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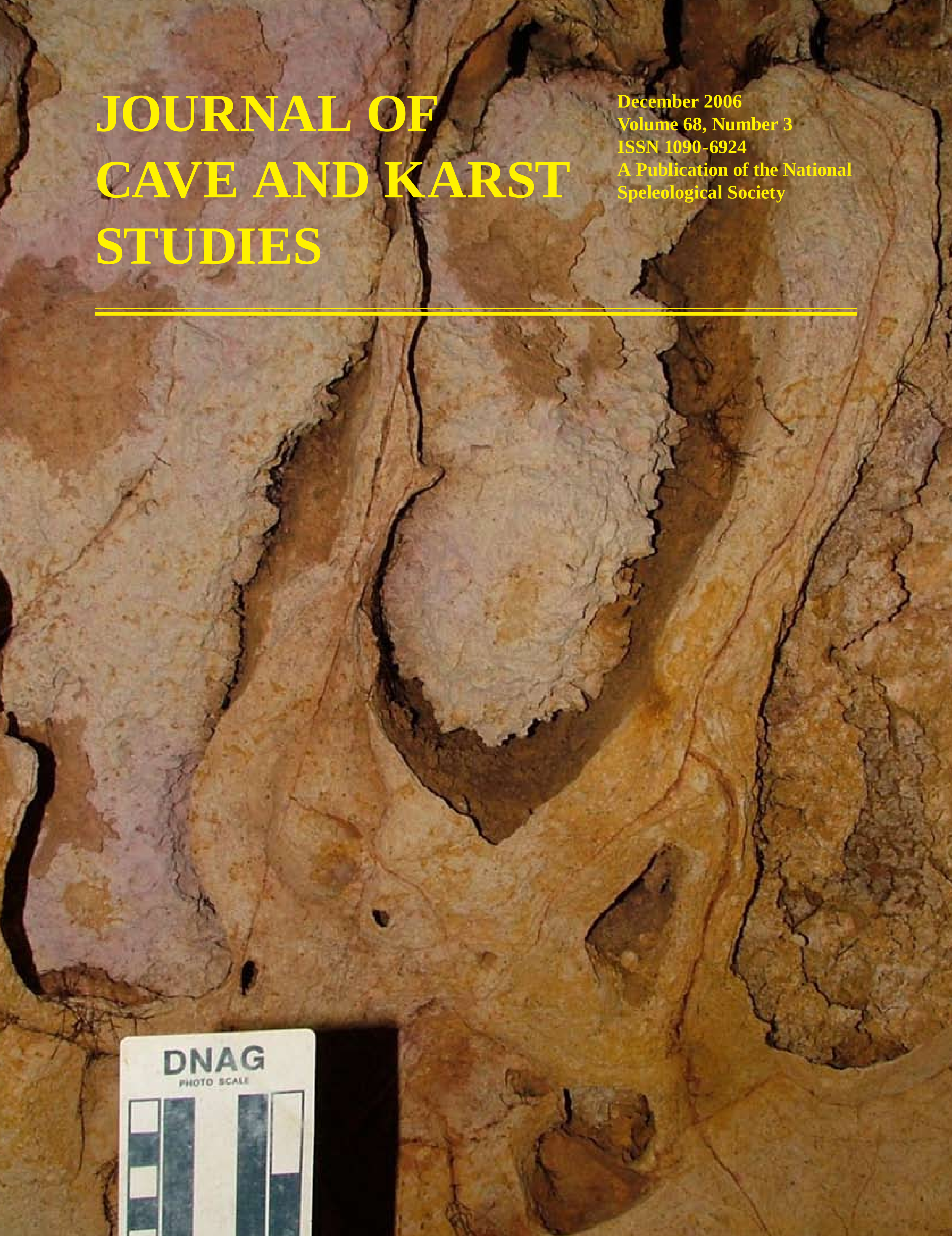

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Front cover: Chert Boxwork in Al-Daher Cave, Jordan. See Kempe, Al-Malabeh, Al- Shreideh and Henschel, p. 107

EDITORIAL
Abbreviations, Acronyms and Terminology Usage in the *Journal of Cave and Karst Studies*

Malcolm S. Field

Introduction

The writing of scientific articles for publication often necessitates the use of abbreviated terms, acronyms, and terminology specific to the field of study. To abbreviate a term is defined as to shorten and word or phrase to a form meant to represent the full form (Webster's II, 1984, p. 66). An acronym is defined as consisting of a word formed from the initial letters of a name or by combining initial letters or parts of a series of words (Webster's II, 1984, p. 75) and implying that the acronym is a pronounceable word. It is apparent from these two definitions that abbreviations and acronyms may often overlap. Terminology is defined as the vocabulary of technical terms and usages appropriate to a particular field, subject, science, or art (Webster's II, 1984, p. 1194).

The Problem

Recently, I was contacted by a reader of the *Journal of Cave and Karst Studies* with a question that surprised me. The reader, an experienced scientist in a foreign country, expressed confusion over some commonly used abbreviations and acronyms (*e.g.*, GC-MS, SPME, EPA, GC-O and SEM study). Or, to be more precise, these are common abbreviations to only some of us. For example, EPA is to me pretty obviously an acronym for U.S. Environmental Protection Agency because I am employed by the EPA. However, although this acronym is obvious to me and may also be fairly apparent to most of our U.S. subscribers, it may not be so obvious to individuals residing outside the United States. As another example, to chemists a GC-MS is a simple acronym for a Gas Chromatograph-Mass Spectrometer, but to individuals with little or no background in chemistry this acronym is virtually meaningless. Scientific terminology is equally problematic for non-specialists. Prior to being contacted, I hadn't been aware of the problem some readers may have been having with various abbreviations, acronyms, and scientific terminology used in articles published in the *Journal of Cave and Karst Studies.*

The Extent of the Problem

The problem identified above likely occurs in all scientific journals, but is compounded in the various cave and karst journals, such as the *Journal of Cave and Karst Studies*, in two ways. First, although karst journals are specific to the subject matter of caves and karst, they are very general in that all aspects of caves and karst are covered. The *Journal of Cave and Karst Studies* includes Associate Editors with specialties in anthropology, conservation, earth sciences, exploration, life sciences, paleontology, and social sciences. These specialties are often then broken down into subspecialties. For example, the anthropology specialty also deals with archaeology while the earth sciences specialty includes chemistry, geology, geography, geomorphology, hydrology, hydrogeology, and others. Such a wide range of subject matter covered in the *Journal of Cave and Karst Studies* makes it very difficult for the professional cave scientist, engineer, journal editor, *etc.* to be able to intelligently read many of the articles published in the *Journal* *of Cave and Karst Studies.* Yes, even the *Journal of Cave and Karst Studies* editors can find the wide range of subject matter covered, even within their general areas of specialties, somewhat daunting. Imagine how much worse it must be for the non-specialists.

The second aspect of the problem is the very high rate at which the various subspecialties are advancing. There are so many people conducting studies, sometimes directly and sometimes only remotely related to caves and karst, using newer equipment and methods, that it is difficult for even the cognoscenti to keep up. In addition, the incredible existing array and proliferation of scientific and engineering journals available throughout the world further exacerbates this problem because it is so time-consuming and difficult tracking down and reading newly published papers, even with the advent of the World-Wide Web. This problem is, of course, much more difficult for non-specialists, especially if they lack access to large university libraries.

Possible Solutions

A Solution for Editors

This problem has caused some difficulties for the Associate Editors who naturally are not experts in all matters related to their specific subject areas. For example, the Life Sciences specialty covers all aspects of biology, which is an extremely wide subject area. To alleviate some of the difficulties our Associate Editors have been experiencing we have added two new Associate Editors. Kathleen H. Lavoie has agreed to accept appointment as Associate Editor for microbiology and Stephen R. Mosberg has agreed to accept appointment as Associate Editor for Human and Medical Sciences. These two new Associate Editors will be able to take on the review and editorial responsibilities in their respective subspecialty areas, which should improve many aspects of the *Journal of Cave and Karst Studies.*

A Solution for Readers

Unfortunately, the above solution does not help our readers. To make reading easier for our readers I would like to suggest the following. First, for acronyms and/or abbreviations, authors should conscientiously write-out the full term and immediately follow the term with the acronym/abbreviation in parentheses. If the list of acronyms/abbreviations is long or somewhat uncommon, then it might be appropriate to also include a complete list of the terms along with their respective acronyms and/or abbreviations in an appendix or set of endnotes at the end of the article that the reader may refer to periodically while reading the manuscript.

Scientific terminology is more problematic. In some instances, specific terms may be briefly defined in the text of the article. Alternatively, in rare instances, the term may be defined in an appendix or endnotes section at the end of the article. This is not a greatly satisfactory method because it can be difficult for an author to determine what needs defining, and it adds length to the manuscript. Another, somewhat extreme alternative, is to do as Hazel Barton did in the last issue of the *Journal of Cave and Karst Studies* (Barton, 2006). That is, develop and publish an introductory article on the subject matter with the intention of assisting the non-specialist to learn about the subject. Although many specialists might consider it very difficult to write such an article, it can be very helpful to non-specialists and should enhance the *Journal of Cave and Karst Studies* in many ways.

Conclusions

Abbreviations, acronyms, and scientific terminology can be very problematic for individuals unfamiliar with the terms used in a published scientific journal article. If full terms are not listed along with their respective abbreviations and/or acronyms, and various obscure scientific terms are not defined, readers will often not be able to follow the context and will cease bothering to read the published article.

I encourage all future authors to make a concerted effort to define all acronyms and abbreviations used in papers submitted for publication in the *Journal of Cave and Karst Studies.* Such an effort will benefit everyone. In addition, I ask that all future authors consider defining some obscure scientific terms used in papers submitted for publication in the *Journal of Cave and Karst Studies* so that readers will better understand the subject matter discussed in the paper.

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Stephan Kempe, Ahmad Al-Malabeh, Ahmad Al-Shreideh, and Horst-Volker Henschel. Al-Daher Cave (Bergish), Jordan, the first extensive Jordanian limestone cave: a convective Carlsbad-type cave? *Journal of Cave and Karst Studies*, v. 68, no. 3, p. 107–114.

AL-DAHER CAVE (BERGISH), JORDAN, THE FIRST EXTENSIVE JORDANIAN LIMESTONE CAVE: A CONVECTIVE CARLSBAD-TYPE CAVE?

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In spite of the vast limestone area present in Jordan, no karstic caves to speak of were known there until 1995 when Al-Daher Cave was discovered. The cave is situated east of Bergish Reserve for Ecotourism in the mountains of Bergish at about 830 m above sea level. The cave formed in the Wadi As Sir Limestone Formation of Upper Cretaceous age. It is a maze developed along NW-SE and NE-SW striking joints which owe their existence to the Dead Sea Transform Fault situated a few kilometers to the west of the cave. Rooms, with a total area of 1750 m^2, were formed within a square of 70 × 70 m. The cave is constrained to certain limestone strata, laminated and non-laminated, divided by four chert layers that form distinctive markers throughout the cave. Chert nodules occur also within the limestone layers. The cave formed phreatically exclusively by dissolution within a small body of rising and convecting water. It is suggested that the very localized solution capacity derived from the oxidation of either H_2S, or possibly even CH_4, by oxygen present near the former water table. Thus, Al-Daher Cave may have formed by a process similar to that which formed the Guadalupe Mountain caves, New Mexico, among them Carlsbad Cavern. The altitude of the cave suggests that it may be as old as upper Miocene. The cave contains several relict generations of speleothems but also active forms. The local government is hoping to develop the cave into a show cave; it would be the first in Jordan.

LOCATION AND TOPOGRAPHY

Al-Daher Cave is the first natural limestone cave in Jordan of any appreciable extent. It was discovered by Ahmad Al-Shreideh in 1995 and is currently being developed by the Ministry of Tourism (Kempe *et al.*, 2004). Other caves in Jordan include lava tunnels (Al-Malabeh *et al.*, 2004; Kempe and Al-Malabeh, 2005; Al-Malabeh *et al.*, 2005), a cave in the Lisan Marls (Rosendahl *et al.*, 1999) and numerous, mostly artificial shelter caves along the deeply incised wadis of the country (*e.g.*, Calandri, 1987; Hofmann and Hofmann, 1993).

Al-Daher Cave is located east of the Bergish Reserve for Ecotourism on Bergish Mountain at about 830 m above sea level (Figs. 1 and 2). The entrance was originally a vertical fissure, opening to the east near the top of the mountain that contains the cave. This flank was artificially terraced in ancient times for agricultural purposes, and a wine press has been carved out of the rock nearby. The terraces are now partly overgrown by oak forest and only locally used to grow olive trees and grapes. During the winter of 2003–2004 the entrance was widened with funding from the Ministry of Planning and a terrace was cleared in front of the cave. These excavations did not yield any archaeological findings, suggesting that the cave had not been known or used in antiquity.

On September 20, 2003, we made a reconnaissance trip through the cave and started to survey it on September 26 and 27, 2003. We returned to the cave in the spring of 2004 and completed the work on March 29 and 30. A total of 76 (2003) and 40 (2004) stations were surveyed. Currently only one tight lead and some upward shafts remain unexplored. Due to the maze character of the cave, a total length is somewhat irrelevant, but the total added survey lines sums up to 280 m and the area covered amounts to 1,750 m^2. The entire cave fits into a square measuring 70 × 70 meters (Fig. 3).

TECTONIC SETTING

Many prominent structural features are present in Jordan. However, the geology and tectonics of Jordan are closely related to the regional geology and tectonics of the Mediterranean area. This region is subdivided into three major plates: the African (Nubian), Arabian, and Eurasian Plates. Jordan lies on the northwestern side of the Nubian-Arabian shield. Tectonism was contemporaneous with the opening of the Red Sea (Africa Red Sea rift system), the collision of the Arabian and Eurasian plates, and the uplift of the Afro-Arabian dome (Barberi *et al.*, 1970; Gregory *et al.*, 1982; Schilling *et al.*, 1992).

