANCES IN MOUNTAINOUS TERRAIN

Hoke, Bob - 6304 Kayboro St., Laurel, MD 20707

In 1988 a paper was presented describing the problems in using a portable LORAN unit for pinpointing cave entrances in the mountains of West Virginia. Recent developments in the military's Global Positioning System (GPS) have reduced the cost and size of GPS units dramatically, and made these units practical tools for recording cave entrance locations. A portable GPS unit costing less than $1,000 was compared to a LORAN unit in a field trial to see if the GPS gave the same erratic results as the LORAN. The GPS unit provided consistent and accurate positions that were within approximately 100 feet of the correct position as shown on a 7.5 minute topographic map (approximately .05 inch on the map). The LORAN unit showed erratic positions, with errors up to 1,000 feet. Although GPS has some limitations, it should see increasing use in the caving community as prices continue to drop.

EXPLORATION - INTERNATIONAL

EXPLORATION IN SISTEMA CHEVE, OAXACA, MEXICO

Oliphant, Matt and Vesely, Carol

The expedition during February and March 1993 was divided into three parts. In the main cave Cueva Cheve, there were two, 7 day underground camps. The length of Cheve is now 23.3 kilometers, and the depth remains at -1386 meters.

For two weeks, six cavers explored the area around San Miguel Santa Flor which is approximately over the Cheve system. Many caves were found; most promising is Cueva Charco, 738 meters long and -268 meters deep, with good air flow.

Relations have improved with Santa Ana Cuautemoc near the resurgence, and a small group was granted permission to explore the resurgence caves for five days. Cueva Amontillado (916 meters long) was mapped and some additional survey was done in Cueva de Mano.

PROYECTO CERRO RABON, MEXICO

Garza, Ernie

The Proyecto Cerro Rabon, now in its eighth year, has been exploring the southeastern side of the Sierra Mazateco in Oaxaca, Mexico. The area is characterized by deep vertical caves along with a few long horizontal ones. The main cave system Kijahe Sontjoa is now over -1000 meters deep with more than 15 kilometers of mapped passages. During the 1993 expedition, Cave P17, which has an initial 612 meter pit, was connected bv to the Xontjoa system at the -650 meter level.

YERBA BUENA, MEXICO

Coons, Don

Yerba Buena is in Chiapas, the southern most state of Mexico. The clinic was founded by an American doctor three generations ago, and the present administrator, Ruben Comstrock, is very supportive of caving. The clinic is situated near one of the high points of the state, which also happens to be limestone. The south slope of the mountain correlates almost exactly with the dip of the limestone. Work is in a series of beds nearly 300 meters thick with a vertical potential of over 1000 meters. Caves in the area are either deep vertical shafts of 100-300 meters or large, dusty horizontal boreholes. Integration of the known caves and drainage have yielded over 15 kilometers of survey so far, with the potential for a great deal more. Last year's exploration opened up the apparent base level of the area, with expectations of a fine system to explore. The hosts are among the nicest we have ever known and the cloud-forested mountain peak and Tzotzil Indian population of the area make it one of the most intriguing projects in all of Mexico.

1993 CRF EXPEDITION TO GUIZHOU, CHINA

Cave Research Foundation

The third CRF expedition to China took place during March and April in the province of Gizhou. Thirteen American cavers and seven Chinese cavers from Guizhou Normal University Geography Department studied 33 caves and surveyed 17 kilometers of passages. The two study areas involved magnifient karst lanscapes west (Pinba) and south (Duyun) of Guiyang, the province capital. Work conducted by the teams included geomorphology, hydrology, biology and archeology.

Five scientists from the Chinese team are visiting the western United States and attending the Oregon NSS Convention with the CRF and the USA/China Caves Project.

CAVES AND KARST OF GUIZHOU PROVINCE, CHINA

Xiong Kangning

The scientists and cavers of Guizhou Normal University Geography Department have been studying the magnificent karst terrain and documenting the caves of western Guizhou Province, China for more than six years. The area contains many major caves and four different styles of tower and cone karst.

EXPLORATION - UNITED STATES

ACTIVITIES ON CAVE RIDGE, KING COUNTY, WASHINGTON, UNITED STATES

Crandell, Chuck - 12750 Renton Ave. S., Seattle, WA 98178

Cave Ridge has seen a flurry of activity during the past two years. Just when it was perceived the area was dead, new discoveries were made. One such discovery was made at the bottom of Newton Cave, which now places Newton back on the "40 Deepest Caves in the Continental US" list. Two new cave were also added, bringing the total to ten. All told, a new understandingof the area is arising.

KMCTF/MARBLE MOUNTAINS

Ream, Cynthia - 6002 NE Bryant St., Portland, OR 97218

The last three years have shown a lot of activity in the Marble Mountains of northern California. Coming at the end of a seven year drought, water in the caves became less of a hazard, there has been a move towards checking areas that were conisdered "finished" in the past.

The Klamath Mountain Conservation Task Force now has 27+ miles of cave passage, and 30 miles of surface surveyed and on the computer. All cave entrances, major karst features, and trails have been surveyed to a system of reference points

RECENT EXPLORATION IN HAWAII LAVA TUBES

Medville, Douglas and Hazel - Hawaii Speleological Survey

Between August 1992 and February 1993, 3 miles of passage were surveyed in lava tubes on the Kona side of the island of Hawaii and on the north side of Mauna Loa, also on Hawaii. The tubes are found in the historic 1801 flow north of Kona, the 1855 flow on Mauna Loa, and recent prehistoric (200 - 2500 years bp) flows. Surveyed lengths are 0.5 to 1.0 miles and internal dimensions are up to 40 feet in width and 20 feet in height. The tubes will be described and illustrated. Also, an overview of the potential for additional exploration in these areas will be presented.

