PHOLEOS

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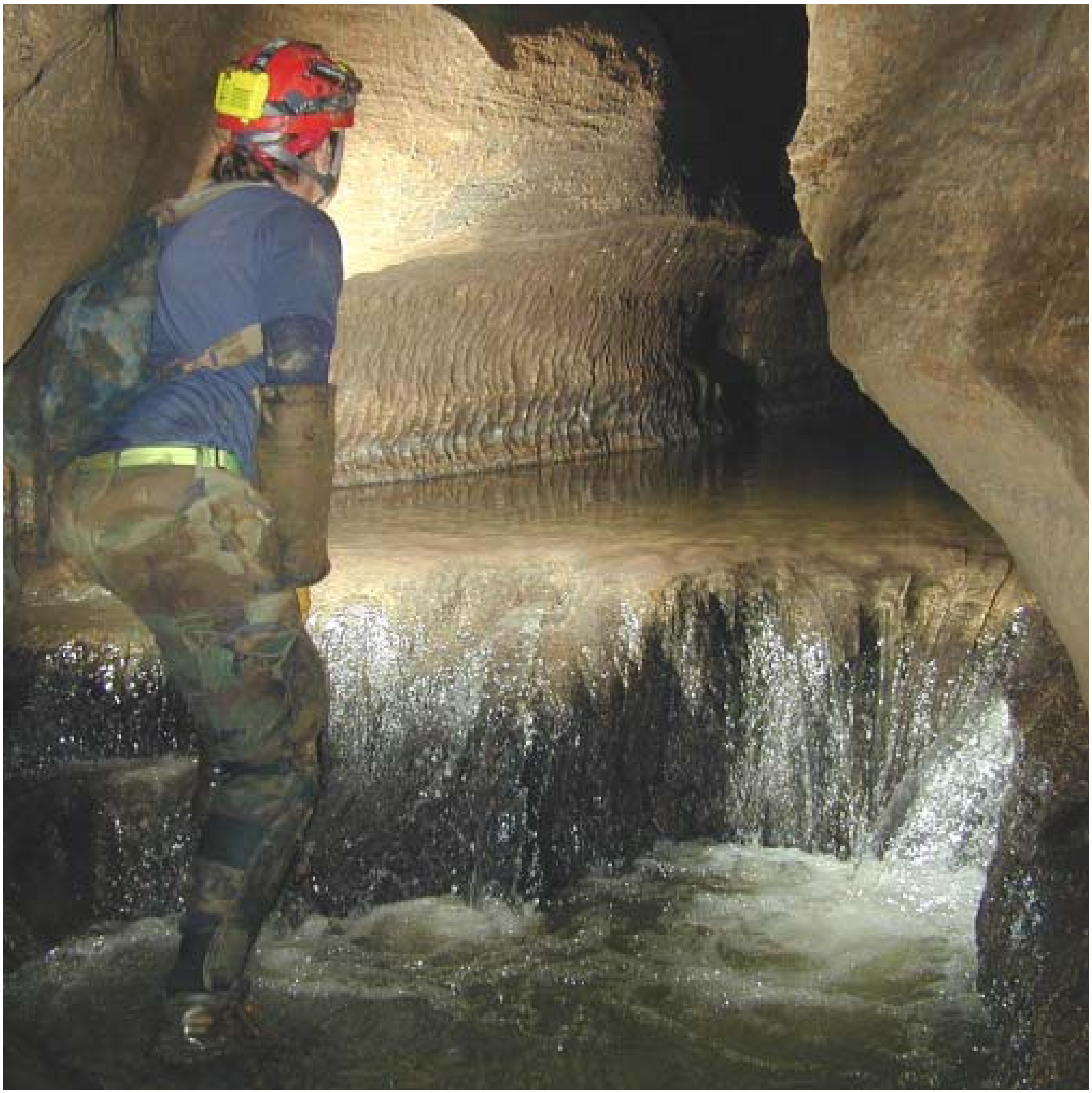

PHOLEOS

Pholeos is a biannual journal of the Wittenberg University Speleological Society (WUSS), an internal organization of the National Speleological Society (NSS).

Purpose

The Wittenberg University Speleological Society is a chartered internal organization of the National Speleological Society, Inc. The Grotto received its charter in May 1980 and is dedicated to the advancement of speleology, to cave conservation and preservation, and to the safety of all persons entering the spelean domain.

WUSS Web page

http://www4.wittenberg.edu/student_organizations /wuss/

Subscription rates are $7 a year for two issues of *Pholeos*. Back issues are available at $3.50 an issue.

Exchanges with other grottoes and caving groups are encouraged. Send all correspondence, subscriptions and exchanges to the grotto address.

Membership

The Wittenberg University Speleological Society is open to all persons with an interest in caving. Membership is $16 a year and comes with a subscription to *Pholeos*. Life membership is $150.

Meetings

Meetings are held every Wednesday at 7:00 p.m. when Wittenberg University classes are in session. Regular meetings are in Room 319 in the Barbara Deer Kuss Science Hall (corner of Plum St. and Bill Edwards Dr. - parking available in the adjacent lot).

Submissions

Members are encouraged to submit articles, trip reports, artwork, photographs, and other material to the Editor. Submissions may be given to the Editor in person or sent to the Editor at the Grotto address. Guidelines for submitting research papers can be found on the inside back cover of this issue.

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PHOLEOS

VOL. 22 (1, 2)
June 2004

CONTENTS

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FRONT COVER: Mike Slay (NSS# 48097), graduate student at the University of Arkansas, in stream passage in Kohm's Cave, Perry County, Missouri.

BACK COVER: *Scoliopteryx libatrix*, the Herald Moth, in Marti's Cave, Delaware County, Ohio.

PRESIDENT'S MESSAGE

As I look back on my four years here at Wittenberg, I can't believe they went by so fast. It seems like only yesterday I was attending my first WUSS meeting and going on my first caving trip with the club. Soon I and the other WUSS seniors will become alumni of Wittenberg and the Caving Club, but I will always look back on my experiences in the caves of Kentucky, Indiana, and West Virginia as some of the best times of my life. As you read this issue of *Pholeos*, you will notice that WUSS members have been very busy keeping up the traditions of exploration, conservation, research, and friendship that were started by those who came long before us.

The fall semester marked the real beginning of my role as President. Along with several other members of the club, I helped Dr. Hobbs with his Cave Ecology class field trips at Carter Caves and surprised him by bringing his wife, Suzie along on their anniversary. Other fall activities included an intro trip to Carter, informational speakers, vertical clinics, and the ACCA sinkhole clean up. Our trip to Indiana during fall break was plagued by poor attendance, a grouchy gatekeeper, and bad directions but we still had fun. We also caved in West Virginia where we saw some incredible cave formations. A few parties were slipped in here and there when we needed to blow off some steam and good times were had by all.

The spring semester started off with a trip to Crawl-a-thon. We also visited Sloans Cave and went to the Mammoth Cave Restoration. Several members went to TAG where they had a chance to show off their vertical skills. We *finally* were able to squeeze in a survey trip down to Carter, but were unable to find the cave we were supposed to survey. However, we used this trip as an opportunity for next year's officers to get a really good feel for the location of the best caves in the park. Again, we had the opportunity to listen to several good speakers, including a very interesting talk about bats during Bat Week. This summer, members plan to do more vertical work, re-visit Sloans, and go back to Carter to find and survey that pesky cave.

I feel that my time spent caving at Wittenberg has been a wonderful experience that helped me get the full value out of my liberal arts education. I hope WUSS will always be here so that others can have the same great opportunities that I had. As I graduate, I will "pass the light" to the newer members of the club. I trust they will continue the tradition of caving and one day pass it on to those who follow. Finally, I would like to thank Dr. Hobbs and all of the past and present members of WUSS for the great times and for making these experiences possible.

Cave on,

Bryan Welch, President
WUSS # 492
NSS # 22422

2003 Awards

During the 2003 NSS Convention in California last summer, two alumnae of Wittenberg and WUSS (both Ph.D. students) received *NSS Fellow Awards*: **Annette Engel** (NSS #31319, WUSS #0244) at the Department of Geological Sciences, University of Texas at Austin and **Megan Porter** (NSS #38171, WUSS #0262) at the Department of Zoology, Brigham Young University in Provo, UT.

Also, the *Mitchell Award* went to **Katie Schneider** (NSS #52155) of the University of Maryland (caved with WUSSes and Crawlathon attendee) for her paper "The Biogeography of the Subterranean Invertebrate Fauna of West Virginia."

Congratulations to all three, we are proud of you!

Life Members of Wittenberg University Speleological Society

Dawn Fuller Kronk (WUSS #0269)

Victor Fazio (WUSS #0045)

Don Conover (WUSS #0356)

Bill Stitzel (WUSS #0132)

Rob Payn (WUSS #0362)

Naomi Mitchell Bentivoglio (WUSS #0116)

Left to Right - Anacel Hidalgo, Claire Sandt, and Rachel Beverly after caving at Carter Caves State Resort Park, Carter County, Kentucky

Use of Fluorescein Dye to Determine the Environmental and Landuse Impacts of Karst Topography and Groundwater Flow in the Warrensburg Road Karst Drainage Basin, Delaware County, Ohio.

Lindsay McCullough, NSS #48931, WUSS #0469
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John B. Ritter

Abstract

The Warrensburg Road Karst, located in Delaware County, Ohio, approximately 64 kilometers north of Columbus, provides a representative sampling of the several small karst areas that are located along the Scioto River in central Ohio. As the edge of suburban Columbus advances northward it becomes increasingly important to understand the hydrology of these landscapes. Due to the close interaction between surface and subsurface water, karst areas require special attention to address potential pollution and engineering problems that will only become more pronounced as the development of the area continues. Fluorescein dye, an environmentally safe and easily detectable substance, was used to make point-to-point connections between surface insurgences and resurgences. In order to understand better the characteristics of ground water flow in this basin, dye detectors were removed from the resurgence at varying intervals. A map also was created of the area using GPS and GIS technology that shows the location of karst surface features and the traced network of subsurface drainage.

Introduction

Increasing suburban growth in the Columbus area has resulted in the development of lands that were originally used for agriculture or left as low-use wooded areas. The Warrensburg Road Karst (WRK), located in Delaware County, Ohio about 64 kilometers north of Columbus, lies on the east bank of the Scioto River (Figure 1). This area, due to its close proximity to the city, has potential for suburban encroachment. The Scioto River serves as local base level, flowing south for approximately 200km before joining the Ohio River at Portsmouth, Ohio. Due to its small size, the WRK is an easily managed study area that provides a sample of the hydrology that may be applicable to other local karst areas located along the Scioto River and a better understanding of karst hydrology in general.

Background Information

The WRK lies in the upper portion of the Devonian Columbus Limestone (Westgate, 1926). In Delaware County, the Columbus Limestone is found below the Delaware Limestone and above the Monroe Dolomite (Figure 2). The Columbus Limestone has been quarried locally on a small scale along with the overlying Delaware Limestone. The Columbus Limestone is slightly dolomitic throughout its thickness as shown by the presence of $MgCO_3$ in varying amounts and the occurrence of small dolomite rhombohedrons in thin section (Westgate, 1926).

By definition, karst "signifies terrain with distinctive characteristics of relief and drainage arising primarily from a higher degree of rock solubility in natural waters than is found elsewhere" (Jennings, 1985). Surface karst features that are present in the WRK include chains of small sinkholes, larger isolated sinks with small caves, swallets at the end of blind valleys that often contain small, accessible caves, and one known spring that serves as a major resurgence for local groundwater flow. These features create a closer relationship between surface and subsurface water than is present in non-karst areas by allowing surface runoff direct access to ground water.

Sinkholes and swallets in the WRK are found in small wooded areas fringing agricultural fields and pastures, and as small pockets of woods within these fields and pasturelands. Current land-use in these wooded areas is minimal, however, at least two sinkholes are used as local small-scale trash dumps (Figure 3). Some of the surface insurgences have well developed, easily seen drainages in the form of gullies and dry stream beds (Figure 4) entering them while others do not, thus showing that they probably are not taking in as much surface runoff.

Dewitt Spring, the only known local resurgence of the WRK drainage basin, is found in pastureland at the base of a small rock outcrop west of the wooded areas that contain the sinkholes (Figures 1 and 5). The spring flows perennially, however, during storm events spring discharge increases significantly. An overflow to Dewitt Spring (Figure 6), located approximately 25m east of the main spring, is activated to accommodate excess discharge during major flow events (Dogwiler, 2001).