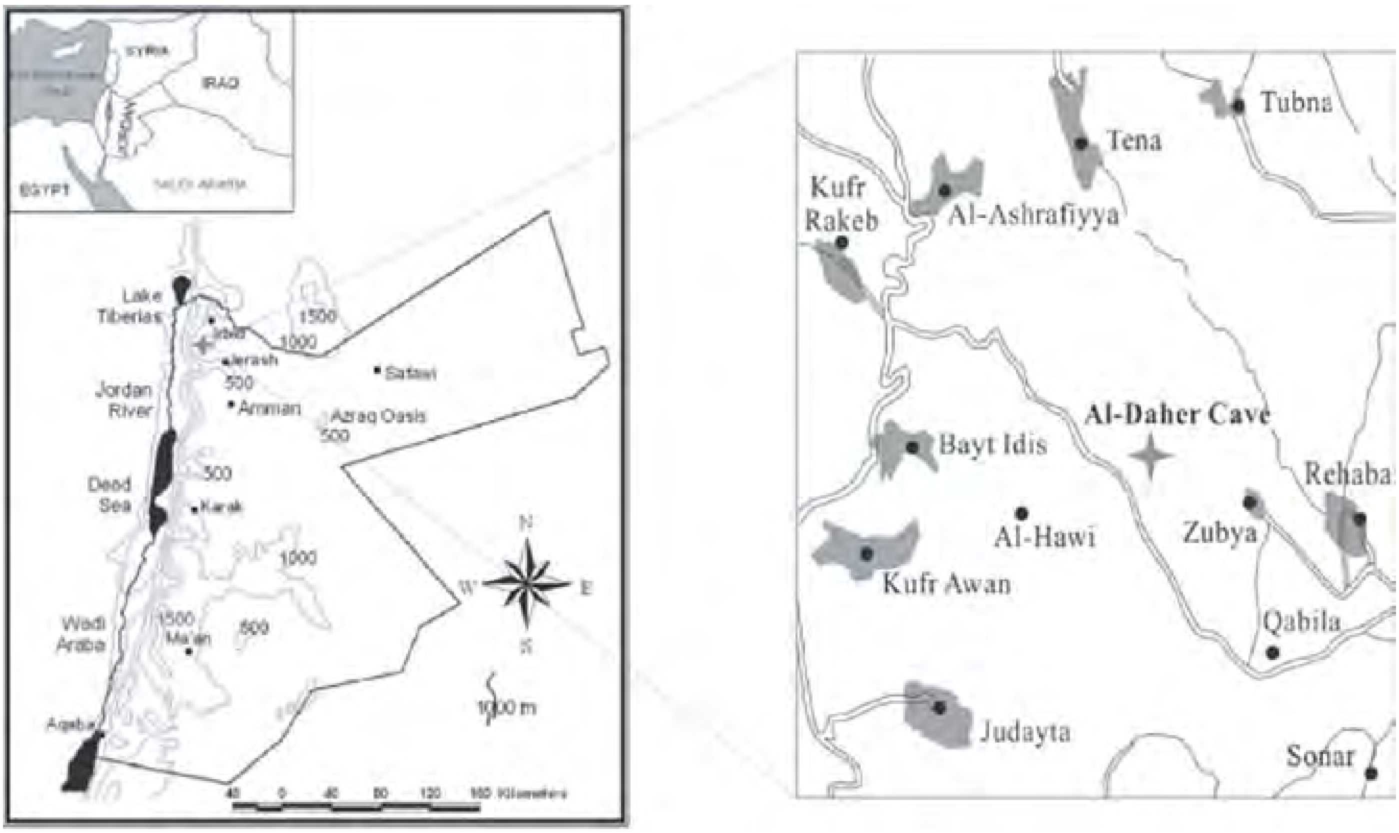

Figure 1. Location of Al-Daher Cave and its geologic setting along the eastern margin of the Jordan Graben.

The Dead Sea Transform Fault system (hereafter, DSFT) is considered the foremost structure of the region (Quennell, 1958; Ginzburg *et al.*, 1979; Mart, 1982). It is a major sinistral strike-slip fault zone, which is ca. 1000 km long, and strikes NNE-SSW from the Gulf of Aqaba to Lake Tiberias and to southern Turkey. It is connected with the Red Sea along the Aqaba Gulf transition zone. The tectonic association between the DSFT and the Red Sea was recognized about 85 years ago, and both are parts of the rifting system (the East African-Red Sea-Jordan Rift) that extends from southern Anatolia in Turkey to East Africa.

The present tectonic picture of the DSFT has been shaped mainly during the upper Tertiary and Quaternary periods (Picard, 1970). Estimates of the amount of horizontal displacement along the Jordan valley have been made previously: Dubertret (1929) suggested that a displacement of 100 km occurred in 36 million years; Quennell (1958) suggested that a 67 km displacement occurred during the Early Miocene, and an additional 40 km during the Late Pleistocene.

Field investigations, aerial photographs and satellite images indicate that four principal fault systems exist in the investigated area. The major trend is in the N-S direction and may be related to the main rift structure since they have a parallel to sub-parallel trend. The NW-SE-trending fault system has the same direction as the fault systems of the Red Sea, Wadi Al-Sirhan fault, and Wadi Abed fault zone (NE-Jordan). The E-W fault system in the study area is consistent with the trend of many E-W fault systems in Jordan (*e.g.*, Zarka Ma'in fault and Sawaqa fault, central Jordan). NE-SW is the least abundant trend, and the major-

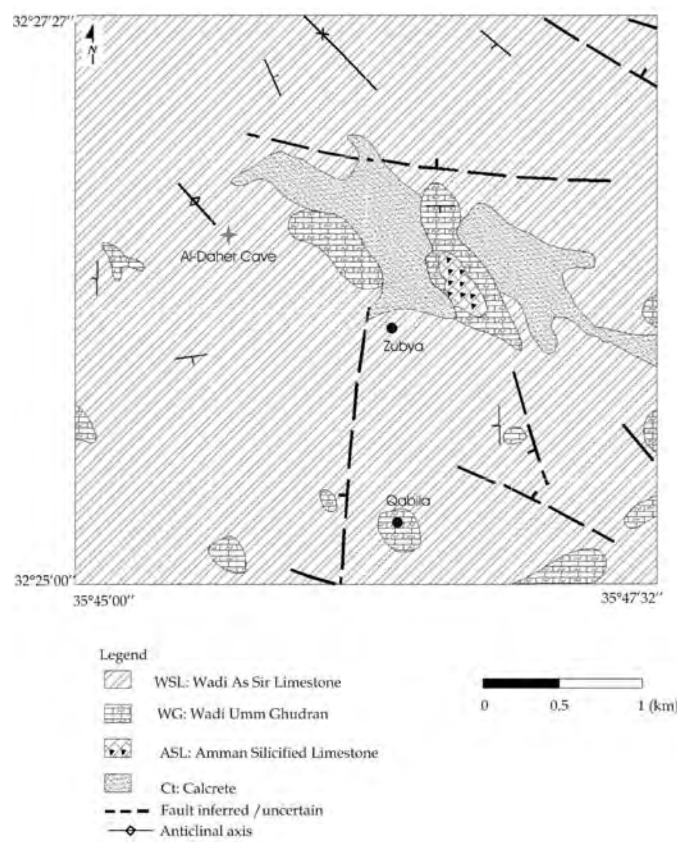

Figure 2. Geologic map of Al-Daher Cave area (modified by A. Al-Malabeh after Abdelhamid, 1995).

ity of these faults are local and of normal displacement type.

Al-Daher Cave is situated about 30 km to the east of the DSTF. The rocks have been jointed and fractured substantially, and the cave is formed mostly along NW-SE and NE-SW-striking joints (compare Fig. 3); directions that are also dominant regionally. Normal to the strike of the DSTF, structures developed that later have been transformed by erosion into deeply incised river courses.

Lithostratigraphic Succession

The rocks exposed in the cave area are of Upper Cretaceous age (Fig. 2). The beds belong to the extensive limestone platform developed on the African and Arabian Plates (*e.g.*, Bauer *et al.*, 2003; Lüning *et al.*, 2004). The Upper Cretaceous in Jordan is subdivided into two Groups: Ajlun (Albian-Turonian) and Belqa (Coniacian-Mastrichtian). The lithostratigraphic nomenclature of the Upper Cretaceous in Jordan used in this study is that adopted by the Natural Resources Authority (NRA) 1:50,000 Geological Mapping (El-Hiyari, 1985; Powell, 1989; Abdelhamid, 1995). The cave formed in the Wadi As Sir Limestone Formation. This formation represents the upper parts of the Ajlun Group. In general, this formation consists of dolomitic limestone (Powell, 1989). The uppermost massive beds contain chert nodules and calcite geodes. The fossil assemblage was that of a fully marine carbonate platform (Powell, 1989). The massive bedded Wadi As Limestone Formation forms a distinctive belt of cliff features. The formation ranges in thickness from 50 to 65 m in the study area.

The other two formations that are exposed in the study area (Wadi Umm Ghudran Formation and Amman Silicified Limestone Formation) belong to the Balqa group (Fig. 2). The Wadi Umm Ghudran Formation (Senonian) is characterized by a soft-weathered, white, massive chalk sequence (Powell, 1988). The Amman Silicified Limestone Formation (Campanian) consists of massive, hard, dark gray, autobrecciated chert interbedded with dolomitic limestone, chert, chalk, phosphatic chert and phosphatic marly limestone (Powell, 1989).

The cave is situated in the upper Wadi As Sir formation. Here, the cherts occur in several morphotypes: (i) as thick horizontal beds, (ii) as vertical sheets, (iii) as round, conical loafs, (iv) in the form of grape-like, small and bundled spheres, (v) or in massive, cone-like vertical bodies. Fossils of silicified rudists (a pachydont bivalve) are commonly found in the weathered layers outside of the cave. None have been noticed inside the cave. The soil above the limestone is terra rossa, mixed with masses of limestone and chert blocks.

The survey of the cave revealed that it is developed along a limited set of limestone beds which are divided by four distinct silicified layers, labled Cherts A to D, each between 0.2 and 0.5 m thick. The section can best be studied in the Geo-Pit, a cylindrical room that transects vertically through the 10 m of the stratigraphic column (Fig. 4). The four chert layers separate five limestone beds, each of which have characteristic properties and vary in the amount of contained chert. The layers between Cherts B–C, and C–D, contain most of the cavity and are the ones most susceptible to dissolution. Above and below Cherts B and D the amount of chert in the limestone increases; these layers are less susceptible to cave formation. The limestone above Chert A is rarely seen and heavily silicified. The chalk bed between Cherts A and B is characterized by chert boxwork formed by vertical sheets (Fig. 5). The next limestone layer is characterized by small chert nodules which form grape-like aggregates (Fig. 6). The limestone is micritic and non-laminated. This is in contrast to the next bed that is finely laminated and where the chert nodules are large, conical-downward and loaf-like (Fig. 7). The next limestone bed is also laminated but contains, at least in the Geopit, large, vertical and cylindrical chert nodules (Fig. 8). This layer is rarely seen in the cave because in the larger halls, the floor is covered with breakdown composed of the chert layers and nodules liberated from the dissolved limestone beds.

With this standard stratigraphy in mind, one can follow the layers throughout the cave. In Figure 9, a panorama view of Stalagmite Hall is given. The chert layers B and C can be followed along the ceiling and walls. The thickness of the layers varies somewhat throughout the cave, and in Fig. 10 a reduction of the non-laminated limestone to the back (*i.e.*, to the SW) is seen. The layers dip slightly towards the S; the lowest part of the cave is therefore SW of the entrance.

Description of Al-Daher Cave

Al-Daher Cave is a maze, dominated by two directions: NE-SW and NW-SE (Fig. 3). It consists of a series of interconnected halls, some of them more than 20 m long and up to 10 m high. These large halls are connected by relatively small passages. Apart from the entrance section (up to the Tea Passage) and the Stalagmite Passage at the southern part of the cave, travel through the cave involves climbing down into these halls and out of them at their far end. Large breakdown blocks, some of them over 10 m long, also characterize these halls. Most important is the observation that the halls have pits at their bottom. These are filled with loose silica nodules and boxwork, collected here as an insoluble residue of the cave-forming process. In spite of these ups and downs, the cave is restricted to one level, determined by two of the least silicified limestone beds (between Cherts B and D). Chert layers form much of the ceiling of the cave. Layer B, for example, defines the roof of the entrance passage (around Station 10) and dips about 5° SSW (ca. 200° N). Similar ceiling sections are seen throughout the cave, for example in the Stalagmite Passage.

Further features of note in the cave are small faults. At station 10-11 (the dead-end small passage parallel to the entrance passage; see Fig. 3) a fault running NE-SW occurs, down-faulting the northern block by ca. 10 cm. All-in-all, faults cannot amount to large displacements since the cave stays at the same stratigraphic level.

Perhaps the most striking character of the cave is the walls. They contain extensive silicified boxwork and protruding chert nodules, which have been left in situ during the limestone dissolution process. In addition, the limestone has been altered to

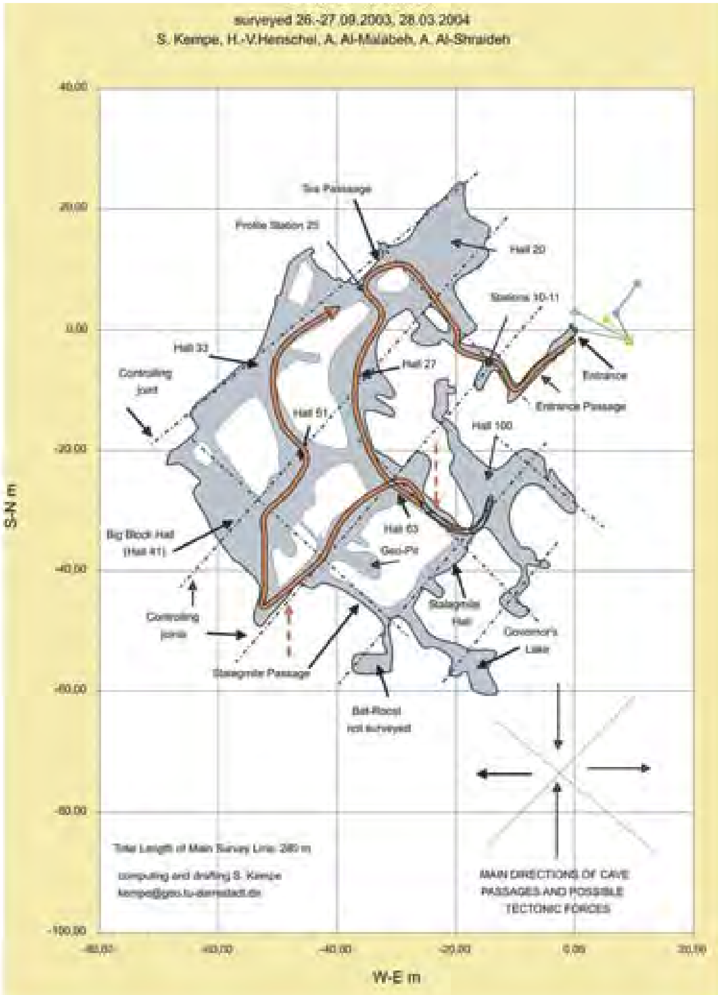

Figure 3. Map of Al-Daher Cave with passages shaded and highlighted directions of passages identical to the jointing of the rock in response to the pressure of the Dead Sea Transform Fault (map by authors, 2003 and 2004). Thick line suggests show cave trail with a minimum of impact to the cave. Dashed arrows indicate passages that must be widened if the cave should be commercialized. Lines mark 10 m squares, north is to the top.