GYPKAP
(NEW MEXICO GYPSUM KARST PROJECT)

Belski, Dave, and Peerman, Steve

New Mexico Gypsum Karst Project, or GYPKAP, began as a Southwestern Region project in 1987. The purpose of the project was to find, explore, survey and study the gypsum caves of New Mexico, with emphasis on the plains of the Pecos Valley near Roswell and Vaughn. Since that date, over 133,000 feet of virgin passage have been mapped in about 70 caves. Geological, hydrological, biological and archeological studies have taken place, and landmark landowner relations have developed.

HURRICANE CRAWL CAVE, CALIFORNIA

DeSpain, Joel - National Park Service

Hurricane Crawl Cave was discovered in July of 1988 by a group of cavers from the San Fransico Bay Chapter and NSS members working in Sequoia National Park. Most of the cave is tall, linear, vadose canyons. However, in several areas sizable rooms and large upper-level phreatic passages have developed. The cave is heavily decorated with speleothems including three types of helectites, many shields, large rimstone dams, 20-foot-long curtains, four-foot-long soda straws, broomstick stalagmites, spathites, and large areas of flowstone. Formations in the cave are often colored orange, red, or black and many areas have large sparkling crystal faces. Primary periods of exploration and mapping in the cave were in 1989 and 1991 (the cave was closed by the Park Service in 1990). In 1992 Schist Canyon Cave was connected to Hurricane. Currently 8,400 feet have been mapped in the cave, and it has two known entrances.

TONGASS CAVE PROJECT, ALASKA

Fritzke, Mark and Klinger, Dave

The Tongass project's work is centered in southeast Alaska, primarily on Prince of Wales and Dall Islands. A brief history, key locations, transportation to the island, facilities, weather and terrain will be presented. Karst, caves and forces that threaten the entire ecosystem of the extensive karst areas of the extensive southeast Alaskan area will be detailed. Sea caves on Baker Island, Alaska and the results of the just completed 1993 expedition will also be covered.

RECENT EXPLORATIONS IN CARLSBAD CAVERNS NATIONAL PARK, NEW MEXICO

Pate, Dale - National Park Service

Carlsbad Caverns and Lechuguilla Cave continue to grow as survey expeditions work in the caves. Carlsbad Caverns is now at 28.5 miles and Lechuguilla Cave is at 65.3 miles in length.

Chocolate High in Carlsbad Caverns has been a focus for exploration since its discovery. There are now 2 miles of surveyed passage in this area.

Six expeditions to Lechuguilla Cave have added over 5 miles of new passage since January 1993. All expeditions for 1993 have as a goal pushing passages to the north, hoping to expand the cave's limits outside the boundary of the park. The western borehole, Northwest Passage, and the East and Far East have yielded most of the passages. The North Rift has seen serious pushing and has extended the boundary north by 70 feet.

The relationship between cavers and the National Park Service is in great shape and will hopefully continue on a long term basis.

WIND CAVE, SOUTH DAKOTA

Yett, Bill

A historic description of the exploration of Wind Cave, Wind Cave National Park, South Dakota from discovery in 1881 to the present prefaces the recent efforts of the Colorado Grotto that began in 1990. Nearly 20 miles of new survey has been added in that period by the monthly trips of grotto members, the efforts of National Park Service staff and Paha Sappa Grotto cavers. The innovative inventory system established there has resulted in 40% of the cave being inventoried since 1990.

A "BLITZ SURVEY" OF CRYSTAL CAVE IN SEQUOIA NATIONAL PARK

Bosted, Ann

Crystal Cave, located in Sequoia National Park, California, has been known since 1918 and commercialized since 1941, but never completely mapped. This was partly because any mapping project must, of necessity, not interfere with the heavily attended summer tours and so meant mapping after hours and not leaving any survey station markers in the cave. Tom Rohr and the late Ellis Hedlund surveyed 4,485 feet between 1961 and 1963; Santa Barbara Underground resurveyed much of this when they charted 1,709 feet in 1986.

A proposal was submitted to the National Park Service requesting permission to work for two weekends between the time the summer tourist season ends and winter snows close the road to the cave. The goal was to do a stage to stage "blitz survey" and map 10,000 feet in two weekends. This goal was achieved in September 1991 when 20 people came for the first weekend and 12 for the second one. As there were remaining leads, a third fall weekend was hurriedly scheduled and about 10 people attended bringing the surveyed length of the cave to 12, 408 feet, plus a surface survey of over 2,200 feet. This made Crystal Cave the third longest cave in California (after Lilburn and Bigfoot).

The "Blitz Survey" team used helium-filled balloons to accurately measure the height of some of the passages and rooms. A lap-top computer and printer were plugged into the cave's electrical system so the occasional loop closure error could be identified and corrected "in the field". The complexity of the cave was also documented; the 12,408 feet of passage is contained in a lens of marble less than 700 feet long, 470 feet wide and no deeper than 208 feet. A significant amount of virgin cave was found and named, and names were also given to visited but unnamed areas of the cave. The exact path of Pirate Stream, the water flowing from Yukka Creek through the cave to Cascade Creek, was discovered, and the Lake Room was found to contain water that had "backed up".

During the survey of the cave, quantities of trash (broken glass, cable, tar paper, etc.) were observed. In the spring of 1992 a fourth weekend trip was organized during which this debris, temporary stations were removed, and a limited number of permanent station markers were placed by a 20 person team.