Dogwiler and others, in a study conducted in 1995, obtained five positive dye traces to Dewitt Spring from surface insurgences and a stream in a small karst window east of the spring. Dogwiler found that during storm events these five insurgences contribute 50-70% of the water discharged from the spring. Several of these dye traces were visibly detected by the Dewitt family (the land-owners at the time of that study) within 12-24 hours after injection of the fluorescein (Dogwiler, 2001).

Figure 1. Map of the study area. Black Triangle shows the location of Dewitt Spring.

Groundwater flow velocity is characteristic of the structure of the material through which it moves. The major types of groundwater flow in karst terrains are diffuse (slow, laminar) and conduit (rapid, turbulent). These two types of flow are end members of a flow continuum and both can exist in different places relatively close to each other (Mull, 1993). The speed at which the Dewitt family detected the dye during Dogwiler's previous study suggests that the WRK is dominated by conduit flow. If conduit flow is dominant, the movement of possible contaminants through the groundwater supply will not only be much more rapid, but water will not be passed through the natural filter provided by soil or bedrock as groundwater in non-karst areas would be. Clearly, defining the dominant flow type in the WRK basin is vital to the analysis of the movement of pollutants through the groundwater system.

Karstic lands, especially those developed as residential areas requiring the use of wells and septic systems, must be given special attention with regard to water quality issues. The fact that the WRK is an area with a well developed surface to subsurface drainage pattern, coupled with the possible domination of rapid conduit flow in the subsurface complicates these issues. Residential growth is dependent upon a clean water supply. Wells and septic systems in karst landscapes do

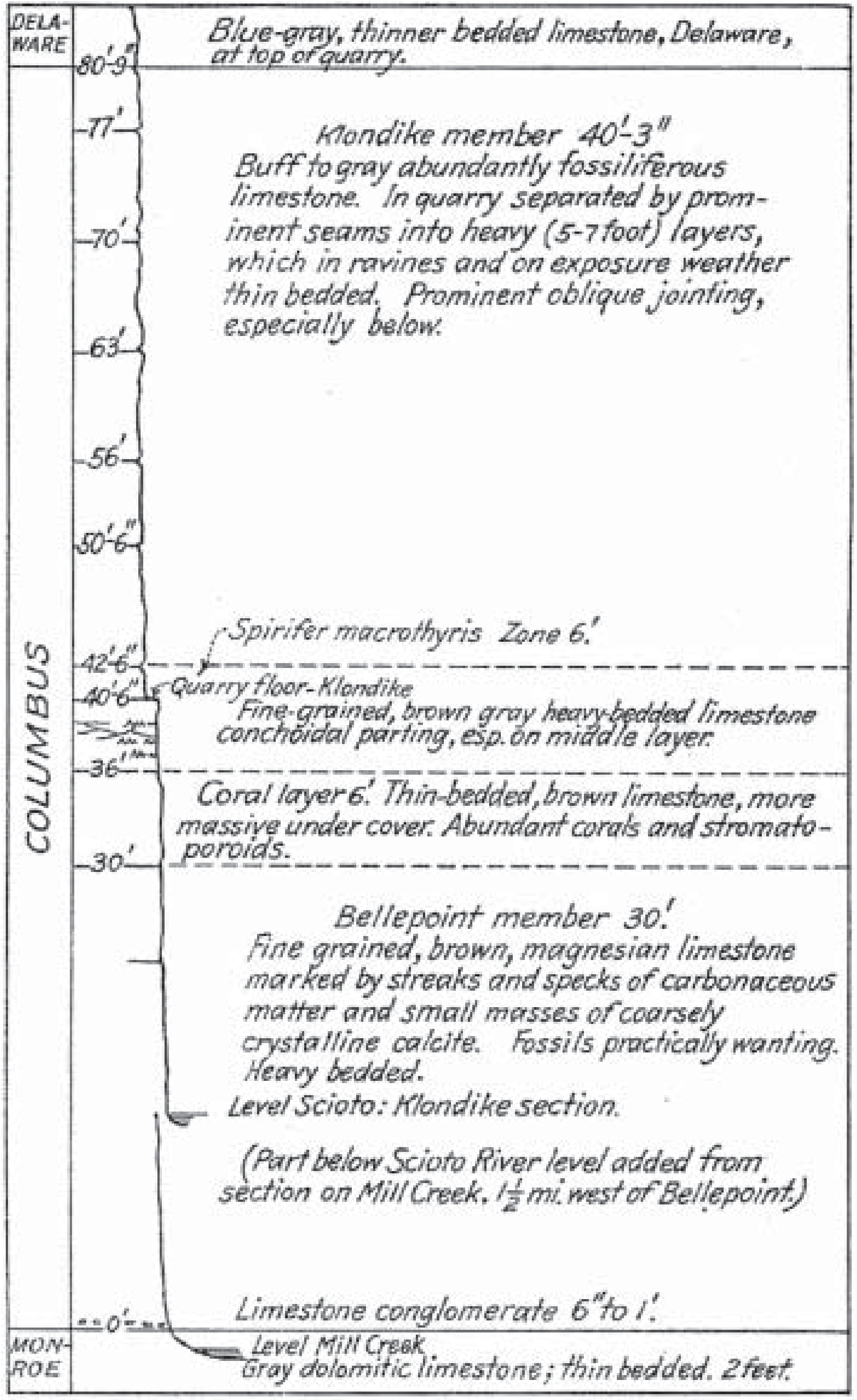

Figure 2. Stratagraphic Column of the Study Area (Westgate, 1926).

Figure 3. Sinkhole used as a trash dump.

Figure 4. Well developed surface drain, leading to a blind valley.

not provide this (Heath, 1983). If this area has potential for development, a much greater understanding of the hydrology must be reached.

Objectives

The objectives of this study were to: (1) conduct more fluorescein dye tests in an attempt to understand further the path of the subterranean drainage system connected with Dewitt Spring, (2) evaluate the potential environmental impacts of current and future land uses in the area by way of dye testing results, and analysis of present trends and future land use possibilities, (3) gain a better understanding of the natural characteristics of groundwater flow in the basin, i.e. diffuse flow vs. conduit flow, and (4) to use GPS and GIS technology to map the surface karst features of the area.

Methods and Materials

Flourescein dye requires large quantities of water to obtain positive, quality traces. Consequently, testing was conducted during precipitation and snow-melt events that provided sufficient runoff for successful dye tracing. Activated charcoal detectors were used to determine the presence of fluorescein.

Figure 5. Dewitt Spring, the only known resurgence in the study area.

Figure 6. The overflow to Dewitt Spring that is activated during high flow events.

The activated charcoal in these detectors absorbs fluorescein from water in which they are placed. Detectors were constructed from fine mesh nylon screen wire. A 12.5 cm by 15 cm square of screen was folded to make a 12.5 cm by 7.5 cm envelope. Approximately 12 grams of activated charcoal were put into each envelope. Envelopes were securely stapled shut to avoid loss of charcoal (Aley and Fletcher, 1976).

Before injection of the dye, the detectors were placed at Dewitt Spring (Figure 7) to protect from contamination that may have taken place if dye was handled prior to touching detectors. Prior to the conduction of the first test, water from the stream and one of each batch of charcoal detectors was tested for initial traces of fluorescein to insure controlled results. Charcoal detectors and dye were kept separate both in the laboratory and during transport to protect against cross contamination. Detectors were changed regularly in order to determine the velocity of groundwater transport in the basin (Figure 8).

Figure 7. Activated charcoal detector at Dewitt Spring.

Figure 8. Changing the detector at Dewitt Spring.

Before elution, detectors used in tracing were rinsed in water to remove sediment and organic matter. The contents of the detector were then emptied into a beaker and covered with a solution of 5 % KOH in 70 % isopropyl alcohol (Aley and Fletcher, 1976). In a positive test, fluorescein that had been absorbed by the charcoal appeared as a green haze above the charcoal. Negative test showed no green color. Strongly positive test were easy to see. However, it was often necessary to use a high intensity white light to distinguish weekly positive and negative test.

Mapping was conducted using Trimble GIS units to obtain accurate coordinates of surface karst landform positions (Figure 9). The data collected were then plotted on a Digital OrthoPhoto Quad. This map will be an important resource for future studies in the area as well as developmental planning.

Figure 9. Mapping a surface karst feature with a Trimble GIS unit.

Results

Using Trimble GIS units, all surface karst features within the Warrensburg Road Karst were mapped and plotted on a Digital OrthoPhoto Quad of the study area (Figure 10). Three positive dye traces were obtained during this study. Combined with the five positive tests conducted by Dogwiler et al. in 1995, these traces give a good indication of the extent of the Dewitt Spring Drainage Basin in the WRK (Figure 10). Removal of detectors every few days after a test has shown that, for the insurgences traced, dye reaches the stream within 36 hours or less. After initial detection, dye input to the spring was maintained in some traces for as long as two weeks.

Discussion

Dye tests conducted during this study were detected at the spring within 36 hours or less. During the study conducted by Dogwiler et al. (1995), the Dewitt family visibly detected several dye traces within 12 to 24 hours of injection (Dogwiler, 2001). The higher rate of transport suggested by Dogwiler may be due to the following factors: 1) As the first worker in the area Dogwiler was testing larger, more open insurgences that most likely have a better development of subsurface conduit systems, 2) Detectors used in this study were only changed every few days, inhibiting the initial dye influx from being well constrained.

In addition to reaching the spring within a short time, dye detection was maintained for as much as two weeks. The combination of both relatively high and slow transport velocities suggests that both conduit and diffuse flow are operating in the WRK. During injection, some dye is probably washed immediately into subsurface conduits by storm runoff while some gets caught up in soil and other organic matter in the insurgence. The latter situation allows for slow release of dye as water is leached from soil and organic matter and moved through the system.

The combination of diffuse and conduit flow in the WRK has important implications for groundwater pollution potential. Not only will pollutants such as nitrates, pesticides, and sewage travel quickly through the system in concentrated amounts, but they also will continue to affect water quality in smaller concentrations for several weeks. For many pollutants, the dilution allowed by slow transport will make them less harmful. Others, however, may degrade water quality even in small doses.

Pollution mitigation is complicated by the fact that many insurgences in the WRK are found in agricultural fields that are being treated with chemical pesticides (McCormick, 2003). In order for successful farming to continue in the WRK and in other similar karst areas along the Scioto, as well as allowing for protection of ground water resources, measures to slow and or stop the movement of pollutants into the subsurface drainage system must be implemented. The Delaware County Soil and Water Conservation District has done considerable work in designing and implementing structures to slow soil loss into sinkholes from agricultural fields (Dogwiler, 2001). Clearly, similar measures should be taken with regard to pollutants.

Far more threatening to the WRK than agriculture is the steady population growth and development of the region. The ubiquity of karst features in the WRK is a serious concern for current and future property owners. As local land-use patterns