Figure 5. Chert boxwork above Chert B.

Figure 6. Non-laminated limestone between Chert B and C with grape-like small chert nodules.

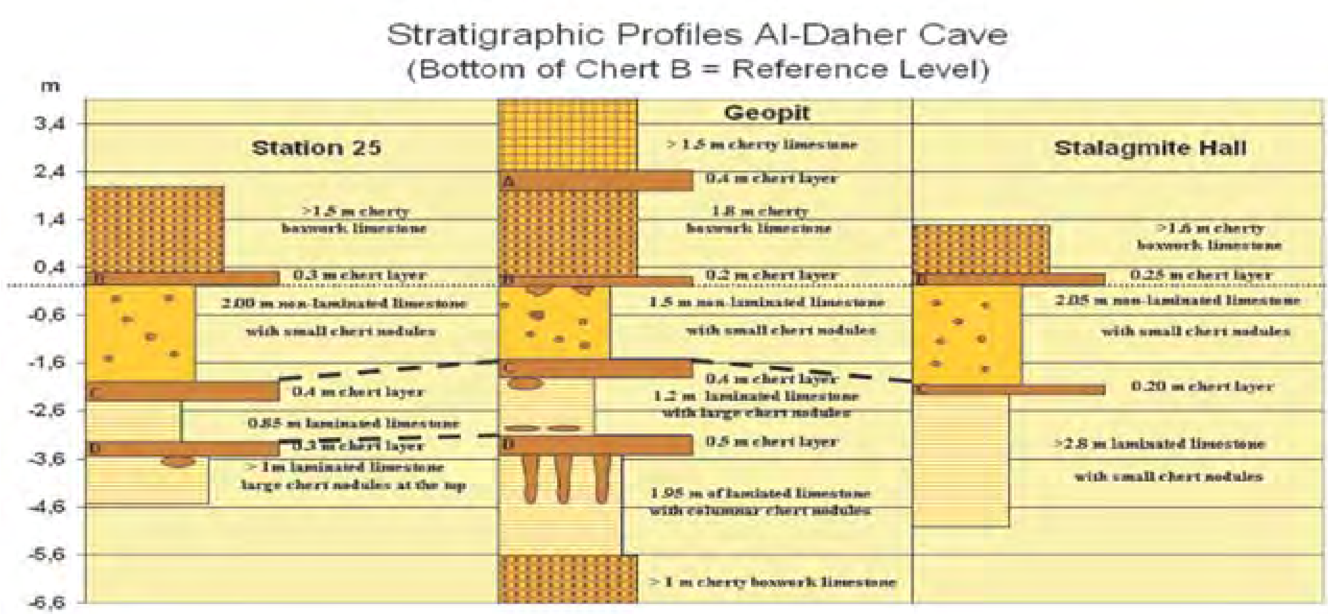

Figure 4. Stratigraphy of the cave (scale in meters) at three different sections. The Cenomanian limestone forms distinct layers with different textures and silica nodules interrupted by chert layers (A to D).

Figure 7. Laminated limestone between Chert C and D with loaf-like large nodules.

Figure 8. Vertical, large nodules from the laminated limestone layer below Chert D in the Geopit.

a soft and powdery white consistency, which can be dug up by hand (entfestigter limestone).

After descending the entrance corridor of the cave, one follows a widened joint-determined passage down to a sharp right turn. After a few meters a stalagmite fill has been removed to ease access to the main part of the cave. The following room leads to Hall 20, which is characterized by many large stalagmites, some of them grown on breakdown blocks. Hall 20 is the only one with an even floor. Three openings lead to the interior of the cave. The furthest connects into the Tea Passage and is still quite level. Further progress involves climbing down either into Hall 27 to the left or into Hall 33 straight on. To the right a narrow lead doubles back into Hall 33. Loose siliceous nodules occur everywhere on the floor. From Hall 33 one can climb down to the left into Hall 51 or ascend to the back of Hall 33 in order to gain access to the Big Block Hall. Big Block Hall has a monumental breakdown block at its center, propped up on other blocks. Hall 51 connects back to Hall 27 and Hall 63 (Fig. 10). It runs NE-SW and is quite high. At the far end, there is an ascent which leads into a passage connecting back into Big Block Hall. Left, the narrow Stalagmite Passage is accessed, blocked by speleothems at its end. We could not enter the small room (Bat-Roost) beyond, the only passage which was not completely explored. A few meters before this choke the low passage turns left (NE) leading towards Stalagmite Hall. Before reaching it, a

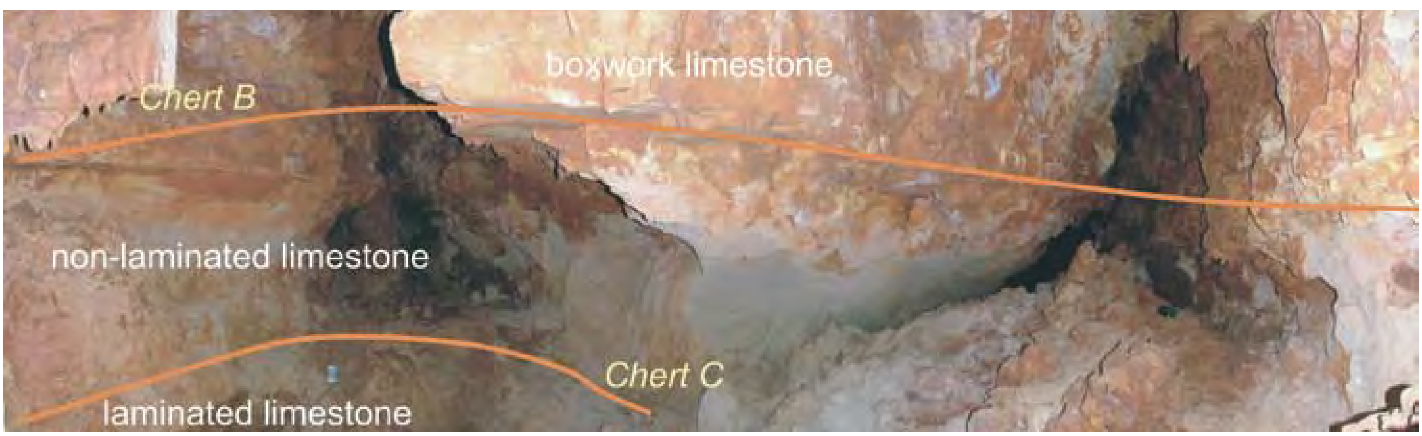

Figure 9. This panorama view (ca. 120°) of Stalagmite Hall (left) and the passage to Hall 63 (right) shows the stratigraphic setting of this part of the cave. Passages in the boxwork limestone are narrow, while in the non-laminated limestone and in the upper laminated limestone wide halls have been leached out. Note 10 cm scale above "s" of "laminated limestone".

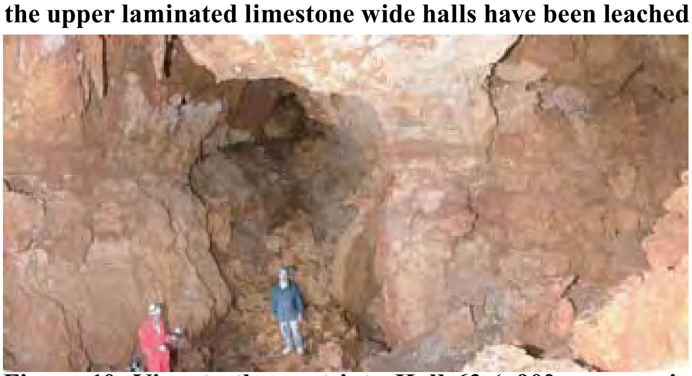

Figure 10. View to the west into Hall 63 (>90° panoramic view). Note the band of Chert B in the upper third of the picture.

Figure 11. Panoramic eastward view into Hall 100 towards station 108 and 109. Note three layers (B, C, and D) of chert on far wall, with layer D forming a flowstone-covered ledge.

crawl turns right, which opens up into a series of small rooms, one with a small pool at its floor (Governor's Lake). In Stalagmite Hall the cave opens up again; in its SW part it even has two levels, the lower one leached out from underneath Chert C (background of Fig. 9). Climbing up again one can pass through a small opening into Hall 100 (Fig. 11). It is quite large with three passages leading off. Stalagmite Hall connects back into Hall 63 which has a high chimney near its NE end.

Speleogenesis

Today Al-Daher Cave is in a fossil state, no longer forming actively. In order to understand its speleogenesis we therefore rely solely on interpreting its morphology. The following observations serve as clues:

- Al-Daher is a maze cave following the local jointing.
- All of its passages fall within a square of ca. 70 × 70 m. No continuation seems to exist, and no further caves are known in the area.
- It consists of large halls, interconnected incidentally by small passages.
- The halls have pits at their floors, largely filled with insoluble silica rubble.
- The cave follows in essence one stratigraphic level, consisting of two limestone units with the least silica content.
- The limestone surface is very soft and silica nodules protrude from the walls.
- Allochthonous sediments are absent; no significant authochtonous sediment layers were encountered (apart from the residual chert and silt).

These observations suggest that the cave has been formed phreatically, (*i.e.*, at or below the water table) by a slow corrosion process, bound to a certain level. The water apparently came from below, rising through the pits in the halls and, after having been saturated with limestone, disappearing again through these holes into the deeper ground water. No lateral outflow channel existed. Examples for such systems caused by water rising from a deeper aquifer and disappearing back into it and are known, for example, from the South Harz Mountains, Germany (*e.g.*, Kempe, 1997a). There, carbonate-saturated phreatic water rises into the overlying gypsum and anhydrite where it dissolves large domes of a principally similar morphology as Al-Daher Cave. The gypsum-saturated water is denser and sinks back into the carbonate aquifer into the deeper ground-water body. Such phreatic slow convective systems have been shown to be responsible specifically for the formation of caves with large halls that are not connected by stream channels, as discussed below.

Well-known examples for this type of cave development are the caves in the Capitan Reef limestone of the Guadalupe Mountains, foremost Carlsbad and Lechuguilla Caverns (New Mexico, U.S.A) (*e.g.*, Hill, 1987; 2000). In fact, Al-Daher Cave can be directly compared to Endless Cavern in the Guadalupe Mountains (*e.g.*, Palmer and Palmer, 2000; map in McClurg, 1986, p. 14–15). Both are developed laterally along stratigraphic units and both are well developed maze caves lacking all morphological and sedimentological indications of turbulently flowing water. Other examples of caves formed by convecting water are reported from Frankonia and the Harz Mountains, Germany, (*e.g.*, Kempe, 1996; 1997a; 1997b; 2005) and from Italy (Galdenzi and Maruoka, 2004).

In the case of the Guadalupe caves it is now clear that rising warm and H_2S-rich formation waters were the cause of their genesis (*e.g.*, Hill, 1987; 2000; Palmer and Palmer, 2000; Palmer and Hill, 2005). The H_2S was oxidized in the shallow groundwater zone, a process which leads to the formation of sulphurous and sulphuric acid according to:

$$H_2S + 2O_2 \rightarrow 2H^+ + SO_2^{2-} \leftrightarrow H^+ + HSO_4^{2-} \quad (1)$$

It in turn attacks the limestone and dissolves it. Due to the high sulfate concentration in the waters, gypsum solubility can sometimes be surpassed, resulting in the precipitation of this mineral. In Carlsbad Cavern, Endless Cavern, and others, some of this gypsum still remains as a testament to this process. In Al-Daher Cave no gypsum was observed, but this does not exclude the possibility of a sulfuric acid genesis. First of all, the precipitation of gypsum does not necessarily occur if the water is circulated down fast enough. Secondarily, the cave receives enough drip water that the gypsum could have been removed long ago.

Nevertheless, geochemically a second oxidation mechanism; for example, that of methane (bacterially mediated) (*e.g.*, Valentine, 2002) could theoretically also lead to the in situ formation of protons plus free CO_2, according to:

$$CH_4 + O_2 \rightarrow 4H^+ + CO_2 \quad (2)$$

both of which could be used in attacking the limestone. This reaction could also create a cave with the observed morphological pattern. It would be very difficult to verify either of the reactions in a fossil cave (specifically in the absence of characteristic deposits such as gypsum and/or endellite, a clay mineral forming under very acid conditions). Nevertheless, both processes could be fueled by locally rising anaerobic water plumes (one for each of the large halls) which mix with oxygenated surface waters seeping in along the fractured chert beds.

This interpretation is in accordance with the observation that there is no sign of any turbulent flow during the cave-forming process (*e.g.*, no stream channels, no stream pots, no scallops, and no water-worn pebbles anywhere in the cave). The cave therefore could not have been formed by the sinking of a stream, nor by an underground vadose river, or phreatically by ground water flowing along a marked pressure gradient. It is remarkable that so far no cave with such characteristics is known from Jordan, in spite of its large limestone area and deeply incised river valleys.

Figure 12 shows the Geopit water-filled with presumed inputs of water and chemicals that could have driven the cave formation. Arrows indicate the kind of slow convective turnover driven by dissolution and in accordance with the morphology of the walls of the cave.

Since the cave is situated near the top of a mountain today, it must predate much of the tectonic uplifting and faulting in the area and must also predate the down-cutting of the adjacent valleys. According to Wakshal (2005) the oldest generation of karst in neighboring Israel dates into the Late Miocene. Its paleo-water-level is now at >500 m a.s.l. (*i.e.*, in accordance to the high elevation of Al-Daher Cave).

Speleothems

This speleogenic interpretation (*i.e.,* the relatively old age of the cave) is supported by the state of the speleothems occurring in the cave. The cave has many up to 2 m high stalagmites and some remarkable ceiling flowstone. First inspection shows that they represent many generations; older specimens with a dull and partly corroded surface stand next to still growing ones. Moreover, much of the flowstone is naturally damaged, a sign of age of these formations. The damage (Figs. 13, 14) could be either caused by earthquakes (*e.g.*, Kagan *et al.*, 2005) or by cave ice that might have formed even in Jordan during cold continental glacial climates (for a discussion of natural speleothem breakage including cave ice see Kempe, 2004). The existence of several speleothem generations suggests that the cave is not of recent age, but could have formed several hundred thousand, if not even millions of years before present.

Anthropogenic Impact/Utilization

This outline shows the scientific potential of this geological feature which is unique within Jordan. The stalagmites offer the possibility to study paleoclimatic changes over a long and possibly continuous time span, and the cave structure offers the possibility to study this relatively rare type of convective phreatic cave. The cave also holds biospeleological potential. It is used by bats which have left copious piles of guano, possibly forming the food base for other cave life.