DISCOVERY AND EXPLORATION OF BARRACK ZOURIE CAVE

Engel, Thom and Haberland, Peter Barrack Zourie, Schoharie, New York

A digging effort, little more than one year ago and within a few miles of the 1991 New York Convention site has yielded over 2 1/2 miles of active stream passage. Dozens of leads in this already fine and major New York State cave keeps northeast cavers busy.

GEOLOGY

CONDITIONS FOR DEVELOPMENT AND MAINTENANCE OF A FRESH-WATER LENS IN CARBONATE ISLAND; RESULTS OF LABORATORY MODELING

Dumont, Kevin A., Frank, Edward F, Kirkova, Julitta T., Mylroie, John E. and Steil, James R. - Department of Geosciences, Mississippi State University, Mississippi State, MS 39762

The fresh groundwater under marine carbonate islands occurs ideally as a lens-shaped volume whose exact shape and dimensions depend on rate and amount of recharge; porosity and permeability of the aquifer; and density difference between the fresh and underlying saline water. The resulting boundary, called a halocline, will occur with varying degrees of sharpness. This halocline has been implicated in the development of large dissolution voids in carbonate islands of the Caribbean. It has been proposed (Williams, 1992), based upon field observations, that a sharp and stable halocline will be produced when the fresh-water is colder than the salt water. Such a stable halocline is necessary for cave development. The "warmer-deeper" hypothesis is initially counter-intuitive, as making the salt water warmer lessens the density contrast; however a warmer bottom layer will produce convection in both layers, which Williams hypothesizes produces the conditions necessary for lens stability.

This hypothesis was tested by establishing an artificial halocline in 4-liter glass jars in a laboratory model. Experimental trials were conducted using a variety of water temperature contrasts between the top fresh-water layer and the bottom salt water layer. Tests were run allowing an initial temperature contrast to equilibrate, as well as test in which the temperature contrast was maintained. Another set was conducted using a sucrose solution the produce density contrast. The final set attempted to establish a two-layer system using fresh-water/fresh-water at different temperatures. Measurements were made of temperature and thickness of the mixing zone between the top and bottom layers at intervals over a period of several days.

In all cases, from an initial sharp boundary the halocline grew gradually into a thick mixing zone through time. No appreciable differences were found between jars at varying initial temperatures, or between jars in which temperature gradients were maintained. The fresh-water/sucrose system behaved similarly to the fresh-water/ salt water systems. The fresh-water system could even be established, and it mixed completely within 60 minutes.

NETWORK FLOW MODELING OF DEVELOPING KARST AQUIFERS; SELECTIVE ENLARGEMENT OF COMPETING FLOWPATHS

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A new computer simulation model has been developed to investigate questions involving the earliest stages of flowpath selectivity within karst aquifers. Results from experiments using the model suggest that important patterns of selective enlargement occur even during the very early, laminar flow states of passage development. In the absence of variations in initial fracture size, major flowpaths to develop are those along the most direct path between flow entrance and exit. Those passages most closely aligned with the hydraulic gradient will also be favored for enlargement.

Runs with randomly varying initial fracture widths within the network suggest that with a large initial variation in widths, the initial fracture distribution will be a major influence on the pattern of flow routes ultimately develops. Of the hypotheses proposed in the literature to explain maze (non-selective) vs. branch work (selective) patterns of cave development, the most strongly supported is that a number of alternate flow-paths can form where flows are forced to seek alternate routes around constrictions. Suggestions that 1) maze caves form as a result of phreatic, artesian flows, and 2) flowpath selectivity will only begin once turbulent flow conditions are reached were not supported by simulation results.

A MASS-BASED EVAPORATION PAN STUDY IN MYSTERY CAVE, MINNESOTA

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Ten evaporation pans were installed in Mystery Cave in September, 1992 to test whether evaporation could successfully be measured in this cold (8.7 deg. C) but humid cave. Plastic evaporation pans are covered by baskets turned upside down to prevent interference from drippage. A measured mass of distilled water is added to the dry pan and a month later that water is poured into a pre-weighed, wide-mouth bottle that holds weighed paper towels used in drying the pan before addition of the next month's water, two towels are added to the bottle after drying. Evaporation rates are as high as 2 to 3.4 $g/m^2/day$ in dry areas; rates in wetter areas range from near zero to about $1g/m^2/day$. Condensation was measured at Flim Flam Creek during the September to October period; at that time relatively warm surface water from the Root River was flowing through the cave and contributed to slightly foggy conditions near the cave stream. Condensation was visible as thousands of tiny drips on the basket. This suggests that condensation did occur directly onto the water; the drops apparently did not coalesce on the inside of the basket and drip into the pan. A set of three pans at floor, mid-passage and near ceiling levels at the Garden of the Gods provide data that suggest drier conditions prevail along the floor, and wetter ones along the ceiling where condensation is common. These results help explain the observed distribution of aragonite crusts, which are confined in a horizontal band to the lower part of 5th Avenue, and are believed to form only in dry wall areas where capillary solutions are drawn to the bedrock surface and evaporate.

FLANK MARGIN CAVE DEVELOPMENT, ISLA de MONA, PUERTO RICO

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Isla de Mona is a 55 square kilometer elevated carbonate platform located 60 kilometers west of Puerto Rico in the Mona Passage. The island is bounded by vertical cliffs as much as 90 meters high consisting of two Miocene carbonate units; the Lirio Limestone and the underlying Isla de Mona Dolomite. A narrow and discontinuous coastal plain of the late Quaternary limestone and sediment lies along the southern and southwestern coasts.