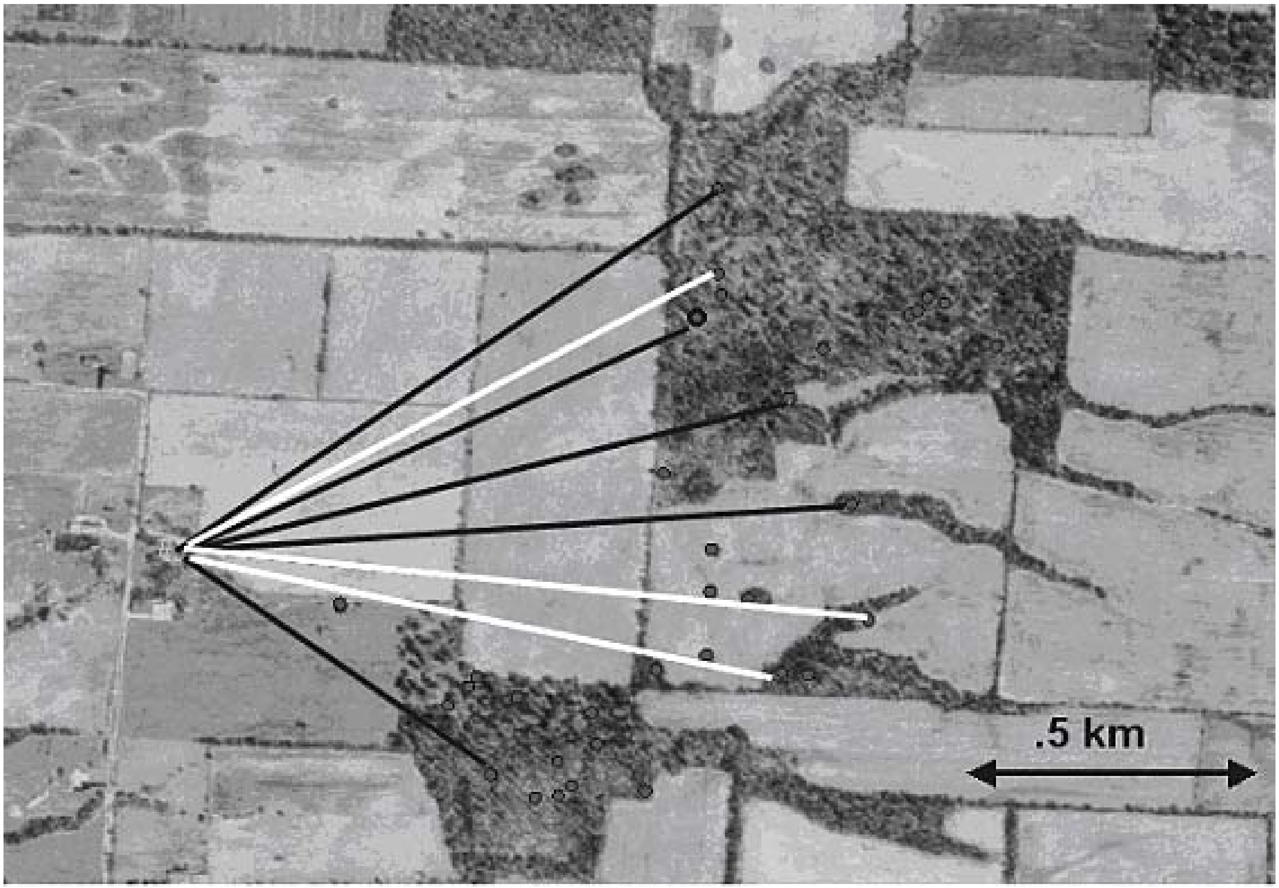

Figure 10. Map showing the connection of surface insurgences with Dewitt Spring. White lines represent insurgences traced during this study and the black lines represent those traced by Dogwiler (1995).

shift towards high-density suburbs, the risk of ground water contamination grows. Responsible residential growth of the region will require careful planning and conservation measures regarding wells and sewage systems to insure water quality. If such implementations cannot be carried out in a cost-effective manner, land use in the WRK should be limited to agriculture and low-impact activities.

Conclusion

The Warrensburg Road Karst, located in Delaware County, Ohio, about 64 kilometers north of Columbus, provides a representative sampling of the karstic areas that are located along the Scioto River in central Ohio. Dye tracing conducted during this and a similar study (Dogwiler et al., 1995) show a well-developed subsurface drainage network. The combination of both relatively high and slow transport velocities suggests that both conduit and diffuse flow are operating in the WRK. Consequently, pollutants will not only travel quickly through the system, but also will continue to affect water quality for several weeks, or possibly a longer duration.

The highly developed surface to subsurface water interaction makes karst areas such as the WRK especially sensitive to possible ground water contamination. Increasing suburban growth in the Columbus area has resulted in the development of lands that were originally used for agriculture or left as low-use wooded areas. The concentration of karst features in the WRK is becoming a serious concern as land-use patterns shift towards high-density suburbs and housing developments. Responsible and successful residential growth will require careful planning and conservation measures to insure water quality. If these needs cannot be met, future development in the area should not take place.

Acknowledgments

We would like to thank Kristen Baughman, Sara O'Donnell, Shannon Hill, Katie Bringman and Laura Davis for many successful days in the field dye tracing and mapping; Tom Aley from the Ozark Underground Laboratory for his help gathering materials; Toby Dogwiler for his past work and advice at the start of this study; and especially Jim McCormick, Charles Marti, Richard Rolland, Michael and Joette Gilliam, and the Fegleys for allowing us access to their property for the duration of the study.

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Entrance to Willie's Cave, Delaware County, OH (photo by H. Hobbs III).

The Degree to Which Inland and Oceanic Blue Holes are Characterized as Limited Ecosystems

Stacey L. Josif

ABSTRACT

Both inland and oceanic blue holes, underwater or underground networks of caves created by the corrosion of limestone, are characterized by their isolation, restricted energy supply, and lack of species diversity. For these reasons, both inland and oceanic blue holes can be classified as limited ecosystems. Research from several studies on these holes provides evidence that the organisms living in inland blue holes face greater spatial heterogeneity, resulting in more extreme environmental conditions, a greater lack of light energy, and a fixed food supply in comparison to those organisms found in oceanic blue holes. As a result, inland blue holes can be characterized as limited ecosystems to a greater degree than oceanic blue holes.

INTRODUCTION

Approximately one million years ago, during the recent ice age, many of the blue holes that can be found in the Bahamas today, were just beginning to form. Throughout this period, sea levels continuously rose and fell, leaving the sea floor entirely covered for periods of time and fully exposed to the corrosion of wind and rain at other times. Further deterioration took place underground, where a fresh layer of water mixed with the saline water of the sea. At this point the limestone rock was dissolved. Because of changes in tide, the level where the two points mix constantly shifted, allowing for decomposition at different levels. Over a long period of time, corrosion produced caves that were hundreds of meters in depth and connected in complex networks under both land and sea. Even today these caves continue to expand as more limestone is dissolved.

Generally, blue holes can be classified into two major types: inland and oceanic. Divers in recent years have only begun to explore these types of caves and to cite the many differences between them. In 1958, George Benjamin, a research chemist from Toronto, became the first scientist to begin exploring oceanic blue holes. Throughout his lifetime he surveyed several dozen holes off of South Andros Island, Bahamas (Belleville 1994). Many other scientists followed Benjamin and continued to explore and gather data from oceanic blue holes. Although work was being done to understand oceanic holes, minimal exploration of inland blue holes took place until 1987 when Mike Madden, a dive operator, began to make yearly dives into the largely known Nochoch Nah Chich, found in Playa del Carmen, Mexico (Belleville 1994). Over the years he and other divers have gathered large amounts of information about this inland blue hole, inspiring others to gather data at other sites as well.

In comparing inland and oceanic blue holes, the degree to which they can be classified as limited ecosystems can be assessed. Before such comparison can be made however it is important to understand what characterizes this type of ecosystem. Limited ecosystems can often be distinguished by their extreme environmental conditions. These can include, but are certainly not limited to, severe temperatures, pH levels, salinity levels, and exposure to UV radiation. Due to their extreme environment, limited ecosystems often have limited species diversity and even several specialized species. Finally, they often are isolated from the ecosystems which surround them, resulting in a limited energy supply.

The intent of this study was to use the data collected by several divers to make comparisons between inland and oceanic blue holes, and using these comparisons, as well as the definition above, to determine to what degree inland and oceanic blue holes classify as a limited ecosystems.

METHODS AND MATERIALS

Inland, Smart (1984) measured the depths as well as the temperature, salinity, and conductivity of eighteen inland blue holes scattered throughout Andros Island, Bahamas: Ocean Hole, Conch Sound, Uncle Charlie's, Swamp Pond, Owens Town, Stafford Creek I, Stafford Creek II, Ken's, Not A, Gollum's, Stalactite, Pig Run, West Twin, East Twin, Cousteau's, Hour Glass, Paul's, and Church's (Figure 1). To do so a 15 meter probe and a YSI-33 Salinity, Conductivity, Temperature meter were used, and samples below 15 meters were collected by a water sampler or a diver (Smart 1984).

Farr and Palmer (1984) observed the size, structure, and marine life found inside several inland blue holes on Andros Island, Bahamas: Uncle Charlie's, Ocean Hole, Stalactite Blue Hole (Archie's Blue Hole). Detailed methods and materials for their observations were not given.

Palmer (1987) observed the marine life found in the inland blue holes of South Andros, Bahamas. Detailed methods and materials for his observations were not given.

Kornicker et al. (2002) collected data on the temperature, salinity, dissolved oxygen, pH values, and marine life in the inland blue holes of Mermaid's Lair and Stargate Blue Hole. In the Mermaid's Lair a diver using a Hydrolab gathered water column profiles diagonally from the surface to a depth of 22 meters. Also divers used a 93 micrometer mesh plankton net, suction bottle, and vials in 18-22 meter depths to collect ostracods, thermosbaenaceans, cirolanid isopods, and copepods. In Stargate Blue Hole a Hydrolab Recorder Water Quality Multiprobe Logger was lowered from the surface to 80-meter depths for the collection of water column profiles. Also divers used plankton net tows or individual vials from depths of 33-36 meters of the North Passage and 33-39 meter depths of South Passage to collect ostracods, copepods, thermosbaenaceans, archeannelids, and polychaetes (Kornicker et al. 2002).

Kornicker and Iliffe (1992) collected samples of three species of ostracods in several inland blue holes near Discovery Bay, Jamaica: East Bull, Dairy Bull I, Dairy Bull II, South Bull, Air Strip #1, Air Strip #2, Air Strip #5. The salinity of each cave was measured against distilled water and seawater standards using a refractometer, and the species occurrence was calculated for *Spelaeoecia jamaicensis, Danielopoina elizabethae*, and *Pontopolycope mylax* at each site (Kornicker and Iliffe 1992).

Oceanic

Warner and Moore (1984) collected data on currents, suspended particulate material, plankon, and sessile organisms

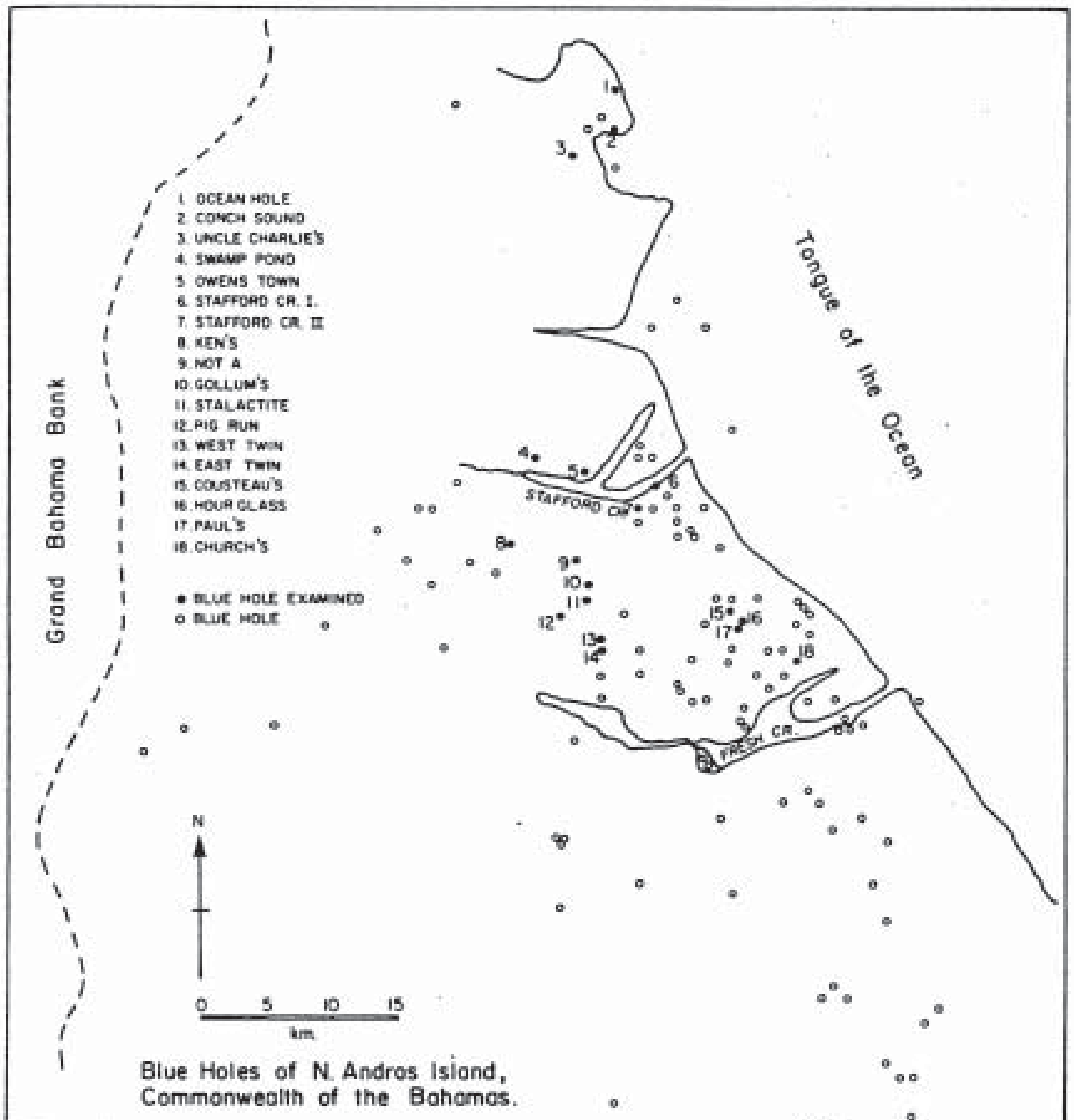

Figure 1. Blue holes on Andros Island studied by Smart (1984).

in the oceanic blue hole of Conch Sound I on Andros Island, Bahamas. Magnetic tape recorded speed and direction of currents every four minutes from 26-29 August 1981. A Plessey Current Meter measured the speed and direction of currents every ten minutes from to 5-20 August 1982. All high and low tide times were taken from a table provided by the Atlantic Undersea Test and Evaluation Center (A.U.T.E.C.) at Fresh Creek. Particulate material was collected and analyzed by two methods: wet oxidation and Carbon/Sulphur Determination. Plankton samples were collected during both suck and blow currents and placed in large petri dishes where they were examined using a Wild M5 stereo microscope. A Nikonos III underwater camera with 28-millimeter lens was used to produce random photographs with quadrats of 0.03 square meters, which were analyzed to formulate estimates of the percentage cover of each sessile organism in the blue holes (Warner and Moore 1984).