The potential for tourism in this cave is interesting. It could well become the first show cave in Jordan. The halls and some of the passages are large enough to allow a limited number of visitors to the cave. In Figure 3 we suggest a path through the cave which causes the least impact to the cave and features most of the sights and educational highlights of the cave. However, the local government must act quickly because the cave has been heavily vandalized since its discovery and is being deprived of much of its original stalactite splendor. The opening of the entrance will encourage this activity if the cave is not gated immediately. Before proceeding with any plans to open the cave to the public, a thorough survey must be conducted determining the best possible guide path through the cave, causing the least damage as well as offering the best views and the largest educational impact. The cave is, however, not large and spectacular enough (in international comparison) to expect a sizeable income from it for the community.

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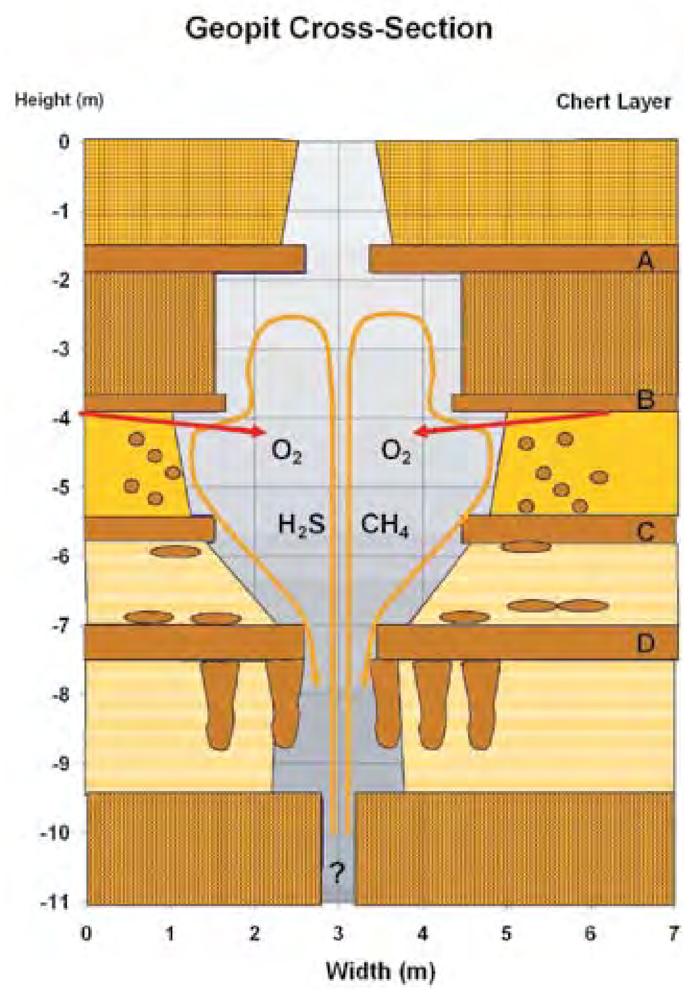

Figure 12. Model of dissolution-driven convection in a stratigraphic cross section of the "Geopit" in the southern part of the cave.

Figure 13. Naturally damaged stalagmite (note new growth across breakage surfaces). This sort of damage could be caused by compression of stalagmitic column between ceiling and floor during an earthquake.

Figure 14. Naturally broken stalagmite, sheared off its base. The nature of such damage is unclear. Earthquakes are suggested as one possible cause, as well as cave ice that could have formed during continental cold climate during glacial maxima.

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A MINIMUM AGE FOR CANYON INCISION AND FOR THE EXTINCT MOLOSSID BAT, *TADARIDA CONSTANTINEI*, FROM CARLSBAD CAVERNS NATIONAL PARK, NEW MEXICO

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Slaughter Canyon Cave (or New Cave), Carlsbad Caverns National Park, southeastern New Mexico, opens in the wall of Slaughter Canyon, 174 m above the present level of the canyon floor. It contains bone-bearing, water-laid sediments capped by a double layer of calcite. TIMS U-Th dates on the two layers are 66.0 ± 0.3 ka and 209 ± 9 ka. Deposition of these two laterally-extensive calcite layers suggests wet periods in this currently-arid region during MIS 4 and 7. The date on the lower layer suggests that the clastic deposit was emplaced no later than MIS 8. This yields a maximum estimate for downcutting rate of the canyon of ~0.87 mm yr^{-1}during the Late Pleistocene. The clastic deposit contains bones of the molossid bat Tadarida constantinei *Lawrence 1960: the date of 209 ± 9 ka is thus a minimum age for this extinct bat.*

Introduction

Slaughter Canyon Cave (also known as New Cave), Carlsbad Caverns National Park, southeastern New Mexico, opens on the southwest wall of Slaughter Canyon (UTM 13 540848E 3553503N). The canyon is one of the many that are incised into the Guadalupe Mountains, controlled by a prominent set of NW-trending joints (Duchene and Martinez, 2000). The cave is developed in the Permian age Capitan Reef Complex (Hill, 2000) of limestone and dolostones. The cave has a simple profile along a single level now opening onto the canyon wall (Fig. 1A). A remnant of the cave can be seen at the same elevation in the opposite wall of the canyon (the Ogle/Rainbow Cave) indicating that the cave was opened when the canyon bisected it (DuChene and Martinez, 2000).

Calcite-capped, fossil-bearing clastic sediments in the cave floor were exposed by guano prospectors between 1937 and 1957. The 3 m thick deposit is mostly a bone-bearing water-lain sediment with horizons of fossil bat guano. The fossil bones show preferred orientations from water sorting. The sediments are partly cemented and capped by a thin but laterally extensive layer of calcite flowstone. Dating of this calcite thus provides an estimate of the minimum age of the deposit. The sediment-guano complex must post-date the opening of the cave by canyon downcutting. In conjunction with the geomorphological situation of the cave, and the present elevation of the canyon floor, this date allows the estimation of the rate of canyon downcutting over the Late Pleistocene. The fossils include abundant well-preserved osteological remains of *Tadarida constantinei* Lawrence 1960; thus the calcite date also allows an estimation of the minimum age for this extinct bat.

Dating

The flowstone sample, collected in 1988 from ~150 m inside the cave entrance (Fig. 1B), is ~10 mm thick, with two distinct layers separated by a depositional hiatus. The upper layer, without detrital contamination, is 4–5 mm thick and overlies the lower, somewhat detritally-contaminated, layer (Fig. 2). This lies directly on, and cements the top of the sediments. A piece of the calcite flowstone was sent to McMaster University in 1988, in the hope of generating a U-Th age by alpha spectrometry, but this was unsuccessful due to detrital contamination (D. C. Ford, *pers. comm.*, 1988). In 2003 the lower and the upper layers were U-Th dated by thermal ionization mass spectrometry (TIMS), after careful removal of material in association with the upper and middle hiatuses that may have been leached. The upper layer yielded 66.0 ± 0.3 ka and the lower layer 209 ± 9 ka (Table 1). The calcite impregnating the sediment could not be separated from the clasts and thus could not be dated.

Speleothem evidence suggests that this region alternates between arid conditions during interglacial periods and pluvial conditions during glacial periods (Hill, 1987). Musgrove *et al.* (2001) also show that speleothem growth correlates with wet periods, in central Texas. Thus the Slaughter Canyon dates are best interpreted as indicative of two wet phases separated by periods of non-deposition presumed to be arid. The fluvial activity that laid down the clastic deposit obviously occurred before the deposition of the basal calcite layer. This could have been during the marine oxygen isotope stage 8 glacial period, but obviously could have been earlier. Thus the date of 209 ± 9 ka is a minimum age for the clastic deposit. If this situation is similar to those encountered by Stock *et al.* (2005), who found that U-Th dates on speleothem overlying clastic sediments were generally considerably younger than cosmogenic ^{26}Al/^{10}Be burial dates on the sediment itself, then it is possible that the Slaughter Canyon

Table 1. Data from Slaughter Canyon flowstone U-Th TIMS dating (activity ratios, 2δ errors).

Layer	Age (ka)	Corr. Age[a] (ka)	U (ppm)	$^{230}Th/^{234}U$	$^{234}U/^{238}U$	$^{234}U/^{238}U_{init}$	$^{230}U/^{232}Th$
Upper	66.0 ± 0.3	N.A.	0.26	0.4722 ± 0.0002	1.807 ± 0.003	1.973 ± 0.004	253
Lower	209 ± 9	206 ± 9	0.38	0.922 ± 0.014	1.40 ± 0.02	1.911 ± 0.005	38

[a] Age corrected for detrital contamination assuming an initial $^{230}Th/^{232}Th$ activity ratio of 1.5. In this case, the corrected age is within the 2δ error, thus the detrital contamination is insignificant.

Table 2. Radiocarbon dates (conventional) associated with *Tadarida constantinei*, Slaughter canyon Cave, New Mexico.

Laboratory Code	Stratigraphy	Reported Age (rcybp)
C 898[a]	Guano, 2 feet below caprock.	>17,800
UCR 1270[b]	Guano, 8–9 inches below caprock.	>28,150
UCR 1208[b]	Guano, 90 inches below UCR-1207.	>32,500
UCR 1543[b]	Unknown.	28,800 ± 2,600

[a] Libby (1954).
[b] U.S. Park Service, Carlsbad Caverns (unpublished records).
Laboratory code C represents University of Chicago.
Laboratory code UCR represents the University of California, Riverside.

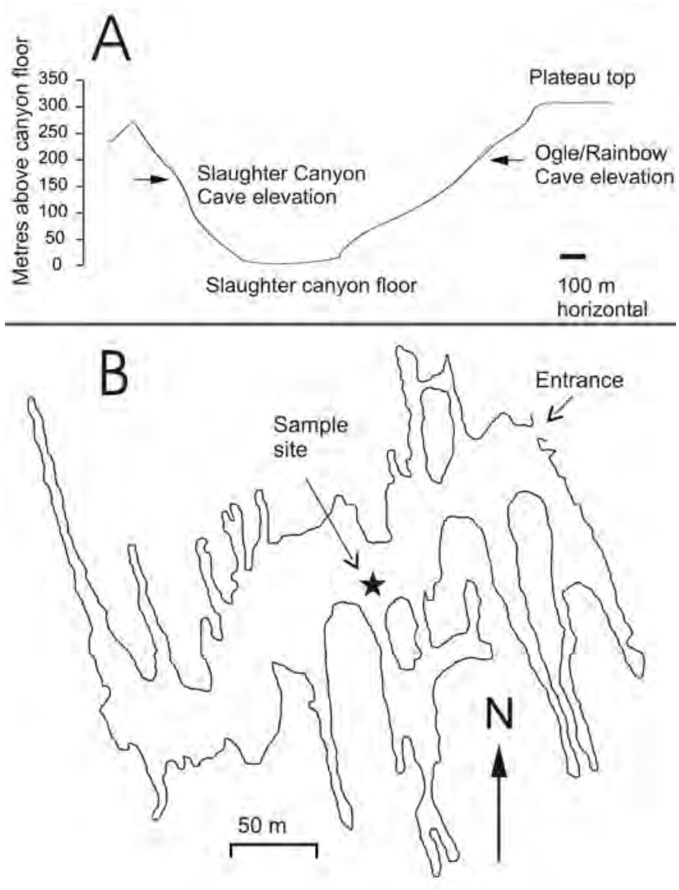

Figure 1. A. Cross section of Slaughter Canyon (from SW to NE across canyon) showing the relationship of the plateau top, the canyon floor and the caves opening into the canyon wall. The Rainbow entrance of the Ogle/Rainbow Cave is directly opposite the Slaughter Canyon Cave entrance, at an elevation of ~174 m above the canyon floor (drawn from data in US Geological Survey, 1979). B. Plan of Slaughter Canyon Cave showing location from which flowstone was collected (drawn from data in Cave Research Foundation, 1976).

Cave sediments are also considerably older than the impregnating calcite.

Downcutting Rate

The clastic deposit consists of waterlain sediments containing fossil mammal bones showing evidence of water sorting, with some horizons of fossil bat guano. It is presumed that the sediment was emplaced when the canyon floor was close to the elevation of the cave entrance.

The geomorphological setting of Slaughter Canyon Cave (New Cave) in the face of the canyon wall directly facing the Rainbow entrance of Ogle Cave in the opposite wall (Fig. 1A) suggests that the two caves had been a single system at the time of speleogenesis (DuChene and Martinez, 2000) long before the canyon began to be incised. With falling base level, the canyon has cut through the cave, bisecting it. If the calcite-capped fluvial deposit indicates the time when the canyon floor was at the level of this passage, then the difference in elevation of the passage and the present canyon floor gives a measure of how far the canyon has been incised in the last 200 kyrs or more. The level of the Slaughter Canyon Cave entrance is 174 m above the canyon floor (Jagnow, 1977). Hill (1987, p. 92) estimated the rate of downcutting at < 45 mm yr^{-1} but only had access to a ^{14}C date on the bat guano of >32,500 rcybp (Table 2). Using the TIMS U-Th date of ~200 ka on the calcite gives a new and considerably lower (but maximum) estimate of downcutting rate of ≤ 0.87 mm yr^{-1}.

No other estimates for down-cutting rates in Slaughter Canyon itself have been published, but DuChene and Martinez (2000) estimate downcutting rates for the Central Section of the Guadalupe Mountains at 0.072 – 0.022 mm yr^{-1} (median 0.046 mm yr^{-1}), using $^{40}Ar/^{39}Ar$ dates on alunites from sulfuric acid caves in the region (Polyak *et al.*, 1998; Polyak and Provencio, 2000). Dethier (2001) offers a broad estimate for downcutting in non-carbonate rocks in the general region of the south-west USA using dates on tephra deposits from the Yellowstone Caldera for the whole region west of the Mississippi River. Although no dat-

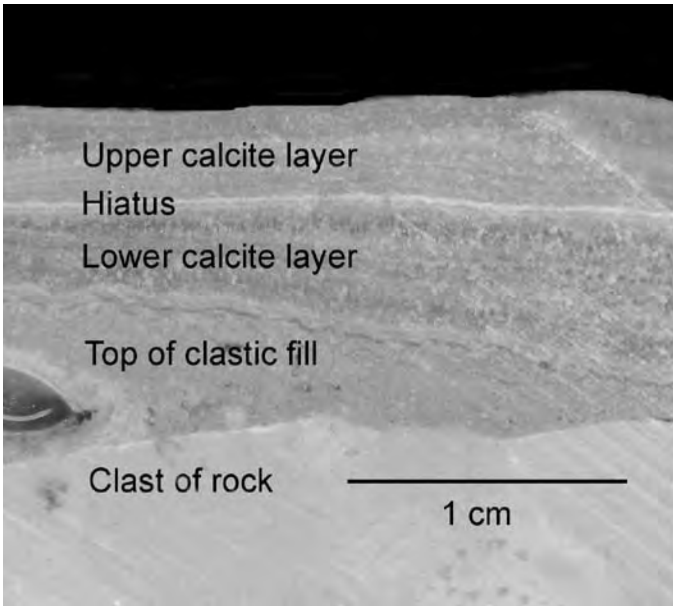

Figure 2. Section of the calcite capping the bone-bearing clastic sediment. The upper calcite layer and the lower calcite layer were U-Th dated by TIMS at 66.0 ± 0.3 and 209 ± 9 ka respectively. (The angled saw marks are artifacts from cutting.)

ed ash deposits are indicated in the immediate area of the cave, the estimated long-term incision rate over the last 600,000 years for the Guadalupe region is ~5 – 10 cm ka^{-1} or ~0.05 – 0.10 mm yr^{-1}. However, incision rate has not been constant over this time period. Although the age control is incomplete, Dethier (2001) observes that incision rates increased in the middle to Late Pleistocene by two to five times the earlier rates. Dethier's Figure 3 shows details for the Rio Grande, New Mexico, ~200 km to the west of the Guadalupe region. Overall incision rate for the last 800 ka was estimated to be ~0.16 mm yr^{-1}, but only ~0.08 mm yr^{-1} for the first 600 kyrs and ~0.38 mm yr^{-1} for the last 200 kyrs. Duchene and Martinez's (2000) estimate, 0.046 mm yr^{-1}, is considerably lower than this and our estimate, 0.87 mm yr^{-1} maximum, is higher (but a similar order of magnitude). The true incision rate is probably somewhere between the three.