Numerous cave entrances dot the cliffs surrounding the island. While most of the caves are located at the contact between the Lirio Limestone and the Isla de Mona Dolomite, they are found at all elevations in both rock units. One cave, Cueva de Agua near Punta Brava, is developed in a Pleistocene reef-rubble deposit that infills a pre-existing cave in the Isla de Mona Dolomite. All the caves are characterized by large, flattened oval chambers commonly connected by short tubes and windows in thin cave walls; an array of remnant limestone pillars, maze passages and honeyard development; and tubular passages that end abruptly. The caves extend along the island margin, often for 1,000 meters or more, becoming smaller inland, ending within 250 meters of the cliff face.

The hypothesis is that these are flank margin caves that developed along the coast near sea level by mixing-zone dissolution in rock units that have since been uplifted; not sea caves or conduits draining closed depressions in the center of the island. Evidence supporting this hypothesis is the fact that cave passages are developed horizontally, regardless of the dip of the contact. Where the dip of the contact is steep, as at Cueva de Dona Gena, the horizontal cave chambers are arranged in a step-like fashion along the contact over a vertical range of 10 meters. The variable elevation of the caves is thought to be a result of changes in fresh-water lens position caused by both tectonic uplift and glacio-eustasy. The caves contain speleothems and intersect phreatic voids filled with paleosol or reef rubble. These features have been partially dissolved, indicating at least one episode of phreatic modification after a vadose interval.

EXPLORING THE MYSTERY BEHIND THE FORMATION OF CAVES IN GRANITIC ROCKS IN THE WESTERN U.S.

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Major caves in granitic rocks have been explored in four areas in California and two areas in Colorado. Although the containing rocks vary somewhat in lithology (tonolite and granodiorite in California, granite in Colorado) and dramatically in age (Cretaceous in California, Precambrian in Colorado), there are numerous shared characteristics. Caves in all six areas contain active streams. The streams in each area are deeply incised into bedrock. The stream channels are roofed by large boulders. Stream gradients within the caves are high and the surrounding surface areas have high relief. All caves are covered by boulders, although well-developed soil and vegetation covers the boulders over some caves. The caves do not always follow the low part of the surface topography as some trend under a hillside. Oddly, Midnight Creek Cave in California and Goose Creek Cave in Colorado have had dams built in association with them. Not surprisingly, both dams have had varying difficulties in holding water.

Factors contributing to the apparent preferential formation of these caves in granitic rocks over other crystalline rock types are the homogeneity and low initial permeability of granitic rocks, their propensity to form and weather along orthogonal joint sets, and their common habit of forming open joint sets and large boulder fields.

CLASS V INJECTION WELLS IN KARST - TENNESSEE'S LAW VERSUS REALITY: A CASE HISTORY

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According to the US EPA regulations, any sinkhole that is modified to better accept storm water runoff becomes a Class V injection well. Prior to the beginning of EPA's nationwide involvement with injection wells, a driller could lose his license in Tennessee if he drilled a well to alleviate sinkhole flooding. New state regulations now allow the drilling of Class V injection wells and the modification of sinkholes, but a permit is required, and it must be demonstrated that no degradation of groundwater quality occurs from the disposal practice. The question is how can you NOT adversely affect water quality from this practice in a karst aquifer system? A catchment basin with a small wetlands placed prior to the injection point can be effective for small to moderate precipitation events but not major storms. Another important question is whether the ground water should be actually considered surface water as dictated by the "Common" or English Ground Water Doctrine. This groundwater law, which is used by most eastern states, says that water moving through "well defined subterranean streams" (i.e. caves) is legally surface water. Therefore, a different set of regulations and water quality standards may apply such as under the new federal NPDES program. These issues were addressed during the construction of a large commercial development in Cookeville where parking lot runoff to sinkholes is being permitted under the state's Injection Well Program.

SINKHOLE DEPTH DISTRIBUTIONS: ANALYSIS AS CORROSION DAMAGE FUNCTIONS ON A LARGE SCALE

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The characteristic doline karst surface has an array of closed depressions of various diameters and depths. Previously published work on large doline populations show that the depth distributions are exponential with exponential coefficients increasing with the relief of the karst region examined but are largely independent of structural setting and bedrock lithology.

Closed depressions in the Appalachians are of two types: roughly circular features occurring on "sinkhole plains" and depressions of more irregular outline associate with fluviokarst. These latter include blind valleys and valley sinks formed along dry valleys. The present investigation is a detailed comparison of sinkhole depth distributions within the Mammoth Cave Area, a segment of the Greebrier limestone karst in West Virginia, a segment of fluviokarst in the Valley and Ridge of East Tennessee, and a segment of karst in northern Florida. Each of the chosen segments spans parts of 2-8, 7.5 minute quadrangle sheets. Closed depressions were categorized into sinkhole plain associations and valley associations and then depth distributions were determined for separate categories within each of the selected areas.

The exponential form of the distribution function was obtained for most of the populations although Gaussian distributions appear in a few of the karst valley settings. These data were analyzed in terms of the "damage function" concept developed by corrosion engineers for etch pit development on metals. This concept also leads to an exponential decrease in the frequency of occurrence with pit depth. As corrosion proceeds, the number of pits increases but the distribution function remains the same. The probability of occurrence of at least a few very deep pits increases, a feature that has implications for the evolution and age relations of karst depressions.

DIGITAL TITRATORS IN KARST STUDIES

Alexander, E. Calvin Jr. and Jamerson, Roy A. - Department of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55455

Researchers have often carried bulky glass burettes into the field for alkalinity and total hardness titrations. Small, hand-held digital titrators have been available from several companies for a number of years. Demonstration of the use of the Hach digital titrator in performing titrations for alkalinity, total hardness, and calcium hardness will be presented. Data from West Virginia show that careful selection of titrant solutions allows field titrations of calcium and magnesium (derived from the difference of total and calcium hardness) whose results compare favorably with those obtained by inductively coupled plasma emission mass spectrometry.