Farr and Palmer (1984) observed the size and structure as well as the marine life found in several oceanic blue holes on Andros Island, Bahamas: Conch I, South Mastic 6, South Mastic Blue Hole Two, Rat Cay, Forfar, Mangrove Cay 31, Mangrove Cay 32, Mangrove Cay 33, Mangrove Cay 34, Coral, and Mars Bay. Detailed methods and materials for their observations were not given.

Palmer (1987) observed the marine life found in the oceanic blue holes of South Andros, Bahamas. Detailed methods and materials for his observations were not presented.

Kornicker et al. (2002) used the data collected from Kornicker and Iliffe (2000) for several of the blue holes they studied: Angelfish, Crab Cay, Sugar Cay, Mystery Cave, Master Harbour Cave, and Conch Sound. For Four Shark Cave however they collected data on salinity, pH, dissolved oxygen, and marine life during different tides. To make water column profiles a Hydrolab Recorder was placed 15m inside the cave and allowed to record at one minute intervals for 12 hours. Divers using plankton nets at depths ranging from 27-33 meters collected ostracods, cumaceans, copepods, larval shrimp, and nebaliaceans (Kornicker et al. 2002).

RESULTS

Inland

The results of the following experiments describe the conditions and marine life found inside an inland blue hole. Smart (1984) found the depth of the inland holes he studied to vary from 2 meters to 110 meters, with diameters of 30 to 250 meters. He also noted that the water clarity improved as depth increased. Thirdly, Smart plotted the salinity profiles for the studied blue holes, noting the halocline layer (Figure 2). Using the collected salinity measurements, he found that a freshwater lens existed in each of the blue holes studied. The depths of these freshwater lenses varied in each hole (Figure 3). Finally, temperatures were plotted for various blue holes, showing a decrease in temperature as depth increased (Figure 4). Smart noted that there are slight increases in temperature at depths in which bacterial plates exist (Figure 4), and suggested that these plates

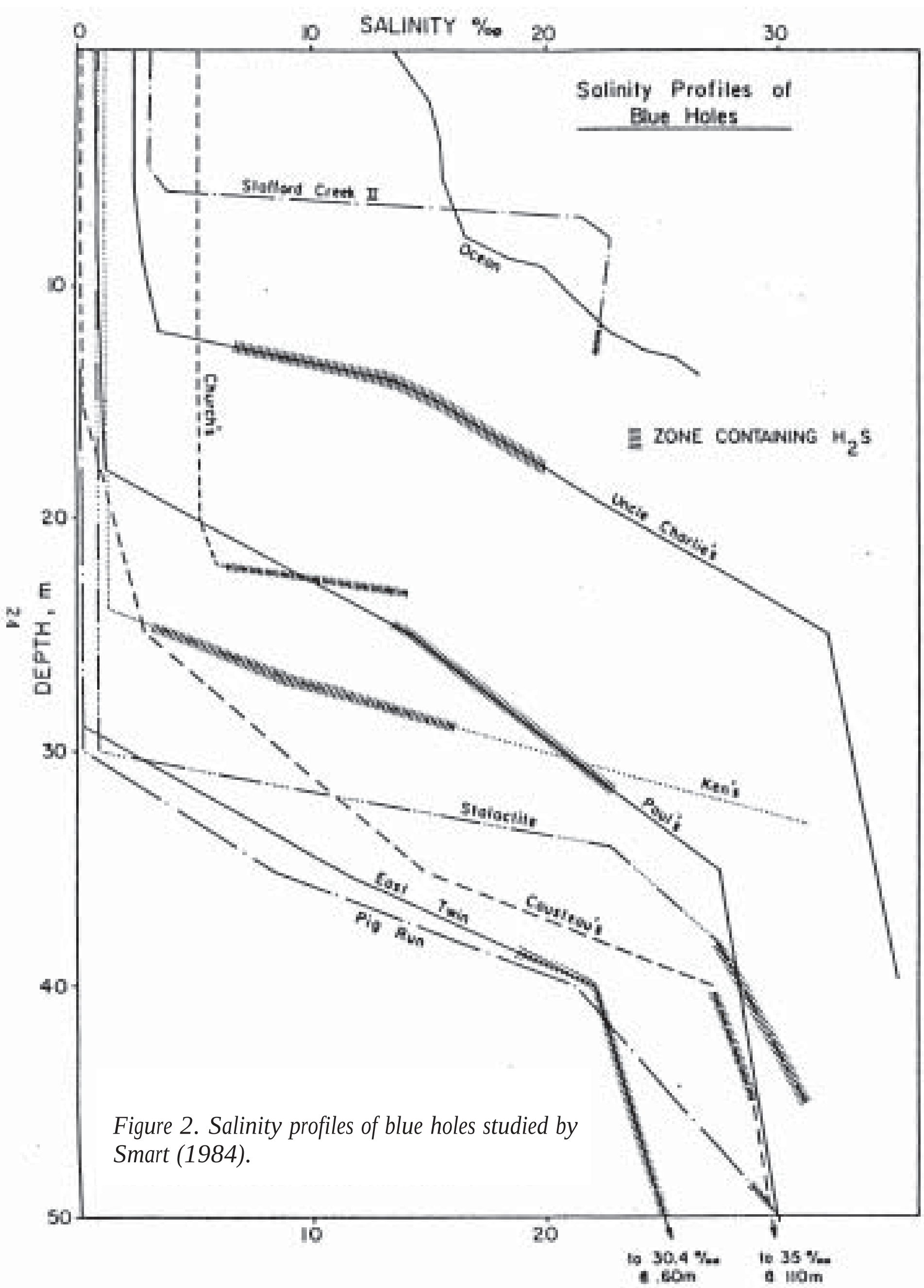

Figure 2. Salinity profiles of blue holes studied by Smart (1984).

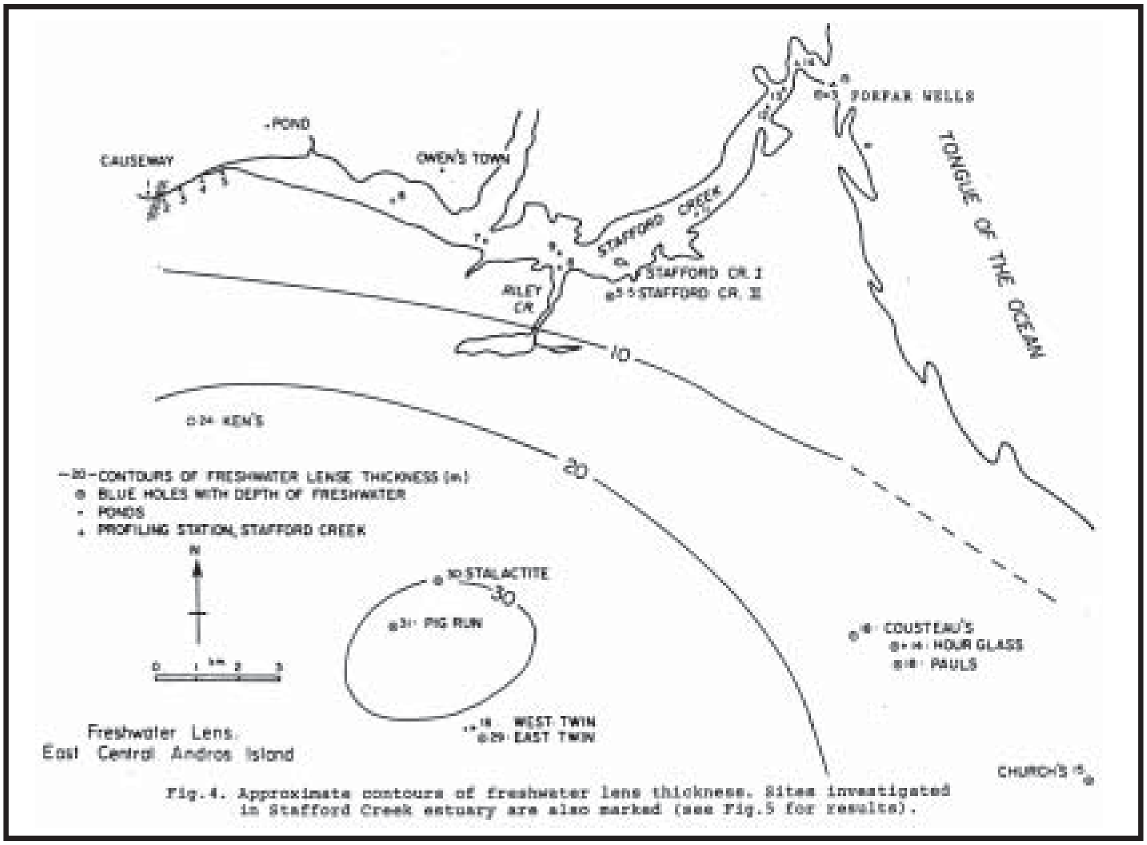

Figure 3. Depths of the blue holes' freshwater lens studied by Smart (1984).

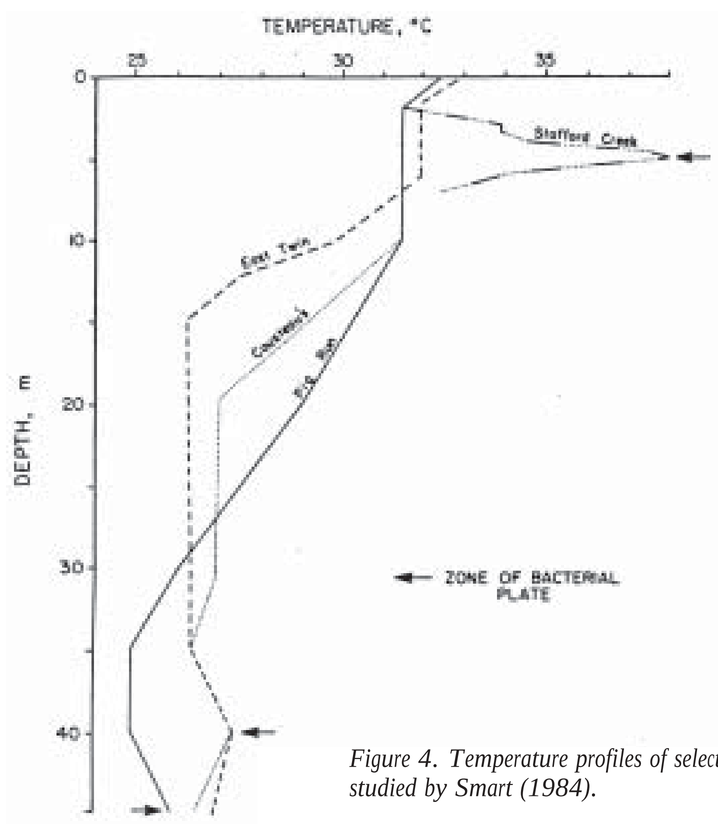

Figure 4. Temperature profiles of selected blue holes studied by Smart (1984).

are likely composed of purple sulphur bacteria, Thiorhodaceae (Smart 1984).