PALAEONTOLOGY

The molossid bat in this deposit, *Tadarida constantinei* Lawrence 1960, differs from the extant *Tadarida brasiliensis mexicana*, abundant in adjacent Carlsbad Caverns, primarily in size. Lawrence (1960) described *T. constantinei* as averaging 13% larger in length of skull, with the means of the two taxa differing by some eight standard deviations. Attempts to date the extinct *T. constantinei* deposit began early (Table 2); a sample of fossil guano from the deposit was reported on by W. F. Libby in his fifth radiocarbon date list (Libby, 1954) and found to be < 17,800 rcybp – the effective limit of the technique at that time. Subsequent efforts by the University of California, Riverside radiocarbon lab in 1981 advanced the age to 32,500 rcybp (unpublished US Park Service records), again the limit of the available technology. The new TIMS U-Th date yields a minimum age on the fossils of 209 ± 9 ka.

Our examination of a sample of crania collected from the cave in 1988 did not reveal any characters other than size that would distinguish *T. constantinei* from the extant *T. brasiliensis*. Morgan (2003) reported that *T. constantinei* differs from *T. brasiliensis* only in having a flatter skull. Given the minimum age of *T. constantinei* and the lack of any *T. brasiliensis* material of a similar antiquity, we regard *T. constantinei* as a chronospecies and junior synonym of *T. brasiliensis.*

CONCLUSION

A U-Th TIMS date of 209 ± 9 ka on the calcite layer capping a fossil-bearing, clastic deposit in Slaughter Canyon Cave, New Mexico, has yielded a maximum estimate for downcutting rate of the canyon of ~0.87 mm yr^{-1}. This date also represents a minimum age on the molossid bat *Tadarida constantinei*.

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Javad Ashjari and Ezzat Raeisi. Influences of anticlinal structure on regional flow, Zagros, Iran. *Journal of Cave and Karst Studies,* v. 68, no. 3, p. 118–129.

INFLUENCES OF ANTICLINAL STRUCTURE ON REGIONAL FLOW, ZAGROS, IRAN

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Carbonate karstic formations outcrop in about 23% of the Zagros Region. Seventy-two karstic anticlines were selected to study regional flow. Based on geometry of the anticline and outflow position, a conceptual model is presented for delineation of flow direction, at least within Zagros. The anticlines were divided into two main groups based on presence or absence of hydraulic connectivity between the limbs. The geological and tectonic settings are the main controlling factors within these two groups. Sixty-four out of the seventy-two anticlines showed no hydraulic connectivity between their limbs. Each group was further classified into four subgroups based on the location of the discharge zones, namely one or both plunge apex noses, limb, traversing river, or a combination of plunge apexes, limbs and river. The discharge zones may be located in the adjacent or in the successive anticlines. The discharge zones are mainly controlled by local base level. In most of the cases having no hydraulic connection between the limbs, the direction of flow is initially along the bedding plane dip and finally parallel to the strike at the foot of the anticline. In most of the cases having connections between two limbs, the regional directions of flow, in the connected part, are opposite from the direction of bedding plane dip and eventually parallel to strike. The results show that the primary controlling factors of regional flow are the anticlinal structure of aquifers and geometry of the bedrock.

Introduction

From a theoretical point of view ground-water flow depends only on aquifer hydraulic parameters and boundary conditions (*i.e.*, geological and geomorphological factors exert their influence on the ground-water movement solely through the hydraulic-parameter fields and the boundary conditions). For instance, geology and geomorphology influence the hydraulic conductivity and porosity through the distribution of voids (Kiraly, 2002). An increase of the density and opening and connectivity of the voids therefore increases the hydraulic conductivity and the porosity. If fracture or microfracture families show a well defined preferred orientation the hydraulic conductivity may become anisotropic, thus conducting ground water better in one direction than in another.

Geological factors, in karst studies, include lithology, stratigraphy, fracture patterns and geological structure which are expected to define hydraulic-permeability fields. Relief and local base level are the main geomorphological factors defining boundary conditions and controlling the recharge and discharge location of the aquifer. Therefore, these factors control regional ground-water flow in karstic aquifers (White, 1969; Palmer, 2000) and there is abundant scientific literature on their control over the regional flow. The interested reader will find more in White (1969); Kastning (1977); Legrand (1983); Palmer (1991; 2000); Klimchouk and Ford (2000).

The aim of this paper is to study the link between aquifer characteristics (aquifer geometry and discharge location) and hydraulic response of karst systems (*i.e.*, delineation and major flow direction). The establishment of such a relationship would help to estimate karst ground-water catchment areas and flow direction, which is often difficult (time consuming and expensive) to obtain, based on more easily obtained information (*i.e.*, aquifer geometry and discharge location). The result of this linkage is expected to show the main factors controlling the regional flow direction, such as the effect of an anticlinal structure. The present approach may be the first step of any study of regional hydrogeology, allowing for creation of a first conceptual model of flow in the region. Low cost investigation is very effective for establishing the first hypothesis, which can then be tested by any further investigation (tracing experiments, hydrographs analyses, chemograph analysis, isotopes, *etc.*). Examples from the Zagros Region of Iran will be used in order to support the proposed approach. Carbonate formations outcrop in about 23% of the Zagros Region (Raeisi and Kowsar, 1997). Information has been collected for 72 cylindrical anticlines in order to determine their flow characteristics and their geological/geomorphological settings.

Approach

Geometrically, the Zagros anticlines are cylindrical forms, which plunge down beneath younger sediments at both ends. The young sediments, which overly karstic aquifers, may be permeable or impermeable. Sediments form a thick cover over the synclines between anticlines. Only the top of the anticlines are bare and present exposed carbonate formations. At their bottom the karst aquifers are bounded by impermeable formations (mostly marls and sandstone). Considering the aquifer geometry, there are two cases. If the elevation of the impermeable formation under the crest of an anticline is appropriately higher than the foot of the anticline most of the recharged water of each limb can flow towards the foot of the same limb (Figure 1). In this manner, the hydraulic connectivity of the limbs is disconnected and each limb becomes an independent subaquifer. The main source of recharge is direct precipitation on the karstic aquifer body. The recharge is mainly autogenic. A combination of joints and bedding planes plays a role in transferring the ground water through the vadose zone to the phreatic zone. The impermeable formation below the karstic aquifer and/or interbedded shales in karstic formations can block ground-water flow in a vertical direction. The steep slopes of the anticline limbs direct the flow toward the foot of the anticline via available pathways.

If the elevation of the impermeable formation under the crest of the anticline is lower than the karst-water level, resulting in the absence of any barriers, the karst water of one of the anticline limbs (donor limb) can flow towards the adjacent limb (receiver limb). Usually the contact elevations of karst formations with the adjacent non-karstic formation or alluvium are higher around the donor limb than around the receiver limb. In other words, hydrological base level is located at the foot of the receiver limb and the easiest way for ground water to flow from donor limb to receiver limb, because the hydraulic gradient is steeper toward this limb. The hydraulic connection between the two limbs is often restricted to small areas of the donor limb. So, the infiltrated water flows first parallel to strike in a donor limb, towards a connection area, and then flows to the receiver limb at the connection area.

A main conduit system may develop at the foot of the anticline, parallel to strike where the branches of diffuse flow or small-conduit flow join each other. The direction of flow in main conduit systems at the feet of anticlines depends mainly on the location of discharge zones. Thus, anticlines of both groups can be further classified into four subgroups in which karst water discharges (I) Down-Plunge Nose: Only from one plunge apex or both plunge apexes; (II) Limbs: Only from limbs; (III) Rivers: To a river traversing the karstic aquifer; and (IV) Combination**:** A combination of more than one of these subgroups (Fig. 1).

Therefore, the appropriate conceptual model defining regional flow in anticlinal aquifers is based on the presence or

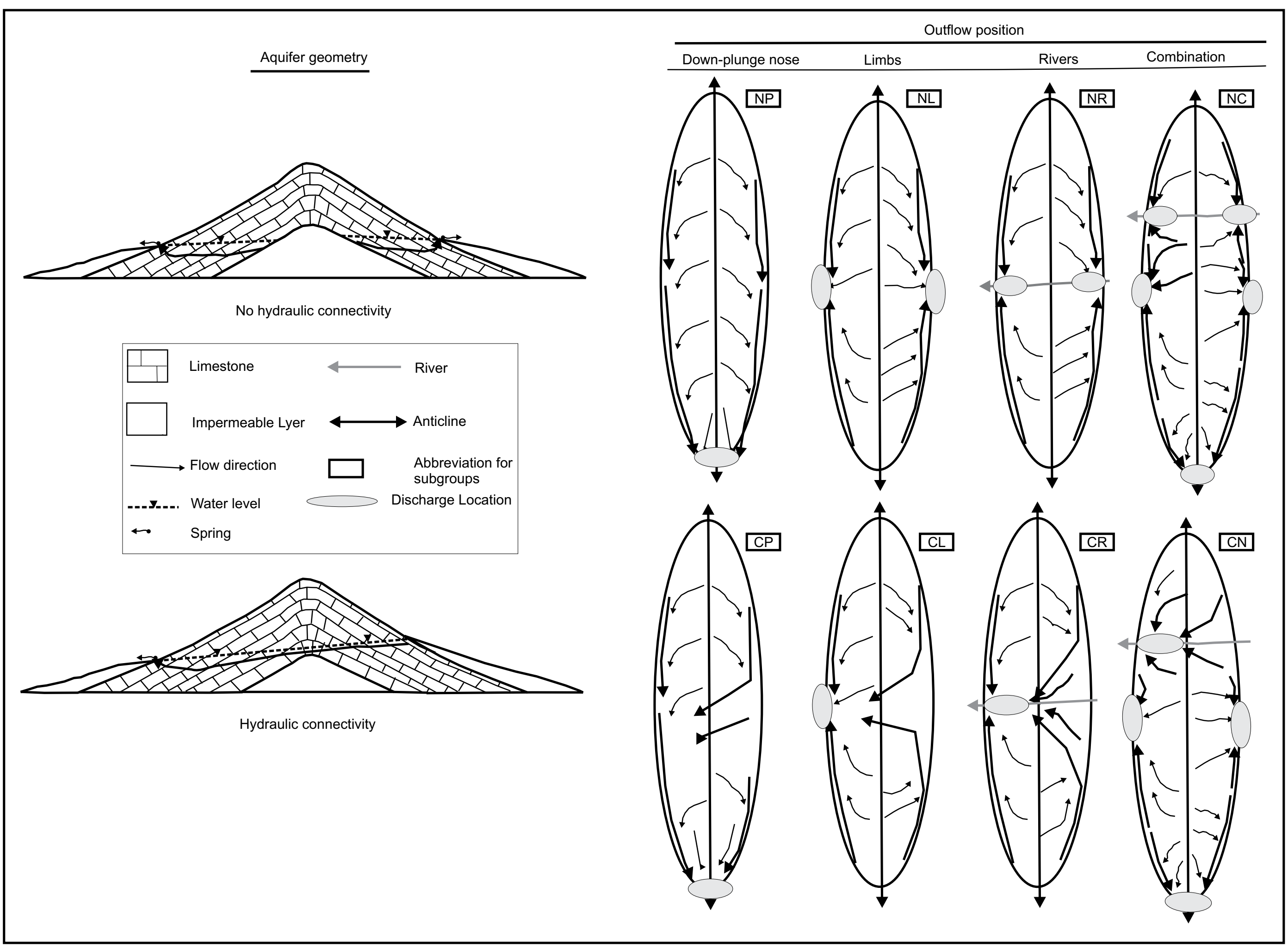


Figure 1: Proposed conceptual model based on geometry and output location.