MONDMILCH REVISITED: AN ETYMONLOGICAL DEFINITION OF THE TERMINOLOGY FOR MOONMILK

Reinbacher, W.R. - 730 Holly Oak Drive, Palo Alto, CA 94303

This paper analyses the origin of words used to describe the white speleothem known as Mondmilch (moonmilk). Etymological incompatibilities and misconception in translations and hypotheses led to terms based on perceived consistency (flour or meal, chalk, rock) and on peddler's names (Milk of the Holy Mary et al.). From the first writing and printing of "Mon-Milch" by Gesner (1555) Mondmilch (moonmilk) is found to be the oldest and most appropriate term based on medieval literature and influences of ancient alchemy. Montmilch, which was used between 1850 and 1950 is a discarded spelling of Mondmilch. The assumption the Montmilch was a hybrid translation into French is linguistically unacceptable. The German term Bergmilch, hardly used since 1975, is correct only if the the right meaning of the word "Ber" as "mining" is applied. An etymonology based on gnomes (little earth men) is difficult to substantiate for lack of continuity and has no basis in words for old, wizened, evil spirits. Mondmilch, in its dialectic variations since the 16th century, is a correct term based on the ancient connection between the moon and silver in the form of a white "sublimation" and based on a flawless etymology. While nothing prohibits use of any personally favored words, Mondmilch (moonmilk) should be given as reference for clarity of meaning in any language.

MAGNETOSTRATIGRAPHY AND GEOCHRONOLOGY OF A KARSTIC GROUNDWATER SYSTEM, CAVE HILL, AUGUSTA COUNTY, VIRGINIA

Kastning, Ernst H. "Kass", III

Paleomagnetism preserved in cave sediments can be used to determine the age of a cave provided that reversals of the Earth's magnetic field are preserved in fine-grained material such as silt or clay deposited under low energy conditions. Over 160 sediment samples from caves within Cave Hill, in the Shenandoah Valley of Virginia, were analyzed with a superconducting magnetometer. Samples were sequentially degaussed to reveal natural remnant magnetization. The resultant paleomagnetic vectors were correlated with known reversals in the Earth's magnetic field. Magnetostratigraphic analysis suggests a minimum age for speleogenesis of Grand Caverns at 0.78-1.1 MA Based on elevations of cave passages above the present local base level (obtained by precise leveling surveys), the average rate of erosion for the Shenandoah region would be 24-37m/Ma. This agrees with published rates for other localities in the humid-temperate eastern U.S.

These results, together with earlier detailed geologic mapping and petrographic, lithologic and hydrologic investigations of this study, suggest a chronology for development of the cave system. Cave origin was strongly controlled by bedrock composition, attitude of bedding, and joints and faults. Passage elevations correlate well with former local base levels; however, deep artesian groundwater flow may have been crucial to speleogenesis at Cave Hill. This is supported by the magnetostratigraphy and various geomorphic features, including lift tubes with dissolution scallops as paleoflow indicators, ceiling pockets suggesting mixing of waters of differing chemical compositions, present-day phreatic passages well below the level of the nearby South River, and positions of former groundwater outlets of the major caves.

SOLUTIONALLY ENLARGED GLACIAL STRIAE; A NEW KARREN FORM ?

Goggin, Keith E. - Department of Geography and Earth Systems Sciences, George Mason University
Medville, Douglas M. - Energy, Resource and Environmental Systems Division, The Mitre Corp.

Glaciated pavements on carbonate rocks are found in several locations on the west slope of the Teton range, Wyoming, US at elevations between 2800 and 3100 meters. One such surface (43 deg 41' N. Lat., 110 deg 54' W Long.), an exposure of the Upper Ordovician Bighorn Dolomite, has an areal extent of approximately 10 square kilometers. This exposure exhibits a wide range of classic karren forms (e.g. large kluftkarren, spitzkarren, trittkarren), as well as an unusual and possibly unique form, consisting of a system of sub-parallel furrows having both linear and lateral extents of hundreds of meters. The furrows have been observed only on the dolomite.

Individual furrows vary from approximately 10 cm to one meter in width and depth. The furrows appear to be a product of solutional enlargement of striae on the dolomite surface resulting from Pleistocene alpine glaciation. While the furrows are found on several stratigraphic horizons in the dolomite, lithologic changes between members exhibit no observable controls on furrow development. The furrows are observed on both horizontal and vertical rock surfaces, follow valley trends, and exhibit on relation to current drainage patterns or structural dip, all of which suggest a synglacial origin for the furrow patterns.

Large kluftkarren that are parallel or sub-parallel to regional strike are crossed by the furrows at oblique angles. Examination of the cross-cutting relations between the furrows and the kluftkarren as well as the sizes and configuration of the furrows above and below the kluftkarren indicates the the furrows predate the kluftkarren.

KARSTLANDS; HELPING THE PUBLIC UNDERSTAND THE SYSTEM

Kastning, Ernst. H. and Kastning, Karen M.

Members of the speleological community, espicially professional geoscientsts, are frequently asked to give presentations or advice about caves and karst to lay groups or to public officials. This is often in response to environmental problems that surface in communities or regions. As speleologists, we inherently understand the workings of karst systems, and likewise we recognize that decision makers and landowners need to comprehend the fundamentals of karstic processes in order to take appropriate measures in averting or alleviating environmental impacts. Yet, communicating the principles of karst to the lay public is made difficult because the term karst is often introduced without sufficient definition or illustration; plus pervasive misconceptions about caves, soluble rock, and ground water flow must first be dispelled.