Farr and Palmer (1984) made specific observations on each of the three blue holes they observed: Uncle Charlie's, Ocean Hole, and Stalactite Blue Hole. They found Uncle Charlie's had a maximum depth of 41 meters, with a diameter of 50 meters. They also noted that it had a halocline layer at a depth of 14-15 meters. In addition sufficient amounts of *Lucifuga spelaeotes*, commonly referred to as the blind Bahaman cave fish, in small tunnels near the 15-meter depth, and land crabs were found at the base of the hole. Farr and Palmer also studied Ocean Hole, finding it to be much larger than Uncle Charlie's. They reported its maximum depth at 50 meters, with three major underwater passages at depths of 48 meters, and a large passage leading east for 150 meters. They also noted that the halocline layer began immediately at the surface and continued to a depth of 20 meters. Finally, Farr and Palmer studied Stalactite Blue Hole, with a diameter of 75 meters and a maximum depth of 70 meters. Notably this hole contained stalactites from the depths of 23 to 33 meters and a halocline layer at 33 meters. Also they reported that Stalactite Blue Hole contained a significant number of large gobies and land crabs (Farr and Palmer 1984).

Palmer (1987), based on his experiences with inland blue holes, generalized their characteristics and the life he has found there. He observed that the holes themselves are surrounded by much plant and bird life. He also noted the existence of a freshwater lens and mixing layer. The mixing layer contains much organic material that serves as a nutritional source for microcrustaceans. These in turn serve as food for larger crustaceans, which are the nutritional source for yet larger crustaceans, such as the Remipedia (Palmer 1987). Other species found in these caves include specialized jellyfishes, crabs, and even fishes. Two notable species of fishes include spiny-cheek sleepers and *Lucifuga speleotes*; both species have adapted to the darkness and salinity variances (Palmer 1987).

Kornicker et al. (2002) examined both Mermaid's Lair (Figure 5) and the Stargate Blue Hole (Figure 6). They found Mermaid's Lair to contain halocline layers at 1.5-6 meter depth and at the 16-19 meter depth. In the upper halocline layer the salinity increased from 3.2 g/L to 10.4 g/L, and in the lower halocline layer the salinity increased from 10.4 g/L to 35.0 g/L (Figure 7). They also noted that the temperature decreased as depth increased (Figure 8). Also pH and dissolved oxygen content were plotted for different depths (Figures 9 and 10). Kornicker et al. (2002) found the halocline layer of the Stargate Blue Hole between depths of 22-27 meters, where salinity increased from 3.4 g/L to 37.0 g/L (Figure 11). As seen in Mermaid's Lair, temperature decreased as depth increased (Figure 12), and pH and dissolved oxygen content were plotted for different depths (Figures 13 and 14). The species of Myodocopa found in both inland blue holes also were counted (Table 1), showing most to be from the order Halocyprida, and the families Halocyprididae and Thaumatocyprididae (Kornicker et al. 2002).

Kornicker and Iliffe (1992) examined several inland blue holes near Discovery Bay, Jamaica for species of halocyprid ostracods. More specifically, they noted the salinity of these holes and the depths at which the species were collected (Table 2). In addition to these species they found that copepods, tanaidaceans, podocopid ostracodes, amphipods, mysids, shrimp, isopods, gobiid fish, mites, and archiannelids also were collected (Kornicker and Iliffe 1992).

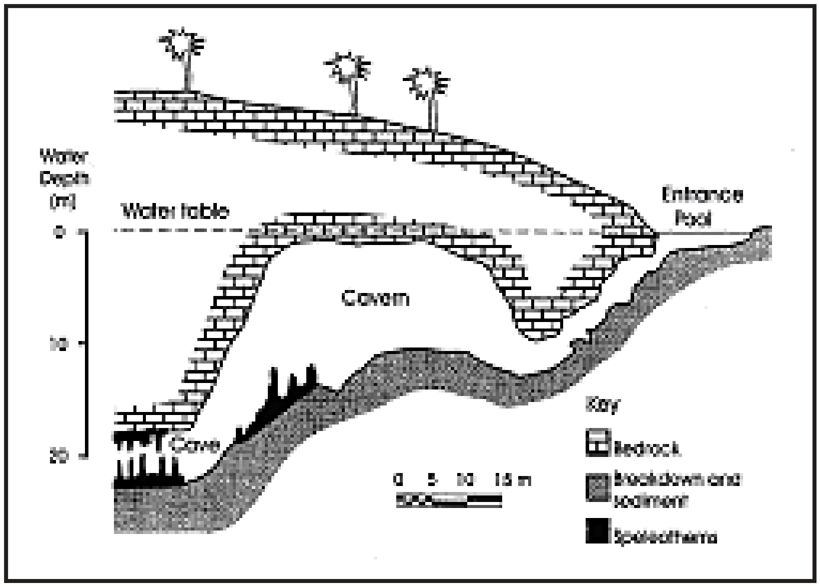

Figure 5. Mermaids Lair Blue Hole (Kornicker et al. 2002).

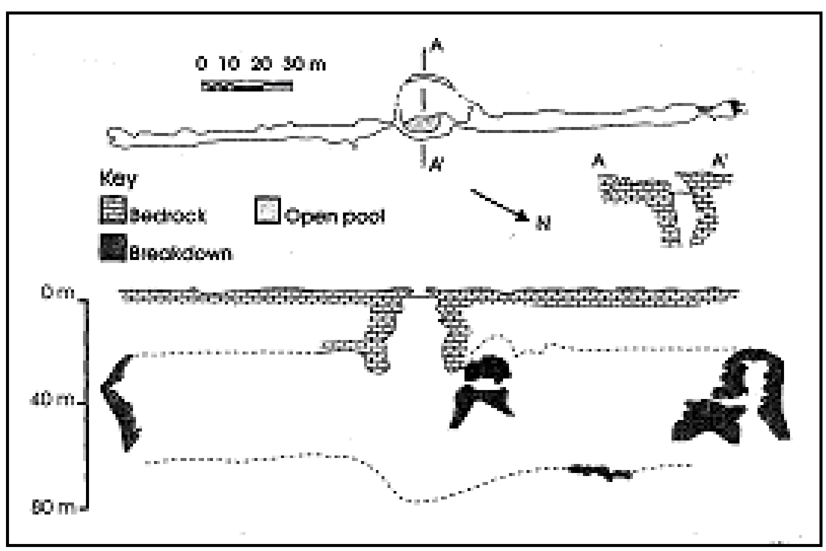

Figure 6. Stargate Blue Hole (Kornicker et al. 2002).

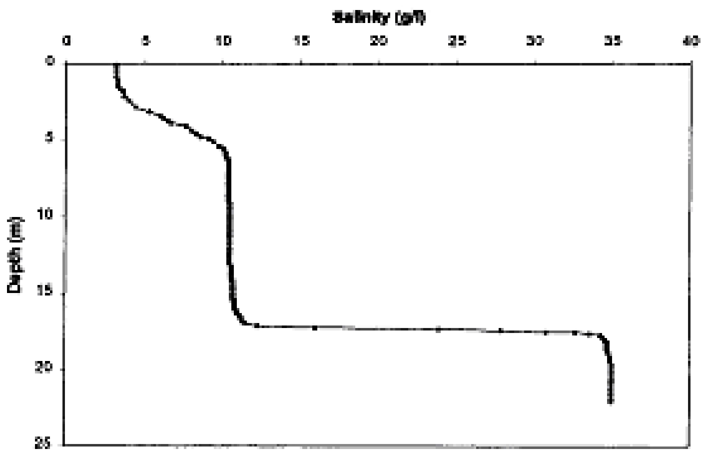

Figure 7. Salinity measurements at different depths of Mermaids Lair, as reported by Kornicker et al. (2002).

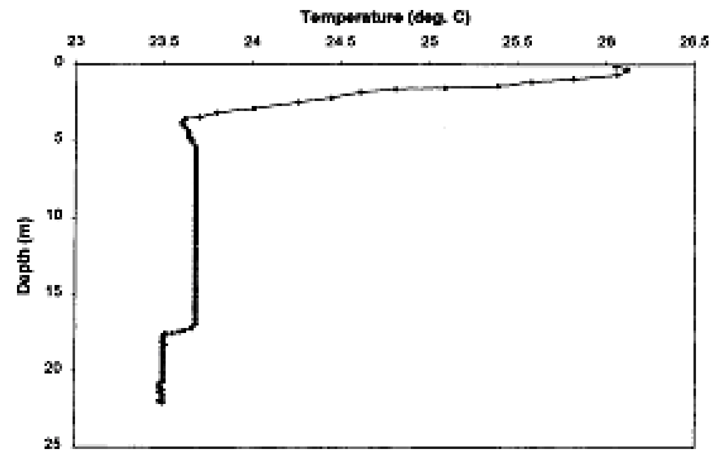

Figure 8. Temperature measurements at different depths of Mermaids Lair, as reported by Kornicker et al. (2002).

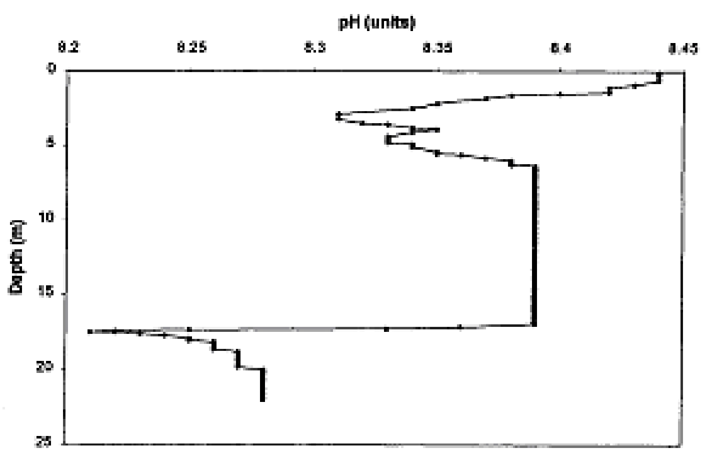

Figure 9. Measured pH values at different depths of Mermaids Lair, as reported by Kornicker et al. (2002).

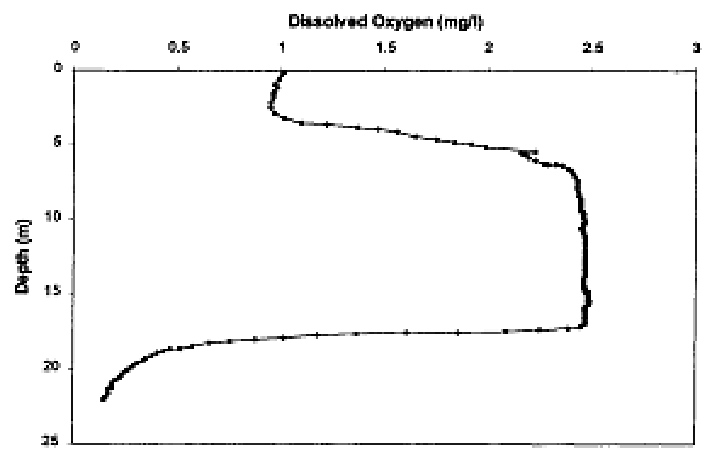

Figure 10. Measured Amount of oxygen at different depths of Mermaids Lair as reported by Kornicker et al. (2002).

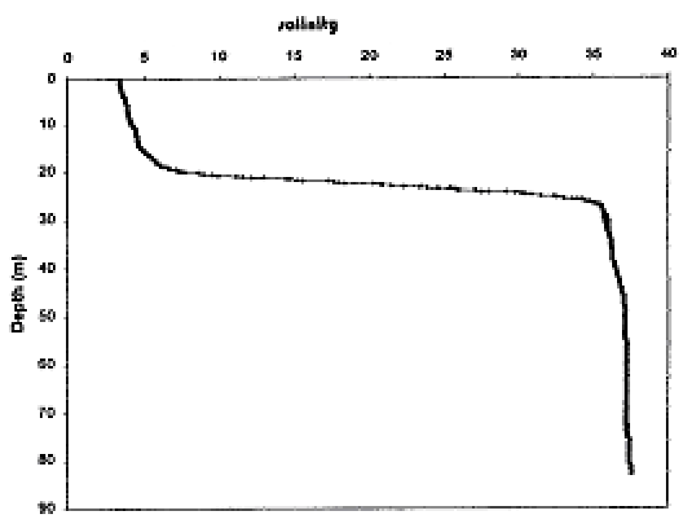

Figure 11. Salinity measurements at different depths of Stargate Blue Hole, as reported by Kornicker et al. (2002).