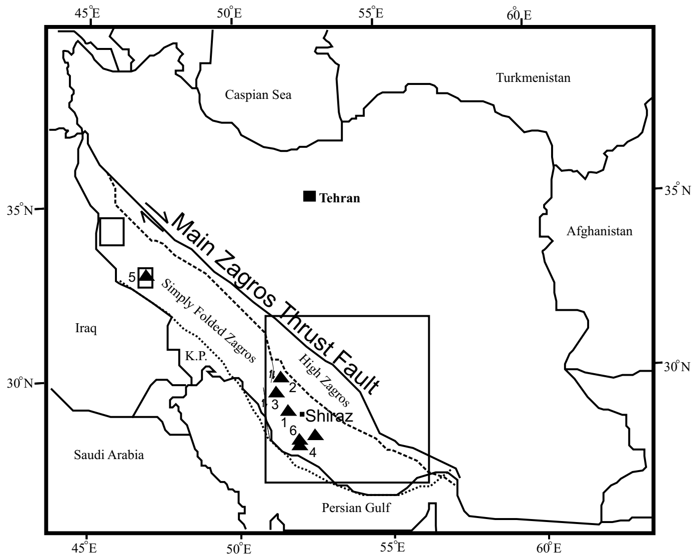


Figure 2. Location map of study areas (boxes and triangles) in relation to the position of selected anticlines discussed in this paper. 1-Derak, 2-Gar and Barm-Firooz, 3-Dashtak, 4-Rooshan, 5-Ravandi and 6-Podenow. Abbreviation K.P. is Khozestan Plain

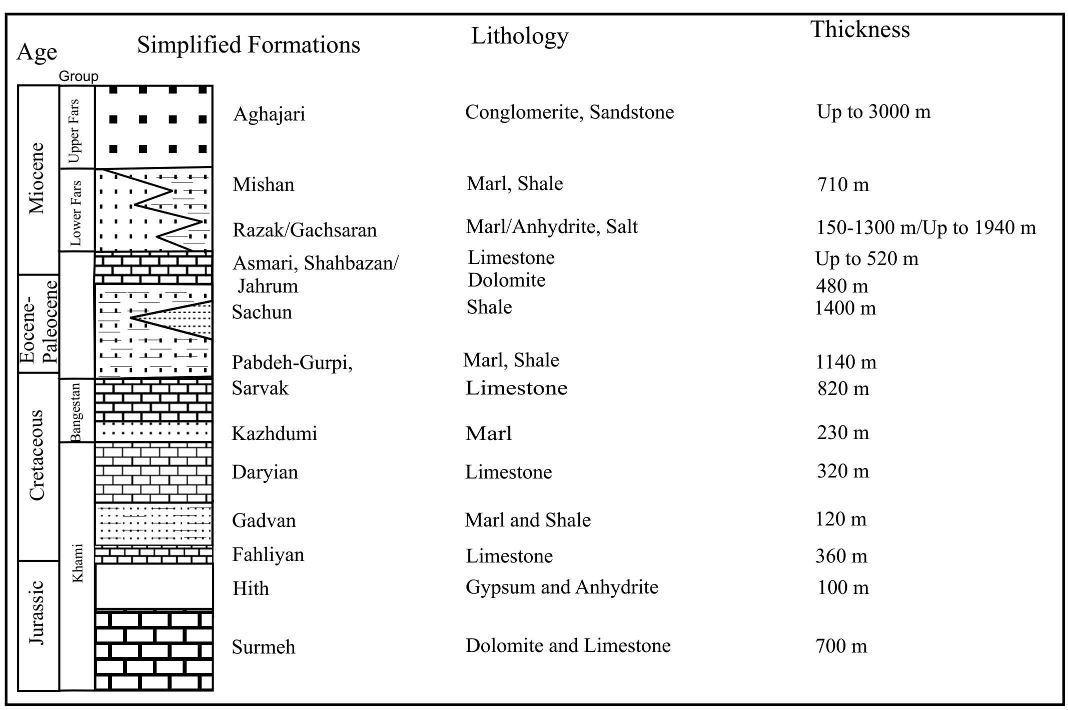
absence of hydraulic connectivity between limbs of anticlines and on the location of discharge zone, leading to eight alternative types of flow patterns.

GEOLOGIC SETTING

In Iran, Zagros extends from the west to south and southeast. The study areas are situated at three different points (Fig. 2). The Zagros consists of three zones, namely the Khozestan Plain, the Simply Folded Zagros and the High Zagros (Darvichzadeh, 1991). The Khozestan Plain Zone consists of alluvial sediments, which cover all older formations. The Simply Folded Zagros consists of long, linear, asymmetrical folds. Anticlines are well exposed and separated by broad valleys (Miliaresis, 2001). Fold axes have a northwest to southeast trend. The High Zagros is very close to the main Zagros thrust fault where it is crushed and intensively faulted.

The stratigraphy and structural characteristics of the Zagros sedimentary sequences have been described in detail by Stocklin and Setudehnia (1971) and Alavi (2004). The geological column of formations outcropping in the study areas is presented in Figure 3. In the following sections, the main outcropping formations of the study areas are discussed in decreasing order of age (Stocklin and Setudehnia, 1971; Darvichzadeh, 1991; Alavi, 2004). The Kazhdumi Formation, within the Bangestan Group, is composed of 230 m of marl at the top and dark argillaceous limestone and marl at the bottom. The Sarvak Formation consists of 250 m of argillaceous limestone at the bottom and 570 m of resistant, cliff-forming limestone at the top. The Gurpi is composed of 350 m of marl, marly limestone, and claystone. The Sachun with a thickness of 1400 m consists of argillite, shale, evaporates (mainly gypsum), and is intercalated with thin-bedded dolomite. The Jahrum Formation overlies it. Pabdeh consists of 800 m of calcareous shale, marl, and limemudstone with subordinate argillaceous limestone. Facies grade toward the southwest into the Jahrum carbonates. The Jahrum is composed of 485 m of cliff-forming dolomite interbedded with dolomitic limestone; it grades toward the deep-marine Pabdeh carbonates. The Jahrum Formation outcrops in most parts of the Zagros and is known as Shahbazan Formation in west of Zagros. The thickness of the Asmari Formation varies from a few meters up to 500 m, consisting of medium-bedded to thick-bedded, and well-jointed limestone. The Razak Formation has a highly variable thickness ranging between 150 to 1300 m. Its

Figure 3. Stratigraphic column through the Zagros in the study areas (Darvichzadeh, 1991; Alavi, 2004; McQuarrie 2004)



lithology is mainly marl, interbedded with silty limestone. It interfingers with evaporites of the Gachsaran Formation. The Gachsaran Formation is composed of multiple sequences of variable thicknesses (up to 1900 m) and lithologies, including alternations of evaporites (gypsum, anhydrite, and subordinate halite), shale, marl, and locally conglomeratic calcarenite. The Mishan Formation is composed of marl, calcareous shale, siltstone, and sandstone. The Aghajari Formation is a thick, up to 3000 m succession, mainly composed of carbonate-clast and polymict conglomerate, calcarenite, cross-bedded sandstone, siltstone, marl, and lime-mudstone.

Method of Study

In the Zagros Region, 72 anticlines were selected for this study. The geologic maps of all anticlines were prepared based on geologic maps of 1/100,000 and 1/250,000 from the Oil Company of Iran. The anticlines consist mainly of several subaquifers. In order to get data on the flow system discharge, specific conductance, water temperature, pH, major ions of water, water level in karstic wells and piezometers, water-tracing results, and rainfall data were collected. The water budget of each sub-basin of each anticline was estimated if it had not already been calculated in previous studies. The inflow is mainly in the form of precipitation and in a few cases as seepage from rivers traversing the anticlines. The average precipitation over anticline sub-basin surfaces was estimated using the rainfall-elevation relation and the topographic map. The recharge coefficient was estimated according to previous studies on karstic regions of Iran (Pezeshkpour, 1991; Karimi, 2003; Karimi, *et al.*, 2005; Karst Research Centre of Iran, 1993).

The discharge rate was estimated based on annual discharge of springs, wells, and qanats (a qanat is a man-made underground gallery transferring ground water to the surface by gravity). In some cases subsurface flow to the adjacent alluvium aquifer had to be assumed to explain exceeding recharge volume compared to known springs, qanats and wells. If the difference between discharge and recharge was more than the maximum expected error (10%), the possibility of flow to or from the adjacent or successive anticlines was evaluated by the following decision criteria.

1. The geological settings confirm a possible flow route from the anticline under study to or from an adjacent or successive anticline;
2. The hydraulic head is sufficient to induce flow; and
3. The water surplus (or deficit) of the anticline corresponds to the water deficit (or excess) of one of the adjacent or successive anticlines.

The catchment area of each spring is determined by the following equation:

$$A = \frac{V}{10^3 (PI)} \qquad (1)$$

In which A is the catchment area of the spring (km^2), V is the total discharge of the spring during one hydrological year (m^3), P is the annual precipitation (mm yr^{-1}), and I is the recharge coefficient (dimensionless) which varies from 0 to 1. In Equation (1), it is assumed that there is no allogenic stream input and the variation of storage over time is insignificant.

Then, the calculated surface area (A) was compared to the probable boundary of the spring catchment area, which was determined by the following assumptions and criteria (Karimi, 2003; Karimi *et al.*, 2005):

1. The catchment area is probably as close as possible to the spring;
2. The elevation of catchment area must be higher than that of the related spring and possible catchment can be determined using a topographic map of the region;
3. There must be no impermeable formations crossing the aquifer and possibly disconnecting one part from the spring;
4. The water budget must be balanced for the total area of the main aquifer (or anticline), in other words, the catchment area of all the subaquifers is determined;
5. Geomorphology, geology, and tectonic settings must justify the catchment area;
6. The physicochemical parameters should be in agreement with the lithology of the related karst aquifers and adjacent formations; and
7. Available dye-tracing data may be used to confirm or refute the proposal boundaries.

Each anticline under study was divided into ground-water catchment areas related to each discharge zone (spring, well, qanat, and flow to adjacent aquifers) based on geomorphology and geological settings.

Results

In order to determine the validity of the proposed conceptual model (*i.e.*, the influence of the anticlinal structure on regional ground-water flow) 72 anticlines of the Zagros Region were examined. Table 1 presents a summary of the lithology, recharge area, recharge coefficient, presence or absence of faults, type of discharge zones, and appropriate model for each anticline. In the following text only one example for each subgroup defined in Figure 1 is presented.

No Hydraulic Connectivity Between Limbs

In aquifers of this group the elevation of the aquifer bottom (impermeable formation) under the crest of an anticline is higher than the feet of the anticline (*i.e.*, most of the recharged water on each limb can flow towards the foot of the same limb). Four subgroups have been distinguished considering the position of outlets (Fig. 1).

Discharge from One or Both Plunges of the Fold

In three separate cases ground water is discharging from the plunging end of an anticline, and the Derak anticline is discussed as the type case of this subgroup. The doubly plunging Derak anticline is composed of the karstic Asmari-Jahrum Formations which are overlain and underlain, respectively, by the impermeable Razak and Sachun Formations except for the southeastern plunge apex, which is in direct contact with the adjacent alluvium (Fig. 4A). The total area of outcropping carbonate formation is 73 km^2. The elevation of the impermeable Sachun Formation under the crest of the anticline is noticeably high, disconnecting the hydraulic connectivity of both limbs (Fig. 4B). Several faults cross the anticline, which are perpendicular to the fold axis.

The main source of recharge is diffuse infiltration. The karst water flows to the adjacent alluvium through the southeastern plunge apex, where water is exploited by several pumping wells in the southeastern part of the anticline with a total discharge of 757 L s^{-1} (Karst Research Center of Iran, 1993). Parab Fars Consulting Engineering Company (1997) calculated the water budget of the Derak anticline in the 1992–1993 water year. The results confirm the unavailability of extra water for transference to the adjacent synclines or successive anticlines. The contact elevation of the Razak Formation with the Asmari-Jahrum Formations in the northwestern plunge apex is 500 m higher than the contact elevation of the Asmari-Jahrum Formations with the alluvium in the southeastern plunge apex. Therefore, a main conduit system has probably developed parallel to the strike, starting from the northwestern plunge apex and going toward the southeastern plunge apex. Karst water enters the adjacent alluvium of the southeastern plunge apex. Several faults cross the Derak anticline axis, but no springs are observed at the fault's trends, implying that the faults do not have any role in the regional ground-water flow. The schematic model of the regional flow in the Derak anticline based on the above discussions is presented in Figure 4A.

Consequently, karst water of the limb area may discharge from one of the plunge apexes or from both plunge apexes. In the single plunge apex case, karst water joins a main conduit system at the foot of the anticline, parallel to the strike, extending from the high elevation plunge apex and leading to the plunge apex related to the local base level. As the main conduit system gets close to the discharging plunge apex, it collects more water from the limb area. The karst water emerges as springs or flows to adjacent alluvium, or to a successive anticline in the plunge apex fold area.

The one plunge apex case, as described above, can be extended to the case where springs are located at both plunge apexes, or even if ground-water flows to alluvium or adjacent formation in both plunge apexes. No spring or discharge zone is located along limbs because the contact elevation of impermeable formations or fine-grained alluvium with karstic formations along the limb of the anticline is higher than the elevation of both plunge apexes. In the case where outflows are located at both plunge apexes, the limb of the anticline is composed of two distinct subaquifers. Their catchment area is limited to the crest of the anticline, the adjacent impermeable formation or fine-grained alluvium, and by the water divide line between the two subaquifers. Three anticlines are typical of discharge from both plunge apexes.

KARST WATER DISCHARGE FROM LIMBS

Twenty anticlines belong to this subgroup. Among them, Gar anticline will be discussed further. The northwestern successive anticline of Gar is the Barm-Firooz anticline. The exposed cores of the Gar and Barm-Firooz anticlines are dominantly made of the calcareous Sarvak Formation, underlain and overlain by impermeable shales of the Kazhdumi and Pabdeh-Gurpi Formations, respectively (Fig. 5A). The southern limb of both anticlines has been completely crushed. One hundred sixty dolines are present in the northern limb of the Gar anticline, and 99 dolines are found along the Barm-Firooz anticline (Fig. 5A). The northern and southern limbs of the anticline have been hydraulically disconnected by the action of a thrust fault, which shifts up the impermeable Kazhdumi Formation in the core of the anticlines (Fig. 5B, Fault F1). Karst water from the Sarvak aquifer of the Gar and Barm-Firooz anticlines discharges at 12 springs, 11 of which (including the Berghan Spring) emerges from the southern limb of the Gar anticline, and one large spring (Sheshpeer Spring) emerge from the northern limb of the Gar anticline. The mean annual discharges of Sheshpeer and Berghan Springs are 3,247 L s^{-1} and 632 L s^{-1}, respectively, while the mean discharge of the other springs ranges from 1 to 68 L s^{-1}.

The geological setting, the water budget calculation (Pezesh-

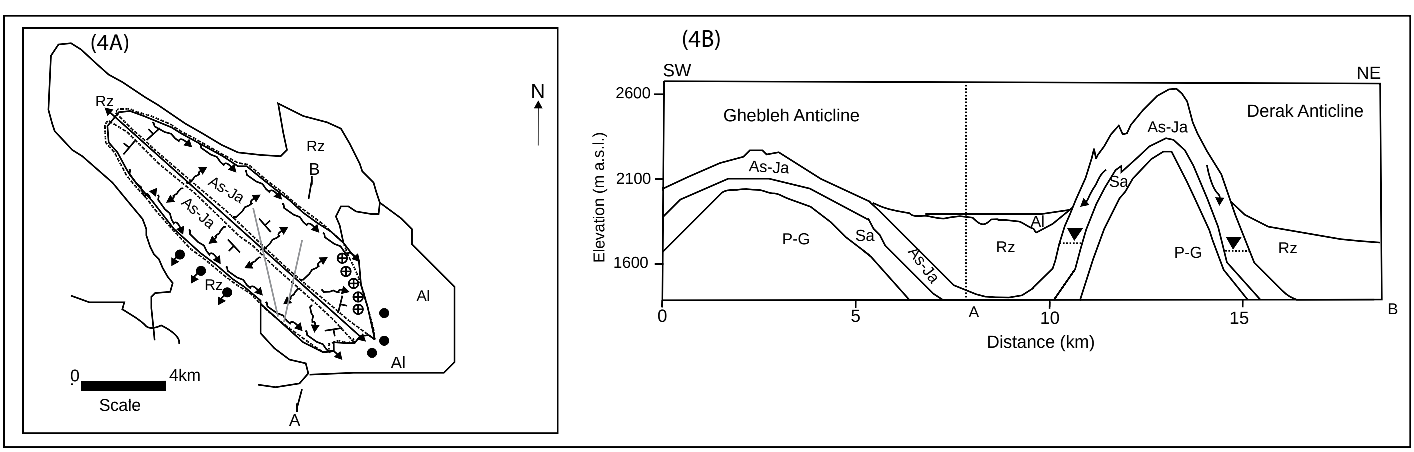


Figure 4. Hydrogeologic maps and regional flow pattern (A) and geologic cross sections (B) of Derak Anticline. Legend is referenced in Figure 5.