The first barrier to overcome is that most of the public do not readily envision the interaction between processes above ground and those underground, largely because the latter are out of sight and go unrecognized. Our contention is that the major premise of all public education about karstlands should be and understanding of karst as an integrated system that includes both surficial and subsurficial processes. Other common misconceptions about karst include: 1) the bedrock in the subsurface is homogeneous, rock-solid (nonporous), and structurally stable, 2) groundwater issuing from springs and wells in bedrock (including karstic rocks) is inherently pure and healthy for consumption, and 3) surficial recharge through sinkholes is merely fortuitous because sinkholes were already present and simply provide places for water to enter the ground.

We favor the term karstlands in communicating with the public. Although it may seem inherently redundant (karst is a type of land), to the lay person this term immediately implies a terrain, whereas the term karst may not. The concept of karstlands is parallel to that of wetlands. Most people are familiar with wetlands and recognize that this environment is not conducive for development and direct human use, and in fact, is very fragile and sensitive to human impact. Laws exist to protect wetlands. A similar approach to karstlands, whereby the public can identify intrinsic problems and manage these lands accordingly, is highly desirable. To attain this level of awareness necessitates effective education about the physical karst system. The speleological community must take a leading role in this pursuit.

HISTORY

NINETEENTH CENTURY PALEONTOLOGICAL INVESTIGATIONS OF THE CARLISLE PENNSYLVANIA BONE CAVES

Grady, Fred and Snyder, Dean

The first scientific investigation of a cave near Carlisle, PA , was by Constantine Rafinesque in 1832 after he was sent several teeth found in Conodoquinet Cave. Rafinesque found notheing in his search of the cave and discribed the teeth as a new species of ungulate

Odocoileus speleus though they were in fact those of a deer.

In 1848 Spencer Baird and some of his students a Dickenson College visited several caves and dug in Conodoquinet Cave and Conodoquinet Rock house. Baird also apparently got a few bones from a cave Harrisburg believed to be Leymone Cave. Other caves visited by Baird and others have not yet been identified. Baird believed that 5% of the bones he found were from extinct animals. A 1940 description of the collection presented by Baird to the Smithsonian Institution revealed only bones of recent age.

The third effort to find bones in the Carlisle Bone caves was by Henry C. Mercer who employed William Whitte to investigate the caves in 1897. Whitte also went to Conodoquinet cave and found quite a few bones all apparently of recent age and no evidence of early man that Mercer had been searching for for several years.

THE DISCOVERY OF A SANDSTONE CAVE BY CUSTER'S BLACK HILLS EXPEDITION

Grady, Fred and Heaton, Timothy H.

In the summer of 1874 George Armstrong Custer led an expedition to explore and survey the Black Hills of South Dakota. In the northwestern corner of South Dakota an Indian scout named Goose led the expedition to a cave held in much regard, religiously by local Indians. Custer named it Ludlow Cave after his topographical engineer, Captain William Ludlow. The cave extended 200-400 feet into the hillside and was said to be decorated with drawings of animals and human hands and feet. Ludlow Cave is located on a recent topographic map and one of us has recently observed the entrance.

THE HISTORY OF MICHIGAN'S FIBORN QUARRY

Warner, Michael - Michigan Karst Conservancy

A man-made pocket in an outcropping lens of Silurian age limestone sits in the eastern end of Michigan's remote Upper Peninsula. Surrounding karst features attracted the Michigan Interlakes Grotto in the mid 1970's, following leads to the area of Fiborn Quarry (now a Michigan Karst Conservancy preserve). Accounts, documents and photographs have been gathered for archiving and publishing. The record dates from the mid 1800's to the present. Visitations to rare northern, post-glacial caves, since quarried, and many facets of development and life at Fiborn Quarry (abandoned in 1935) are known.

PALEONTOLOGY

RECENT PALEONTOLOGICAL AND ARCHEOLOGICAL DISCOVERIES IN MADAGASCAR CAVES

Burney, David, Grady, Fred, James, Helen,Ramilisonina, Jean-Gervis Rafamantanantsoa, and Wright, Henry

A 1992 expedition to caves in northwestern Madagascar revealed significant paleontological and archeological deposits in 2 caves and one rock shelter. Anjohibe Cave is spectacular in its size and many formations. Surface finds included pottery and many bones. One excavation in Anjohibe Cave uncovered an accumulation of bones of the extinct pygmy hippotamus, Hippotamus cf. lemerlei while another site contained many bones of bats, birds and other small animals along with a few bones of larger taxa.

A second cave, Anjohikely produced remains of several individuals of the extinct lemur, Archeolemur cf. edwardsi along with bones of many smaller mammals, birds, reptiles, and amphibians. A small rock shelter contained a few fragments of relatively thick eg shell believed to be from the extinct ratite bird Mullerornis.

While this was not the first scientific trip to the caves in this region of Madagascar, it is the first one in which systematic excavations were undertaken.

PALEONTOLOGICAL DISCOVERIES IN CAVES OF PRINCE OF WALES ISLAND, ALASKA

Grady, Fred and Heaton, Timothy H.

Bones of bears were first discovered in El Capitan Cave, Alaska during the 1990 POWIE Expedition. Systematic excavations at El Capitan Cave in 1992 demonstrated the presence of bones of at least four black bears, Ursus americanus, and two grizzlys, Ursus arctos. One of the grizzlys was exceptionally large and was Carbon 14 dated at 9,760 +/- 75 years bp while one of the black bears dated at 10,745 +/- 75 years bp. Screening of the sediments enabled the recovery of teeth and bones of small birds, shrews, bats, rodents and mustelid carnivores including otters. Large masses of fish bones found are believed to represent scats or stomach contents of otters or bears. Teeth and bones of 2 grizzly cubs were also found in Blowing in the Wind Cave. Only black bears now inhabit Prince of Wales Island.