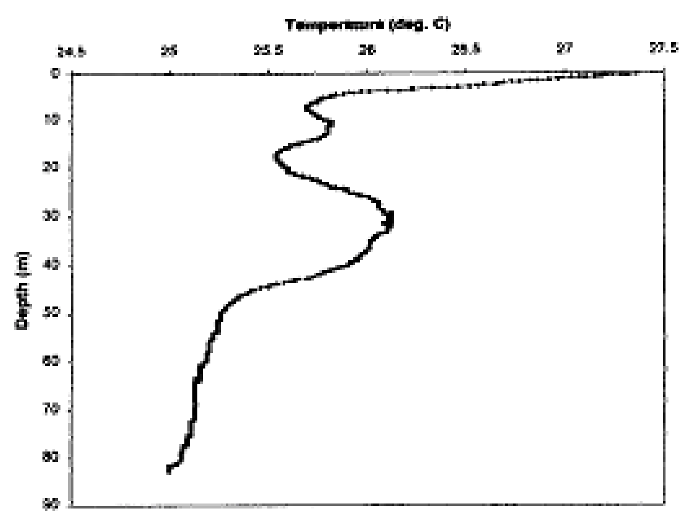

Figure 12. Temperature measurement at different depths of Stargate Blue Hole, as reported by Kornicker et al. (2002).

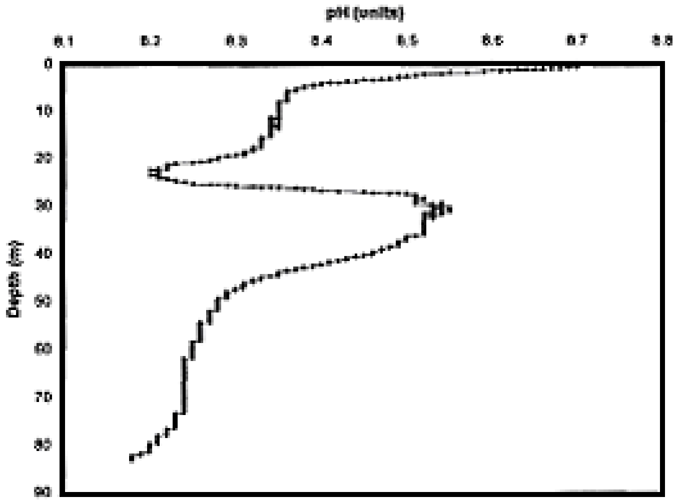

Figure 13. Measured pH values at different depths of Stargate Blue Hole, as reported by Kornicker et al. (2002).

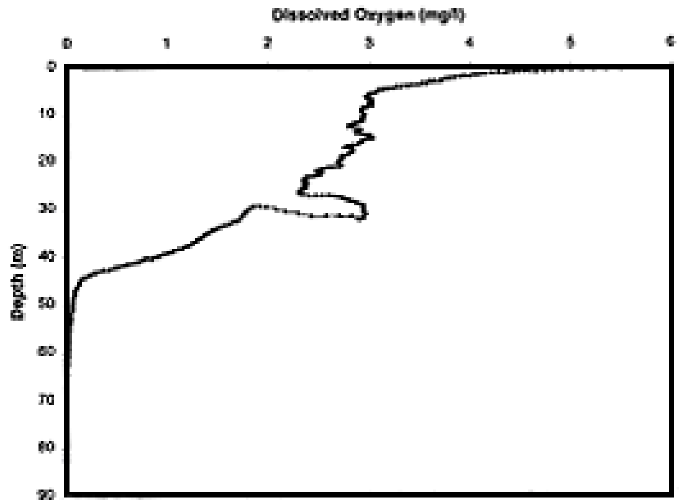

Figure 14. Measured amount of oxygen at different depths of Stargate Blue Hole as reported by Kornicker et al. (2002).

Rainbow Blue Hole, Andros Island, Bahamas (photo by H. Hobbs III).

Table 1. Myodocopa in Bahamian Blue Holes as reported by Kornicker et al. (2002).
OO= open ocean OBH= Oceanic Blue Holes IBH= Inland Blue Holes.

Taxa	OO	OBH	IBH
Order Halocyprida			
Family Halocyprididae			
Deeveya bransoni	–	–	33–39
Deeveya exleyi	–	–	0–1
Deeveya hirpex	–	–	?
Deeveya jillae	–	–	0–3
Deeveya medix	–	–	?
Deeveya spiralis	–	–	?
Deeveya styrax	–	–	?
Spelaeoecia barri	–	–	0–2
Spelaeoecia capax	–	–	0–20
Spelaeoecia sagax	–	–	?
Spelaeoecia styx	–	–	0–39
Family Thaumatocyprididae			
Danielopolina bahamensis	–	–	0–3
Danielopolina exuma	–	–	6–43
Order Myodocopida			
Family Cypridinidae			
Jimmorinia gamma	105	–	–
Jimmorinia gunnari	88–105	–	–
Skogsbergia lerneri	shallow–105	5–35	–
Vargula exuma	62	–	–
Family Philomedidae			
Harbansus paucichelatus	1–20	22–31	–
Pseudophilomedes ferulana	6		
Zeugophilomedes multichelata	shallow	–	–
Family Sarsiellidae			
Chelicopia arostrata	1–3	–	–
Eurypylus eagari	67	35	–
Eurypylus hapax	142	–	–
Eusarsiella capillaris	2–20	–	–
Eusarsiella costata	2–67	–	–
Eusarsiella gigacantha	1–20	–	–
Eusarsiella merx	–	22	–
Eusarsiella punctata	1–5	–	–
Eusarsiella ryanae	67	27–33	–
Eusarsiella truncana	1–20	–	–
Eusarsiella warneri	–	1	–
Eusarsiella species x	1–20	–	–
Junctichela pax	–	35	–
Family Rutidermatidae			
Alternochelata polychelata	1–5	–	–
Rutiderma darbyi	–	35	1
Rutiderma dinochelatum	1–20	–	–
Rutiderma schroederi	67	–	–
Family Cylindroleberididae			
Actinoseta chelisparsa	3–67	5	–
Amboleberis americana	3–10	5–22	–
Asteropella monambon	3–20	5	–
Diasterope procax	88–142	–	–
Parasterope extrachelata	shallow	–	–
Parasterope muelleri	shallow–67	–	–
Synasterope browni	96	27–50	–
Synasterope setisparsa	1–5	–	–
Total no. species	28	12	13

Oceanic

The results of the following experiments describe the conditions and marine life found inside an oceanic blue hole. Warner and Moore (1984) examined the suck and blow currents in Conch Sound I (CSI) (Figures 15 and 16). They made several observations: current speeds were greatest during maximum high and low tides, peak current speeds varied to a greater degree during suck phases, and the total volume of water blown out was greater than the volume sucked over a period of two days (Warner and Moore 34). They also found that suspended particulate material concentrations in the suck phase were greater than the concentrations in the blow phase in all three sites (Table 3). Detailed plankton samples were taken for both Blue Hole and Rat Cay, and show similar trends but are significantly different from one another (Table 4). Finally, they reported the percentages of various sessile organisms found on the floor, walls, and roof of CSI entrance, CSI at 300 meters, and Rat Cay entrances (Table 5). The results showed a correlation between the CSI and Rat Cay entrances, but a significant difference between the entrances and the interior of the hole (Warner and Moore 1984).

Farr and Palmer (1984) observed similar characteristics in several oceanic blue holes on Andros Island, Bahamas. They noted the large amounts of marine life found near the entrances of the caves, including fishes, hydroids, tube fans, sponges, and crustaceans. However, even at 300 meters from the entrance, lobster, snapper, snake eel and *Lucifuga spelaeotes* were found. As depth increased marine life decreased. They also found strong currents present at most of these sites (Farr and Palmer 1984).

Palmer (1987), based on his experiences with oceanic blue holes, generalized their characteristics and the marine life he had observed. First he stated the importance of the currents to the marine life in oceanic blue holes. The suck currents, containing organic debris, plankton, and algal fragments, bring an abundant nutritional supply to the marine life inhabiting blue holes. Common marine organisms include corals, sponges, ascidians, anemones, hydroids, and bryozoans. Larger species such as arrow crabs, shrimp, cowries, soldierfish, snappers, cardinalfish, and brotulids also can be found. Finally, in the deepest part of the holes marine life dwindles due to loss of light and nutritional sources, and only occasional sponges, fanworms, and nurse sharks can be found (Palmer 1987).

Kornicker et al. (2002) examined Four Shark Cave (Figure 17). They also used the findings from Kornicker and Iliffe (2000) for the blue holes of Angelfish, Crab Cay Crevasse, Sugar Cay, Mystery Cave, Master Harbour, and Conch Sound. They reported the salinity of Four Shark Cave to increase from 35.9 g/L to 37.4 g/L as depth increased (Figure 18). Also temperature, pH, and dissolved oxygen decreased as depth increased (Figures 19, 20 and 21). The species of Myodocopa

Table 2. Ostracoda in Jamaican Blue Holes as reported by Kornicker and Iliffe (1992).
D.e. = Danielopolina elizabethae *P.m.* = Pontopolycope mylax *S.j.* = Spelaeoecia jamaicensis

Station	Cave	Depth (m) (max., sampling)	Salinity surface/bottom*	Species D. e.	P. m.	S. j.
90-005	East Bull Cave	(2, 0-2)	14.5/14.5	X		
90-006	Dairy Bull Cave	(3-4, 0-2.5)	16.5/22.5		X	
90-033	Dairy Bull Cave	(3-4, 0-3)	16.5/22.5	X		
90-032	South Bull Cave	(3, 0-3)	18/22.5			X
90-035	Air Strip Cave #1	(5, 0-5)	25/29.5			X
90-036	Air Strip Cave #2	(5, 0-5)	25/28			X
90-010	Air Strip Cave #5	(3, 0-3)	26/29.5			X

*Bottom salinity is salinity at bottom where sample was collected.

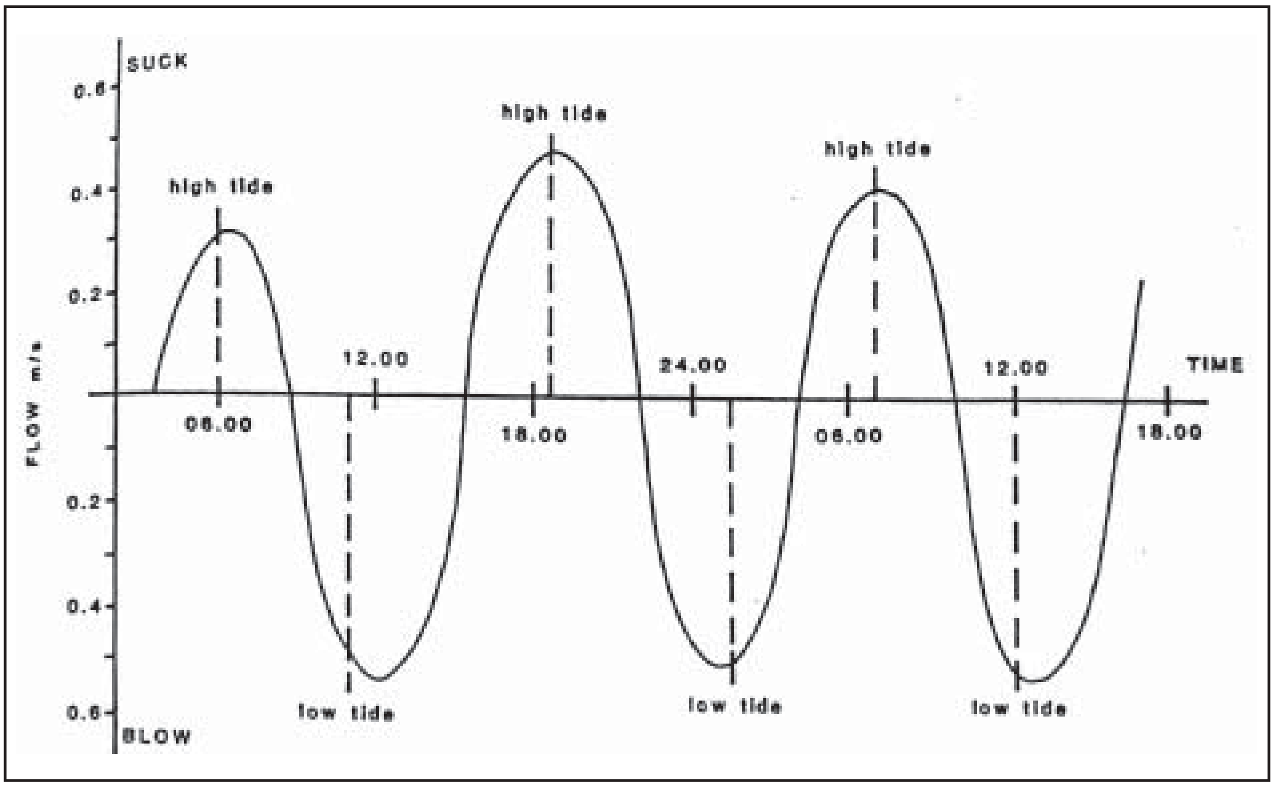

Figure 15. Current cycles measured in Conch Sound I on 8/27/81 as reported by Warner and Moore (1984).