Table 1. Summary of geologic and geomorphologic characteristics of studied anticlines.

Anticline Name	Recharge Area (km^2)	Annual Precipitation (mm yr^{-1})	Recharge Coefficient (%)	Lithology	Position of Main Faults	Type of Discharge[a]	Type of Aquifer[b]
Ab-Siah	210	370	70	Limestone. [c]	South limb.	S,A	CC
Ahmadi	360	490	30	Limestone and dolomite. [c]	South limb.	S,A,Q	NC
Alhare I/II	290	320	30	Limestone and dolomite. [c]	South limb.	S,A/S	NC/CL
Baghestan	80	650	60	Limestone and dolomite. [c]	Intensively.	S	NC
Bamu	220	520	21	Limestone and dolomite. [c]	Intensively.	A,Q	NC
Behkhun	40	250	35	Limestone and dolomite. [c]	South limb.	S	NC
Bareaftab	40	250	40	Limestone and dolomite. [c]	South limb.	S	NC
Bareh	50	600	75	Limestone.	No fault.	S,A	NC
Benekhoshk	110	485	57	Limestone. [c]	No fault.	S	NC
Chapeer	30	356	37	Limestone and dolomite.	South limb.	S	CL
Dalneshin	240	580	46	Limestone.	Transverses.	S,Q	NP
Daloo-sefidar	980	680	45	Limestone and dolomite. [c]	South limb.	S,Q,A	NC
Darishak	630	841	65	Limestone and dolomite. [c]	Intensively.	S,A	NC
Darughak	65	580	40	Limestone. [c]	North limb.	S,Q,A	NC
Dashtak-Fars	320	570	45	Limestone. [c]	No fault.	S,A	NC
Dashtak	240	813	37	Limestone and dolomite. [c]	South limb.	S,R	NC
Derak	37	660	50	Limestone and dolomite.	No fault.	Q,A	NP
Droudzan	131	560	70	Limestone.	South limb.	S,A	NC
Emam-Hassan	126	450	50	Limestone. [c]	South limb.	SU	NC
Gar/ Barm-Firooz	200	650	75	Limestone.	South limb.	S/S,SU	NL/NC
Ghalajeh	300	500	76	Limestone.	North limb.	S,SU	NL
Ghareh	610	500	50	Limestone and dolomite.	No fault.	S,Q,A	NC
Ghasreh-Ghomsheh	60	660	50	Limestone and dolomite. [c]	North limb.	S,Q	NC
Galisakan	200	700	40	Limestone and dolomite. [c]	Both plunges.	S,A	NC
Hajiabad	190	450	70	Limestone. [c]	South limb.	S	NL
Kaftarak	170	450	50	Limestone and dolomite. [c]	Both limbs.	S,Q,A	NL
Kalehbadi	160	460	35	Limestone. [c]	No fault.	A	CC
Kalkush	95	480	57	Limestone.	No fault.	SU	NC
Karba	240	320	35	Limestone and dolomite. [c]	South limb.	S	NC
Kartang	280	310	37	Limestone and dolomite. [c]	South limb.	S,A	NC
Khanehkat	310	420	35	Limestone and dolomite. [c]	Intensively.	S,Q,A	NC
Kharmnkuh	160	370	45	Limestone and dolomite.	No fault.	S,Q,A	NC
Khurmuj	140	410	37	Limestone and dolomite. [c]	Transverses.	S,Q	NC
Laeisavar/Plagan/ Zarabi	120	450	40	Limestone. [c]	North limb.	A/A/A	NC/NC/NC
Namak	280	260	28	Limestone and dolomite. [c]	Transverses.	S,A	NC
Nazarabad	20	610	40	Limestone and dolomite. [c]	South limb.	S,Q,A	NL
Omarmussakhani	240	370	35	Limestone. [c]	No fault.	A	NL
Patagh	230	510	63	Limestone. [c]	No fault.	S,SU	NC
Paree-Payeen	70	430	40	Limestone and dolomite.	Intensively.	S,Q	NL
Podenow				Limestone and dolomite. [c]		S,Q,A,R,SU	CC
Rahmat	220	510	50	Limestone.	South limb.	S,A	NC
Ravandi	50	210	50	Limestone and dolomite.	No fault.	S,R	CR
Rijab	450	550	40	Limestone. [c]	Intensively.	S,SU	NC
Rooshan	58	410	50	Limestone and dolomite.	No fault.	S,Q	CL
Sabzposhan	360	614	50	Limestone and dolomite.	North limb.	S,Q,A	NL
Salbiz	35	830	40	Limestone and dolomite.	South limb, south plunge.	S	NP
Sangesiah	130	450	37	Limestone. [c]	Both limbs.	S,A	NC
Saravn	140	470	62	Limestone.	South limb, north plunge.	S	NC
Sarbalesh	250	710	60	Limestone and dolomite. [c]	North limb, both plunges.	S	NP
Shahneshin	270	890	40	Limestone and dolomite. [c]	Intensively.	S,A	NC
Bostang	530	520	60	Limestone and dolomite. [c]	Intensively.	S,R	NC
Siah-Bushehr	150	410	37	Limestone and dolomite. [c]	Transverses.	S,Q,A	NC
Siah-Sydan	390	460	30	Limestone. [c]	South limb.	S,Q,A	NC
Sayeedmohammad	160	350	70	Limestone. [c]	North limb.	S,A	NC
Siah-Hossein	190	480	60	Limestone. [c]	South limb, north plunge.	S,Q,A	NC
Sim	130	420	45	Limestone and dolomite.	No fault.	S,Q,A	NP
Sinehaftab/Gandash	40	450	50	Limestone and dolomite.	No fault.	A/A	NL/NL
Siroo/ Jayeen	120	210	35	Limestone and dolomite. [c]	South limb.	S,A/S,A	NL/NL
Tammar	20	950	75	Limestone.	Transverses.	S,A	NC
Vanaman	270	390	40	Limestone and dolomite. [c]	South limb.	S,A	NP
Layzangan	640	380	40	Limestone and dolomite. [c]	South limb.	S,A,SU	NL
Yar	220	540	60	Limestone and dolomite. [c]	Both limb.	S,A,SU,R	CC
Zarghan/Chahanari	200	410	36	Limestone and dolomite.	South limb.	A/A	NC/NC
Zena/Panjkarteh	200	550	47	Limestone. [c]	South limb.	S,A/A	NL/NC

[a] Abbreviations on column: S=Spring, A=Alluvium, Q=Qanat, SU=Successive anticline, R=River.
[b] Abbreviations on column refer to Figure 1.
[c] The impermeable layers outcrop inside the anticline.

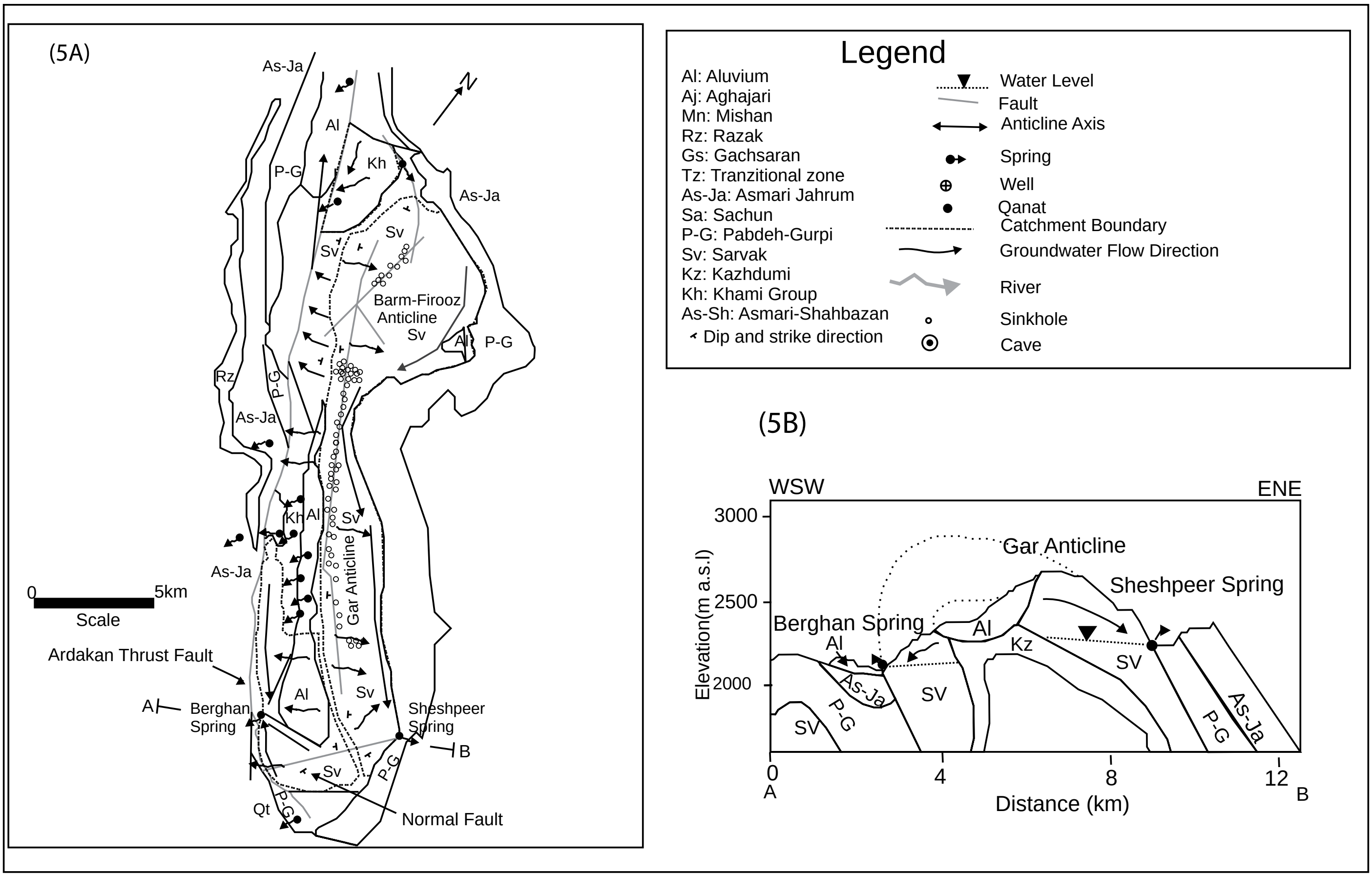


Figure 5. Hydrogeologic maps and regional flow pattern (A) and geologic cross sections (B) of Gar and Barm-Firooz Anticline.

kpour, 1991), and dye-tracer experiments (Raeisi *et al.*, 1999) have shown that the catchment area of the Sheshpeer Spring is the northern limb of the Gar and Barm-Firooz anticlines (Fig. 5A). Therefore, karst water of the northern limb area is expected to flow along the foot of the anticlines and finally emerge from the Sheshpeer Spring. Although the local base level is located further down the southeastern plunge, the Sheshpeer Spring emerges from the limb due to the presence of a normal fault.

Karst water of the southern limb discharges from several springs located along the foot of the limb area. It seems that the southern limb is composed of several independent subaquifers. The southern limb has been brecciated by one thrust fault and several normal faults. The autogenic water stored in a network of interconnected small fissures and pores seem to prevent the development of major karst conduit systems along the foot of the anticline. The southern springs show mainly diffuse recharge (Pezeshkpour, 1991; Raeisi and Karami, 1997). For example, autogenic recharge, the absence of any shafts or dolines, extensive non-cemented breccia in the catchment area, small values and slight differences in hydrograph recession coefficients, high percentage of base flow, and no significant variation in the time series of electrical conductivity, temperature, and major ions indicate diffuse recharge, flow, and discharge in the Berghan Spring.

Consequently, in this subgroup, karst water of the limb area joins the main conduit system parallel to the strike at the foot of the anticline, but the regional ground-water flow direction is changed and the karst water emerges as springs, or flow to the adjacent alluvium aquifer, or adjacent syncline or anticline in the limb region. Each limb may be only one subaquifer with one interconnected main conduit system at the foot of the anticline with numerous overflow discharge zones, or it may consist of several subaquifers with independent conduit systems and catchment areas.

Karst Water Discharges to the River Traversing

No typical example of this subgroup has been found in any of the 72 cases studies.

Karst Water Discharges from a Combination of Plunge Apex(s), Limb(s), and/or River

Karst water discharges from a combination of plunge apex(s), limb(s) and/or river in the fourth subgroup. In other words, it is a combination of at least two of the above-mentioned subgroups. Karst water may discharge from a) limbs and one or two plunge apexes, b) limbs and river, c) one or both plunge apexes and river, and d) one or both plunge apexes, limbs and river. The Dashtak anticline will be discussed as a typical case among the 38 anticlines belonging to this subgroup. The Dashtak anticline consists of the Asmari-Jahrum (221 km^2) and Sarvak (17.1 km^2) Formations. The Sarvak Formation is sandwiched between the Kazhdumi and Pabdeh-Gurpi Formations, breaking the hydraulic connection of the Sarvak and Asmari-Jahrum Formations (Fig. 6A). The Asmari-Jahrum Formations are in direct contact with the Gachsaran Formation and alluvium. The Gachsaran Formation is covered, in some parts, by thin alluvium. The Shapour River traverses the Dashtak anticline near the north-eastern plunge apex, developing a deep valley, namely the Chugan Valley, resulting in the flow of this river over the impervious Pabdeh-Gurpi Formations. Therefore, hydraulic connectivity of the Asmari-Jahrum Formations in the northern and southern limbs is disrupted by the high elevation of the Pabdeh-Gurpi Formations beneath the crest of the anticline, except in the northwestern plunge apex area (Figs. 6B and 6C). The Pabdeh-Gurpi Formations outcrop in some parts of the southern limb at high elevations. The Shapour River acts as a local base level. The karst water of the northern limb in the east of the Chugan Valley flows partly to the adjacent coarse-grained alluvium aquifer, appearing as the upper and lower Renjan Springs (discharge 590 L s^{-1}), and partly as direct discharge from the Asmari-Jahrum Formations into the Shapour River at the beginning of the Chugan Valley. The small Pire-Sabz (40 L s^{-1}) and Shir Springs (8 L s^{-1}) discharge a small area of the northern limb at the west side of the Chugan Valley. The Sasan and Sarab-Shir Springs, with an average annual discharge of 2.6 and 1.8 m^3 s^{-1}, respectively, appear on the southern limb at the west side of the Chugan Valley. Sasan Spring emerges near the end of the Chugan Valley, a few meters above the Shapour River water level. The karst area of the west side of the Chugan Valley is 24 km^2 in surface area, which is not large enough to supply the high discharges of the Sasan and Sarab-Shir Springs. Water budget and dye-tracing studies revealed that the recharge areas of these springs are located in adjacent anticlines and reach the Dashtak anticline via its northwestern plunge apex (Karst Research Center of Iran, 2002; Milanović and Aghili, 1993).