INVESTIGATIONS AT YARIMBURGAZ CAVE, MARMARA, TURKEY

McMahon, Jill - Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48109-1063

Yarimburgaz Cave, located about 20 kilometers west of Istanbul on a hill overlooking a small embayment of the Sea of Marmara, is the oldest stratified archeological site in Turkey (Howell and Arsebuk, 1990). Located at the crossroads between Europe and Africa, it is of significant interest with respect to early human migration between the two continents as well as local and regional pre-history.

The site includes the upper and lower entrance areas of a solutional cave formed in Eocene limestone. The thick sedimentary fill includes breakdown, cave stream deposits ranging from cobbles to clay, a possible marine sand, windblown sand and silt derived from the valley flanks and floor, microfaunal (e.g. bat, rodent) and macrofaunal (e.g. cave bear, lion, wolf) remains, and archeological deposits (Lower Paleolithic to Byzantine).

In addition to its archeological importance the site also has major potential as a source of paleontological and paleoecological information for a region whose paleo-environmental history is not known in detail.

PHOTOGRAPHY

PHOTO CD AND THE COMPUTER; NEW TOOLS FOR THE CAVE PHOTOGRAPHER

Bunnell, Dave

With the Photo CD, you can put up to 100 slides or negatives on a CD-ROM in digital form. With appropriate hardware, the images can be viewed on your TV or your computer. The real power of a computer interface is that it permits editing of the images. Hardware and software aspects of editing your photos on the computer will be discussed. Examples will be provided both on a computer monitor and on slides output from the editing process.

KEYS TO SUCCESSFUL PHOTOGRAPHY IN LAVA TUBES

Bunnell, Dave

Many people who attempt pictures in lava tubes end up with underexposed photos. This talk focuses on some of the techniques and equipment I use to photo in lava tubes, including the "mondo gun", a flash with a large polished reflector that adds up to two F-stops worth of flash power to your bulbs. Also discussed are the pros and cons of high-speed film as a solution, and approaches to the problem of lighting dark walls without burning out the models in the photo. Slides from Hawaiian and Californian tubes will be shown to demonstrate techniques.

SURVEY AND CARTOGRAPHY

GSS PETTYJOHN CAVE PROJECT

Crowell, Hubert C. - 3105 Mary Drive NE, Marietta, GA 30066

The Pettyjohn Cave Project (PCP) was formed in an effort to compile as much information as possible on this great cave and make this information readily available to cavers. The format for the information is on 3 1/2 inch diskette with CAPSVIEW software for viewing on a PC with DOS 3.3 or higher and a hard drive.

All of the raw survey data is shown along with a 3-D map of the cave which can be rotated. A search method will be discussed for locating possible leads and points of interest within the cave. A demonstration will be given showing a tour through parts of the cave with cross sections, notes, and photographs.

The diskettes are distributed at cost plus 20% for the GSS. Cavers are encouraged to share the experience with others by sending us the information for inclusion on the disk. All trips will be placed in a file by date for others to read.

A well known cave like Pettyjohn's points out a strong need to maintain detailed records and maps. The efforts of many are lost due to not having a central location or collection point for cave data. A local Survey section can provide that collection point provided that the information is easily made available to others. Future cavers will thank the Georgia Speleological Survey for maintaining the local cave records.

SUCCESSFUL MANAGEMENT OF A CAVE SURVEY PROJECT: A CASE STUDY

Hoke, Bob - 6304 Kaybro St., Laurel, MD 20707

The 3 year effort to resurvey the 7+ miles of passage in Paxton's Cave (Virginia) was an unusual project: it ran smoothly and efficiently, and the survey trips were consistently productive despite having over 90 different surveyors with varying skill levels. Some of the more significant reasons for the Project's success were that survey quality was maintained by the consistent use of backsights, detailed sketches, and no booty scooping; data was reduced and drafted quickly, with updated maps being available for every survey team on every trip; trips were open to all cavers and training was willingly provided to new surveyors; and various other organizational and personnel problems that frequently plague significant projects were avoided.

DESIGNING A GENERALIZABLE CAVE INVENTORY

Vesely, Carol

The Federal Cave Resources Protection Act mandates that cave resources on federal land be inventoried and management classifications be recommended for all caves. A variety of individual cave inventorying procedures have been implemented in specific parks and caves across the country. However, to date, no nationally accepted cave inventorying system exists. I would like to foster a discussion on the pros and cons of various existing cave inventorying systems and solicit recommendations for a model cave inventorying system that would be generalizable to cave ntionwide. Some of the topics to be discussed include: stages of cave inventorying, mapping standards, data base management, the role of scientific "experts" and inventorying forms and protocols.

TECHNIQUES FOR USING AUTO CAD FOR CAVE CARTOGRAPHY

Petrie, Garry

During the past several years using computers to draw cave maps has become much more practical. Developments such as inexpensive, fast, high resolution displays, high capacity mass storage, 32 bit processors and programs optimized for the hardware have enableD individuals to create very portable and revisable drawings. One such computing platform and program is the IBM PC and compatibles using Auto Cad.