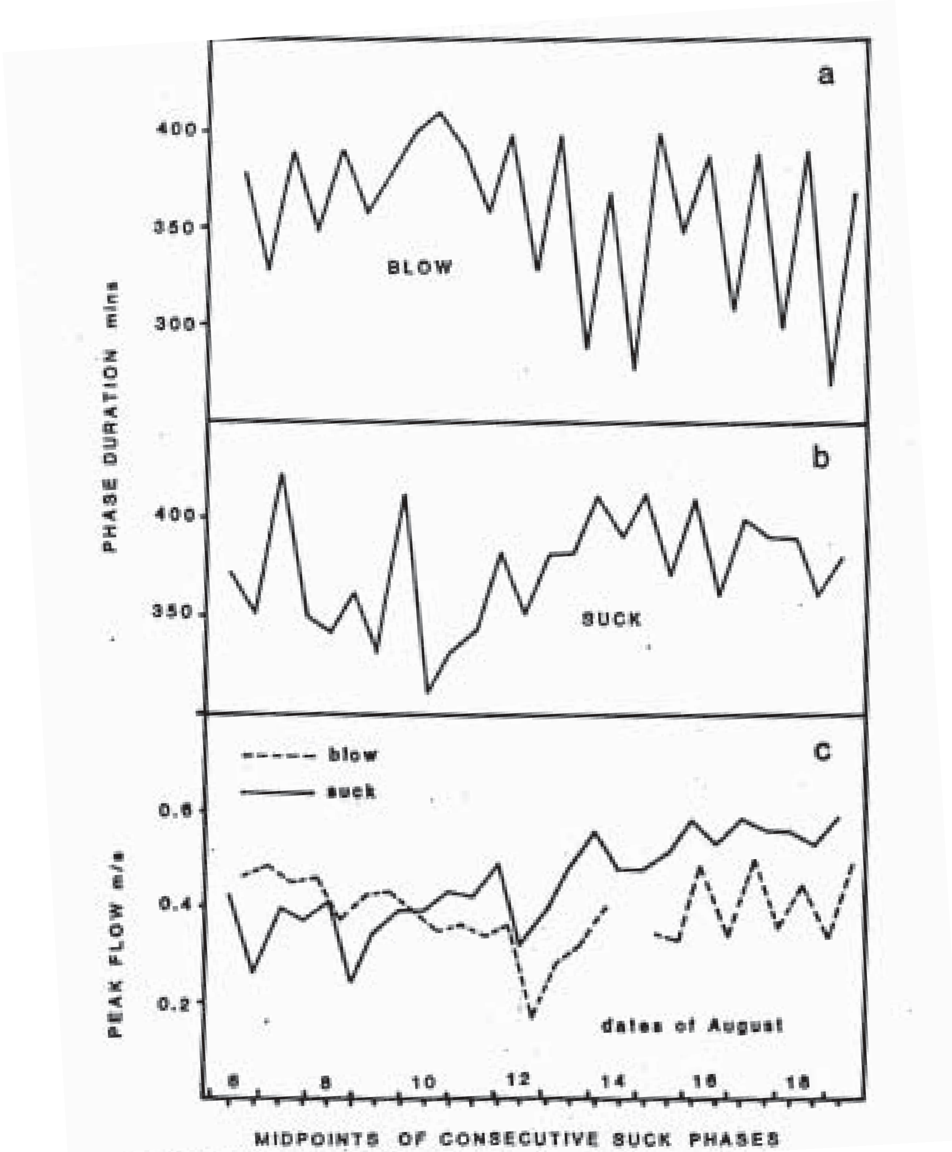

Figure 16. Patterns in the currents of Conch Sound I recorded between 8/6/82 and 8/19/82 as reported by Warner and Moore (1984).

Table 3. Concentrations of particulate material in samples collected from Conch Sound I, Rat Cay, and Blue Hole Cay as reported by Warner and Moore (1984).

site	date	current phase	sample volume, l	POC, mgl^{-1}
Conch Sound 1	18/8/81	mid-suck	1.5	0.54
“	“	mid-blow	“	0.42
“	23/8/81	late blow	“	0.32
Rat Cay	19/8/81	mid-suck	1.5	0.48
“	“	mid-blow	“	0.32
Blue Hole Cay	20/8/81	mid-suck	1.5	0.37
“	“	early blow	“	0.38

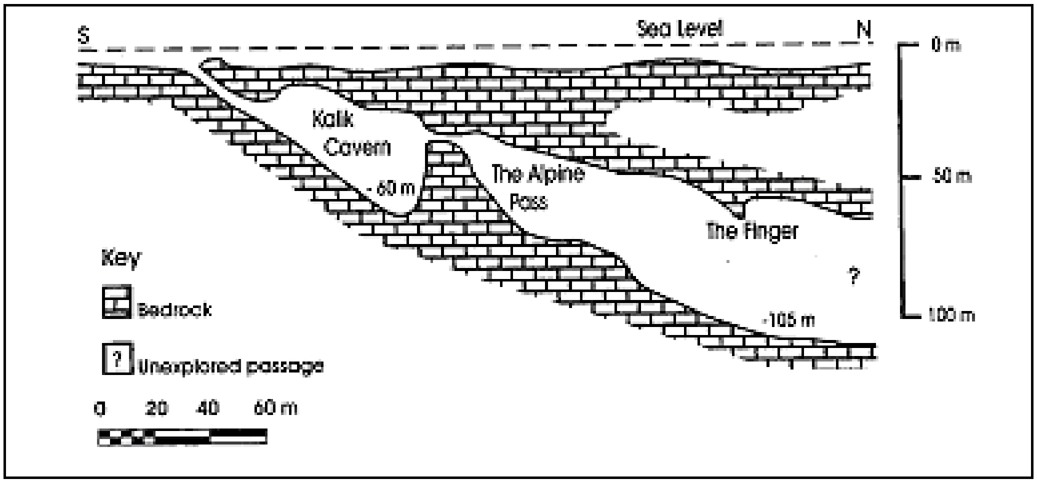

Figure 17. Four Shark Cave, Bahamas (Kornicker et al. 2002).

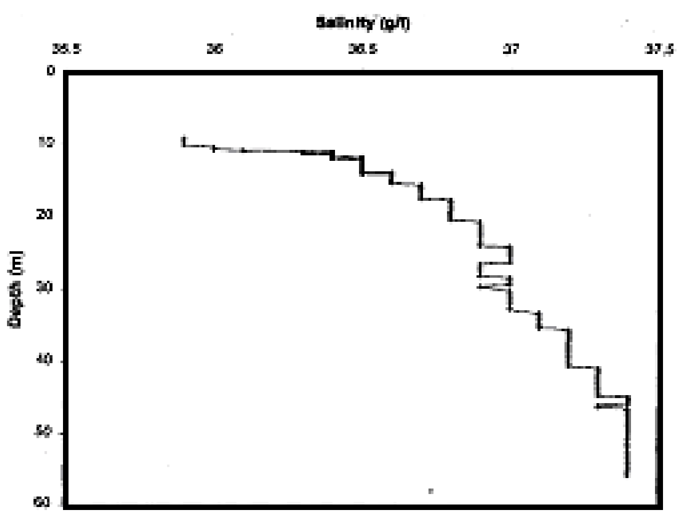

Figure 18. Salinity measurements at different depths of Four Shark Cave as reported by Kornicker et al. (2002).

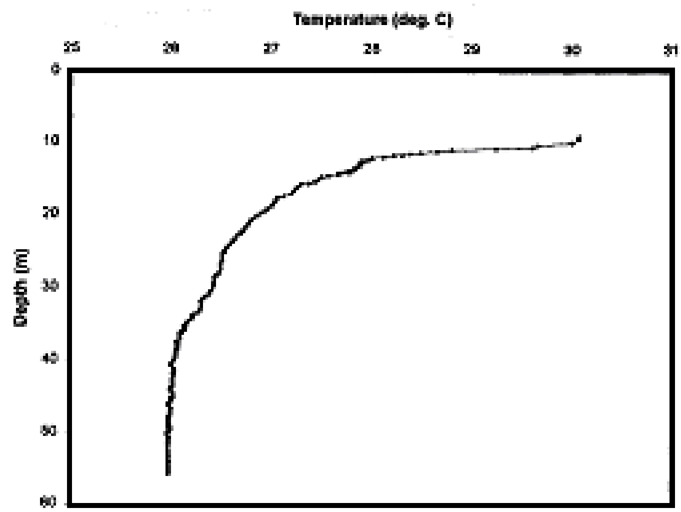

Figure 19. Temperature measurements at different depths of Four Shark Cave as reported by Kornicker et al. (2002).

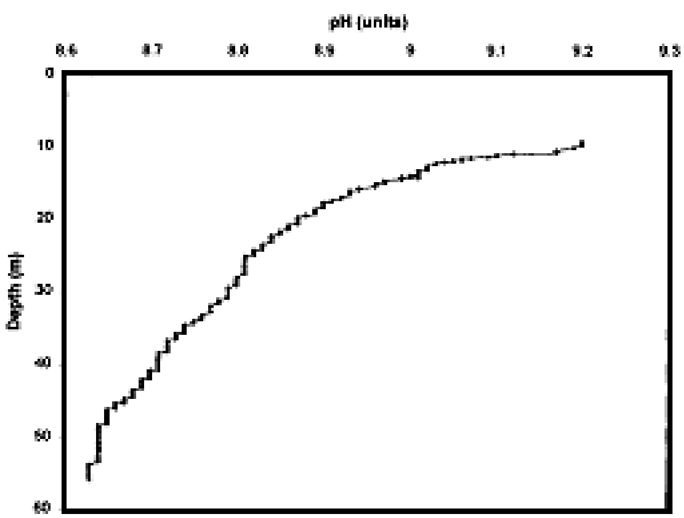

Figure 20. Measurements of pH at different depths of Four Shark Cave as reported by Kornicker et al. (2002).

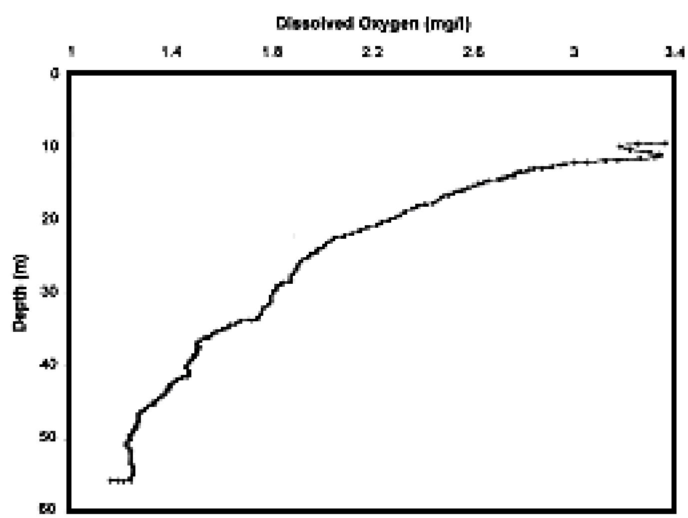

Figure 21. Amount of oxygen measured at different depths of Four Shark Cave as reported by Kornicker et al. (2002).

Table 4. Concentrations of plankton samples in Blue Hole Cay (BH) and Rat Cay (RC) taken in 1981 as reported by Warner and Moore (1984).

	10/8/81 BC mid suck	19/8/81 RC mid suck	20/8/81 BC early blow	12/8/81 RC mid blow	19/8/81 RC mid blow
sand	918	990	1386	2052	5472
biogenic sand	108	54	1008	576	558
algal filaments & fragments	2052	1098	1350	648	108
crustacean exuvia	234	252	360	738	414
ostracod valves	36	-	234	234	324
faecal pellets	162	72	14274	414	630
amorphous detrital aggregates	1602	288	3078	1746	1386
hydroid pieces	-	-	990	306	144
foraminiferans	36	54	288	180	216
tiny gastropods	-	36	72	162	162
ostracods	9	-	234	108	126
planktonic copepods	35	3420	7	90	72
harpacticoid copepods	-	-	162	36	-
cumaceans	3	-	46	8	23
amphipods	4	-	11	21	48
isopods	20	-	26	5	6
crustacean larvae	18	254	54	-	-

Table 5. Percentage of sessile organisms found in Conch Sound I and Rat Cay as reported by Warner and Moore (1984).

	CS1 entrance			CS1 300 m			RC entrance		
	floor	walls	roof	floor	walls	roof	floor	walls	roof
Sand	66	-	-	20	-	-	63	-	-
unidentifiable	14	38	26	54	74	67	9	17	26
sponge	10	46	70	24	19	28	6	68	30
ahermatypic coral	2	7	1	-	-	-	22	15	40
colonial ascidian	8	9	3	2	1	2	-	-	4
yellow tubes	-	-	-	-	6	3	-	-	-
hydroid	23	1	-	-	-	-	46	36	4

found in the oceanic blue holes also were counted (Table 1), showing most to be from the order Myodocopida, and the families Cypridinidae, Philomedidae, Sarsiellidae, Rutidermatidae, and Cylindroleberididae (Kornicker et al. 2002).

DISCUSSION

Environmental Extremes

Different degrees of spatial heterogeneity can be found in oceanic and inland blue holes. However both holes experience comparable patterns of change in temperature, pH, and salinity at different depths. First, the temperature in both inland and oceanic holes decreases with increasing depths, though it is important to note that the surface of most oceanic holes is slightly warmer than that of inland holes. This can be inferred through a comparison between the data in Figures 8, 12 and 19. Secondly, pH decreases in both inland and oceanic holes as depth increases; the overall pH of inland holes is significantly lower than that of oceanic holes at their corresponding depths. Evidence of this can be seen in the differences between the data in Figures 9, 13 and 20. Finally, salinity increases with depth in both types, however the amount of increase is significantly greater in inland holes than in oceanic. For example, most inland holes increase in salinity from 0 g/L to about 40 g/L, whereas most oceanic holes only increase slightly from 30 g/L to 40 g/L.

Further examination of inland blue holes shows that they display a greater degree of spatial heterogeneity than oceanic blue holes: a possible explanation for the differences cited above. While oceanic blue holes only experience change in temperature, pH, and salinity at varying depths, inland blue holes contain three distinguishable layers that contribute to their varying environmental conditions: a freshwater lens, a halocline layer, and a salt-water layer. Smart (1984) noted the freshwater layer, as reported in Figure 3, in several blue holes he studied. He also observed the halocline layer, as reported in Figure 2. Farr and Palmer (1984), Palmer (1987), and Kornicker et al. (2002) found the halocline layer in the inland blue holes they studied. With each of these layers variations in temperature, pH, and salinity were observed.

Limited Energy Supply

When examining the degree to which blue holes are limited, energy also is an important factor. In both inland and oceanic blue holes energy becomes limited at greater depths. This can be measured by several factors: amount of light, amount of dissolved oxygen, and food sources. The amount of light that reaches the greater depths of both inland and oceanic blue holes is limited. As a result, photosynthetic plants do not have the opportunity to thrive there. Inland blue holes experience this limited amount of light energy to a greater degree however. While oceanic blue holes lose light energy as depth increases, Smart (1984) noted that the upper layer of inland blue holes is quite cloudy. Therefore organisms in inland blue holes must adapt to a diminished amount of light energy on both the surface of the holes, as well as at great depths. For this reason many of the organisms must remain in the water depths between the upper layer and furthermost bottom layer of inland blue holes. In addition, both inland and oceanic blue holes experience a loss in the amount of dissolved oxygen as depth increases (can be seen in Figures 10, 14, and 21), further limiting the organisms that can survive there. Finally, although both inland and oceanic blue holes experience a limited food supply, oceanic blue holes do so to a lesser degree. Several divers, notably Warner and Moore (1984), have examined the suck and blow currents found in oceanic blue holes. Their data in Table 4 illustrate that the suck currents allow for nutritional material, i.e., plankton, to be brought into these holes. Because such currents do not exist in inland blue holes, their food supply remains somewhat fixed, providing a greater challenge to find food.

Species Diversity

Much study on species diversity is still needed in both inland and oceanic blue holes. From what little data scientists have gained it is not unreasonable to theorize that the diversity of species will be more limited in inland than oceanic blue holes. This hypothesis can be made based on the challenges organisms living in these holes must face. A lack of changing water layers and a continual supply of nutritional material via currents, gives organisms living in an oceanic blue hole a greater advantage to those in inland blue holes. Due to these benefits, and direct tidal connections, it is very likely that a more diverse community of organisms is able to survive within an oceanic hole. From the few observations that have been made this appears to be the case. Inland blue holes have been reported to contain various types of plankton, ostracods, jellyfish, shrimps, and mites. Oceanic blue holes however appear to contain a wider variety of larger species as well as some of those species found in inland blue holes, including sponges, brotulids, crustaceans, lobster, snapper, snake eels, arrow crabs, soldierfish, and cardinalfish. Again, further research is necessary to provide absolute proof of this hypothesis.

Conclusion

Current data support that organisms living in inland blue holes face greater spatial heterogeneity, resulting in more extreme environmental conditions, a greater lack of light energy, as well as a limited food supply in comparison to the organisms found living in oceanic blue holes. As a result, while both inland and oceanic blue holes demonstrate environmental extremes, a limited energy supply, and a lack of species diversity, defining them as limited ecosystems; inland blue holes can be classified as such to a higher degree.

ACKNOWLEDGMENTS

Special appreciation is extended to Dr. Hobbs for his guidance in the research and development of this paper, as well as the technical correction he provided. Appreciation is also given to the Wittenberg students in Biology 215, spring semester 2003, for their input on early drafts. Finally, appreciation must be given to the divers and scientists who have devoted their time to the exploration and study of blue holes.

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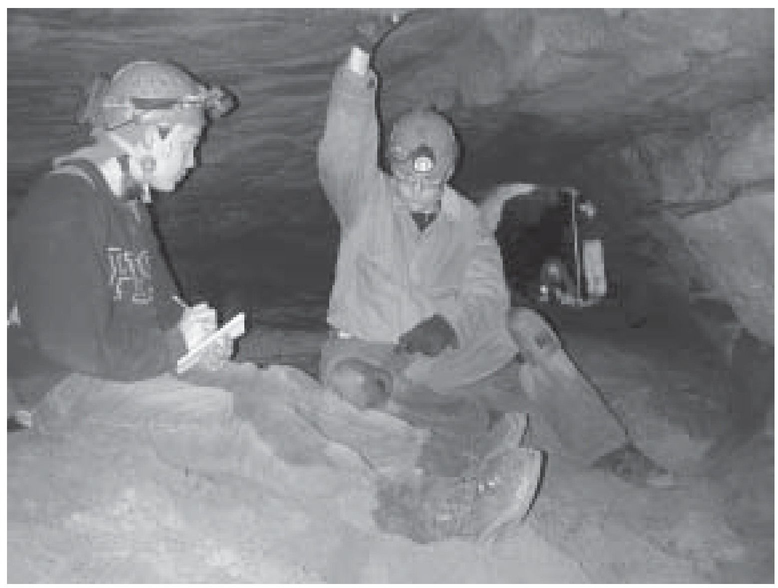
Rainbow Blue Hole, Andros Island, Bahamas (photo by H. Hobbs III).

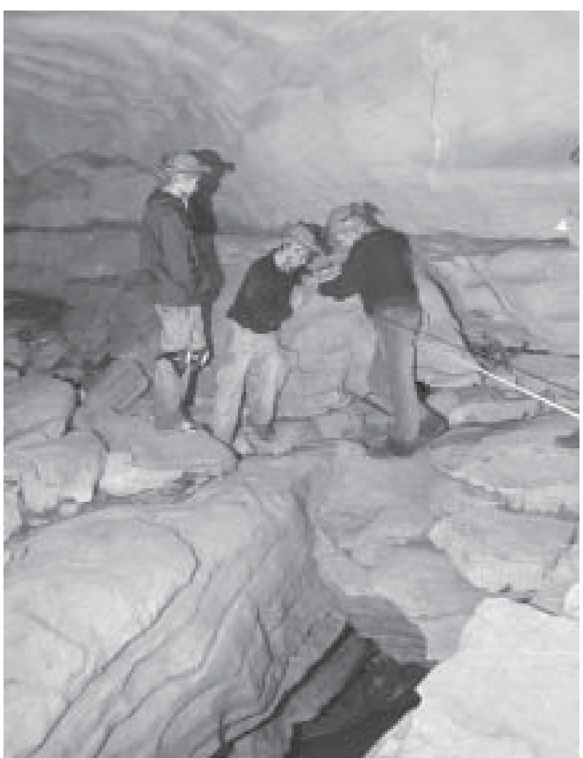
Obtaining water sample with Kemmerer Bottle at Stafford's Creek Blue Hole, Andros Island, Bahamas (photo by H. Hobbs III).

PHOTO GALLERY

Ice stalagmites in Cascade Cave, Carter County, KY, 1 February 2003 (photo by H. Hobbs III).



Two survey stations in Cascade Cave, Carter County, KY (photo by H. Hobbs III).

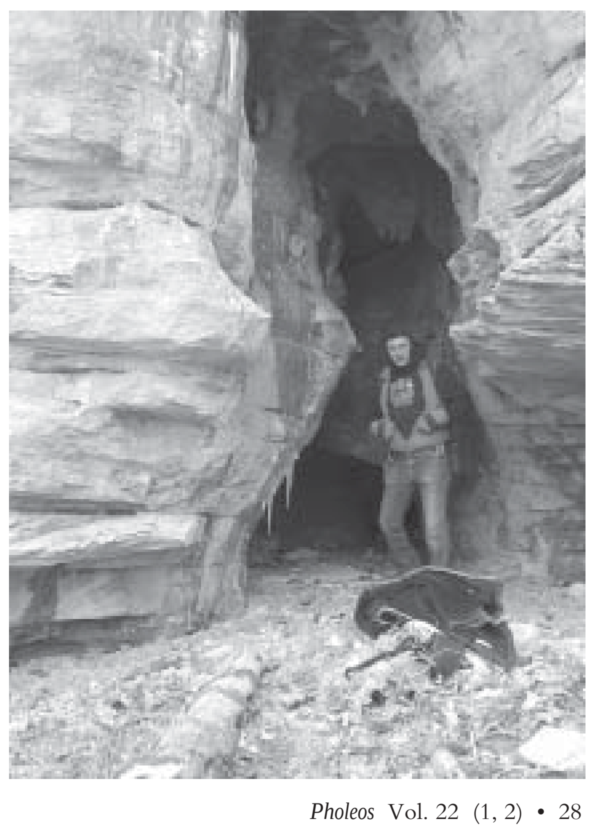


"On point" in Cascade Cave, Carter County, KY (photo by H. Hobbs III).

PHOTO GALLERY

Entrance to Hot Dog Cave, Carter County, KY (photo by H. Hobbs III).

Looking out of entrance to Sinus Cave, Carter County, KY (photo by H. Hobbs III).



KBH Cave entrance, Carter County, KY (photo by H. Hobbs III).

INFORMATION FOR CONTRIBUTORS

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All manuscripts are to be in English. Metric and Celsius units must be used, and SI units are preferred. The CBE Style Manual, the Handbook for Authors of Papers of the American Chemical Society, and Webster's Ninth Collegiate Dictionary are useful guides for matters of form and spelling.

The original of the manuscript must be typed double-spaced on one side of white bond paper approximately 8.5 x 11 inches, leaving margins of one inch. Use triple-space above headings. Submit three copies for prompt review. Number pages consecutively at the top right-hand corner. Underline scientific names of genera and lower categories. Acknowledgments should be on a separate, double-spaced page. Each figure and table must be referred to in the text. Text references are by author, followed by year of publication. The sequence of material in the manuscript should be as follows.

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   Book:

   Moore, G. W., and N. Sullivan. 1997. Speleology: Caves and the cave environment. St. Louis, Missouri: Cave Books.

   Chapter:

   Hobbs, H.H. 1992. Caves and springs *IN*, C.T. Hackney, S.M. Adams, and W.A. Martin (eds.), Biodiversity of Southeastern United States/Aquatic Communities. John Wiley & Sons, pp. 59-131.

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