While a program as complex as Auto Cad has many methods to achieve similar results, all routes will include entering the survey data as a reference backbone, planning the layout of overlapping and connecting passages, rendering the walls, adding features, noting locations and references and eventual updating as new passages are discovered. Auto Cad has many capabilities such as superimposing drawing layers, copying and changing properties of symbols and lines, hidden line removal and z-plane sorting, trimming lines to a reference and area filling that are useful in drawing cave maps. One of the most important capabilities Auto Cad has is the outputting of "electronic" maps at various scales for a variety of physical drawing devices

USING GPS UNITS IN THE KARST OF MEXICO - HOW WE ESTABLISHED A WORLD DEPTH RECORD WITHOUT LIGHTING A HEADLAMP !

Hose, Louise D - Department of Geology, University of Colorado, Colorado Springs, CO 80933-7150
Withrow, Skip - Colorado Grotto

Two Global Positioning System (GPS) receivers were used extensively this year in three southern Mexico, high-relief karst areas. The main objective of the work was to determine the relative positions and elevations of the entrances to Sistem Cheve and, thus, determine the depth of the world's deepest hydrologic system. Once this goal was obtained, the units were used to assist in geologic mapping and route finding, and determining the location of archeological sites, key permanent surface stations, springs and other important surface features in the Huautla and Cerro Rabon areas, as well as the Cheve area.

The precision of the work depended on factors such as the forest canopy, the relief of the area, nearby movements of spectators, length of the sessions, and the amount of pre-planning. Strategies were learned to minimize the problems and some tests had repeatable precisions of less than +/- 5 meters.

Index to Volume 56 of the National Speleological Society Bulletin

Ira D. Sasowsky

Nittany Geoscience, Inc., 120 Radnor Rd., State College, PA 16801

This index contains references to all articles and abstracts published in volume 56 parts 1 and 2. Abstracts for the 1993 NSS Annual Meeting are contained in this volume.

The index consists of three sections. The first of these is a **keyword index** which starts on **page 119.** Keywords include: unique words from the article title, cave names, geographic names, and descriptive terms. The second section is a **biologic names index** on **page 124.** These terms are Latin names of organisms discussed in articles. The third section is an alphabetical **author index** starting on **page 125.** Articles with multiple authors are indexed under each author.

Citations include only the name of the authors, followed by the page numbers of the article. Within an index group, such as "Archaeology", the earliest article is cited first, followed by consecutive articles.

Index data was input on an IBM-PC using the SDI-Soft front-end program designed by Keith Wheeland. The index was prepared on an IBM 4341 computer running a VM/CMS operating system. Indexing was performed by the IBM KWIC/KWOC program as modified by William H. Verity at The Pennsylvania State University Center for Academic Computing. Formatting was accomplished using the SCRIPT text formater, and Generalized Markup Language, with camera-ready copy produced on a HP Laserjet4m printer.

The author thanks William H. Verity for his tireless assistance. Computer funds were provided by the College of Earth and Mineral Sciences, The Pennsylvania State University.

Keyword Index

Biologic Names Index

Author Index

Guide To Authors

The *NSS Bulletin* is a multidisciplinary journal devoted to speleology, karst geomorphology, and karst hydrology. The *Bulletin* is seeking original, unpublished manuscripts concerning the scientific study of caves or other karst features. Authors need not be associated with the National Speleological Society.

Manuscripts must be in English with an abstract, conclusions, and references. An additional abstract in the author's native language (if other than English) is acceptable. Authors are encouraged to keep in mind that the readership of *The Bulletin* consists of both professional and amateur speleologists.

For general style refer to the present *Bulletin* and the following guides: "Suggestions to Authors" (U.S. Geological Survey), "Style Manual for Biological Journals" (American Institute of Biological Sciences), and "A Manual of Style" (The University of Chicago Press). For assistance in writing an abstract see "A Scrutiny of the Abstract" by K. Landes, Bulletin of the American Association of Petroleum Geologists, vol. 50 (1966), p. 1992. Because good figures are an essential part of any paper, authors are encouraged to see what bad figures look like in the editorial on figures by K. Rodolfo in the *Journal of Sedimentary Petrology,* vol. 49 (1979). p. 1053-60.

Each paper will contain a title with the author's names and address. This will be followed by an abstract and the text of the paper. Acknowledgements and references follow the text. References are alphabetical with senior author's last name first, followed by the date of publication, title, publisher, volume, and page numbers. See the current issue of *The Bulletin* for examples.

Authors should submit two copies of their manuscript (include only copies of the illustrations) to the appropriate specialty editor or the senior editor. The manuscript must be typed, double space on one side of the page. Authors submitting manuscripts longer than 15 typed pages may be asked to shorten them. All measurements will be in Systèrne Internationale (metric). Other units will be allowed where necessary if placed in parentheses and following the SI units.

Figures and lettering must be neat and legible. Figure captions should be on a separate sheet of paper and not within the figure. Most figures will be reduced, hence the lettering should be large. Once the paper has been accepted for publication, the original drawings (with corrections where necessary) must be submitted to the editor. Black-and-white photographs must be sharp, high contrast, and printed on glossy paper. Color prints will be printed at author's expense only.

All submitted manuscripts are sent out to two specialists for review. Reviewed manuscripts are then returned to the author for consideration of the referee's remarks and revision (where necessary). Revised manuscripts are returned to the appropriate editor who then recommends acceptance or rejection. Upon acceptance, the author should submit all photographs and original drawings to the editor.

Once the paper has been typeset and laid-out, the senior author will be sent one set of proofs for review. Any corrections other than printer errors will be done at the author's expense. A reprint order form will be sent with the proofs. At this time all authors will be requested to contribute page charges of $25 per page to help defray the cost of publication. The actual cost to the society is about $100 per page. Acceptance of manuscripts for publication is not contingent upon payment of page charges.

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