The extensive outcrop of Pabdeh-Gurpi Formations in the southern limb at the eastern side of the Chugan Valley creates several isolated areas of Asmari-Jahrum Formations. The outcrop of the Pabdeh-Gurpi is most probably due to the action of local faults. Karst water of these areas discharges into the Sarab-Dokhtaran Spring, adjacent alluvium aquifers, the Ghaleh-Naranji Spring, and the Parishan Lake (Fig. 6A). The Sarvak Formation is limited to small parts of the southern limb and its karst water emerges from the Pole-Abgineh Spring. The general direction of flow is mainly towards the Shapour River in the Dashtak anticline, except in some parts of the southern limb at the eastern side of the Chugan Valley in which the Pabdeh-Gurpi Formations have created isolated aquifers.

Therefore characteristics of this subgroup are complex, depending on the type and numbers of elements involved in the combination and on those subgroup properties that play a dominant role in controlling the regional ground-water flow. As a result, each limb may be composed of one subaquifer with several discharge zones, or several subaquifers with a distinct catchment area. These subaquifers may have one or more discharge zones.

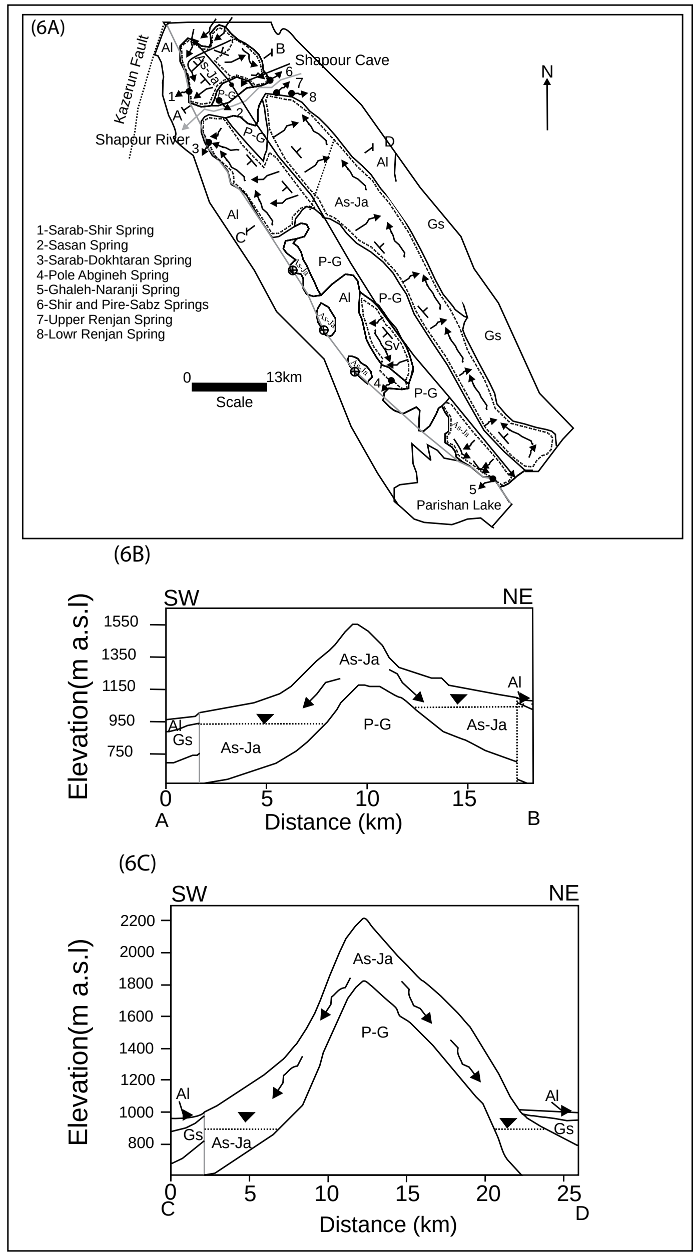


Figure 6. Hydrogeologic maps and regional flow pattern (A) and geologic cross sections (B and C) of Dashtak Anticline. Legend is referenced in Figure 5.

Northern and Southern Limbs are Connected

In this situation karst water of one of the anticline limbs (the donor limb) flows towards the adjacent limb (receiver limb) either through a restricted number of link areas or all along the anticline. After the transfer of karst water to the receiver limb, the flow patterns are similar to anticlines which have no connectivity between limbs. For this reason, the group is further classified into four similar subgroups as the cases with separate limb hydraulic (Fig. 1).

KARST WATER DISCHARGE FROM ONE OR BOTH PLUNGE APEXES

No case representative of this subgroup was found in any of the 72 anticlines under study.

KARST WATER DISCHARGES ONLY FROM ONE LIMB OF THE ANTICLINE

The subgroup contains three anticlines. Rooshan anticline is the type case of this subgroup. It is a small anticline with an area of 58 km^2 (Fig. 7A). It consists of the Asmari-Jahrum Formations surrounded by impermeable transition and Razak Formations. The geological setting indicates the northern limb is higher than the southern limb (Fig. 7B). A spring and a qanat emerge from the southern limb. Geological setting and water budget show that the karst water of the northern limb of Rooshan anticline and a part of the water from the southern limb of the adjacent anticline (Podenow anticline) emerge from the spring and the qanat (Karimi et al. 2005). The karst water of the northern limb flows towards the foot of the southern limb.

GROUNDWATER DISCHARGES TO THE RIVER

Only one case study belongs to this subgroup. The Ravandi anticline consists of the Asmari-Shahbazan Formations underlain and overlain by the Gachsaran and Pabdeh-Gurpi Formations respectively (Fig. 8A). At the foot of Ravandi anticline, a thin alluvium overlies the Gachsaran Formation in small parts. The Symareh River, with an average discharge of 12.5 m^3 s^{-1}, flows on the surface of the Gachsaran Formation and through a narrow and vertical cliff valley in the Asmari-Shahbazan Formations. The impervious Pabdeh-Gurpi Formations are located below the river, allowing hydraulic continuity between the northern and southern limbs (Fig. 8B). Karst water of the Ravandi anticline discharges only into the Symareh River along both sides of the valley via 39 springs on the eastern and two springs on the western side of the valley, respectively. The locations of all the springs are below and around the anticline crest line, implying that the water of the northern limb transfers to the southern limb. Water budgets, together with the absence of any other discharge zones around the anticline, confirm that all the karst water of the Ravandi anticline emerges into the Symareh River (Asadpour, 2001). The Symareh River has incised the canyon, which controls karstification processes in the anticline (*i.e.*, the Symareh River is the local base level).

Groundwater discharges from a combination of limb, plunge apex and river: The subgroup consists of four anticlines. A typical example of this subgroup is the Podenow anticline, which displays a combination of limb, plunge apexes, and river discharge zones.

Karst water of the Podenow anticline discharges from 60 springs, wells, and qanats on the southern and northern limbs, plunge apexes and river. The Podenow anticline is a very long anticline and divided into eastern, central, and western parts. The central and part of the eastern and western sections are shown in Figure 9A. There is no hydraulic connectivity between the southern and northern limbs in most parts of the anticlines, except in the central part and in both plunge apexes (not visible on Figure 9A), because the elevation of the Pabdeh-Gurpi Formations under the crest of the anticline in these areas is higher than the adjacent alluvium aquifers. The northern and southern limbs of the eastern and western sections are independent aquifers, discharging at the foot of the anticline and plunge apexes as karst springs or flowing to the adjacent alluvium and flowing through the intervening syncline to parallel anticline (Karimi, 1998). Central sections slope down toward the saddle-shaped area, including the U-shaped Tangab Valley. The Firoozabad River flows through this valley. This central section is composed mainly of carbonate formations of the Asmari-Jahrum. The contact of Asmari-Jahrum Formations with the Razak Formation is transitional with alternating layers of marl, marly limestone, and limestone. Since the underlying Pabdeh-Gurpi Formations are below the level of the adjacent alluvium aquifers, water can flow from the northern to the southern limb in the saddle area of the central section (Fig. 9B). Uranine and Rhodamine B dyes (Acid Yellow 73 and Basic Violet 10, respectively) were injected into two drillholes on either side of the Tangab Valley on the northern limb, and they appeared in Tangab and in 18 small and

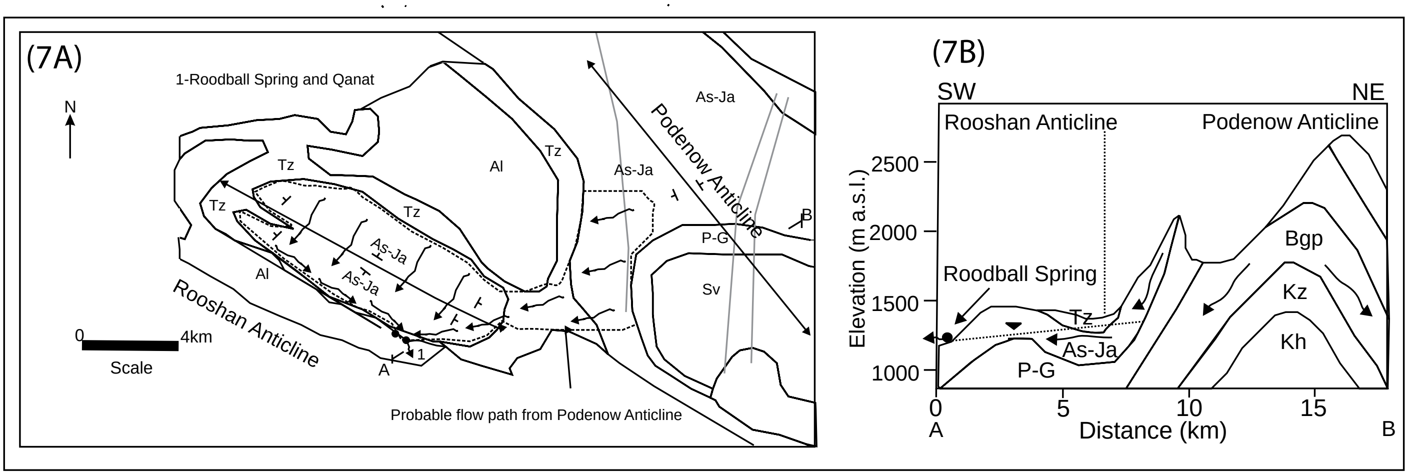


Figure 7. Hydrogeologic maps and regional flow pattern (A) and geologic cross sections (B) of Roshan Anticline. Legend is referenced in Figure 5.

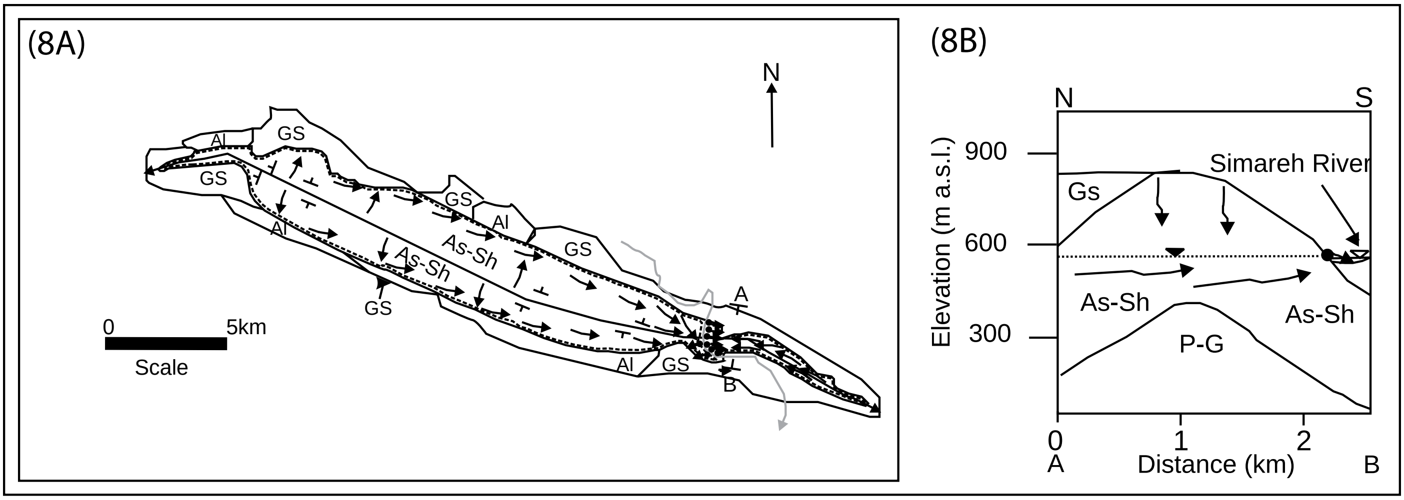


Figure 8. Hydrogeological maps and regional flow pattern (A) and geological cross sections (B) of Ravandi Anticline. Legend is referenced in Figure 5.

big springs (Asadi, 1998). The catchment areas of these springs were determined using water budget and geological setting (Karimi, 1998). Consequently, the Tangab Valley and the feet of the anticline at the southern limb act as base levels for the central section.

Discussion

All 72 anticlines under study have been categorized into six subgroups expected by the model, which is therefore confirmed by field data.

Subgroups of the two main groups have similar geometric characteristics, except on bedrock geometry. Discharge from one plunge apex fold can be observed in anticlines having the following characteristics: (I) The local base level is in one of the plunge apex folds or in a successive anticline; (II) The aquifer, at the feet of anticline, is surrounded by impermeable formation(s) or fine-grained alluvium such that the regional groundwater flow is parallel to the strike and directed towards the local base level; (III) There are no deep subsurface flows of karst water to the karst formations of adjacent synclines or anticlines; (IV) The contact elevation of the impermeable formation(s) or fine-grained alluvium with the karstic formation in the limb area is higher than the water table in the karst aquifer, preventing the formation of overflow springs at the foot of the limbs; (V) There are no extensive faulted zones in the anticline to create independent aquifers.

For the limb subgroups, the lowest outcrop of carbonate formation has to be located along the limbs instead of plunge apex. Faults and/or impermeable layers inside the karst formation block the discharge to the plunge apexes. If the water level in the karst formation is higher than the contact elevation of the karstic formation with the adjacent impermeable layer, overflow springs are expected. If the karst formation is in direct contact with permeable alluvium, the karst water may seep into the alluvium in the large contact area.

The geometry in the subgroup with discharge only to the

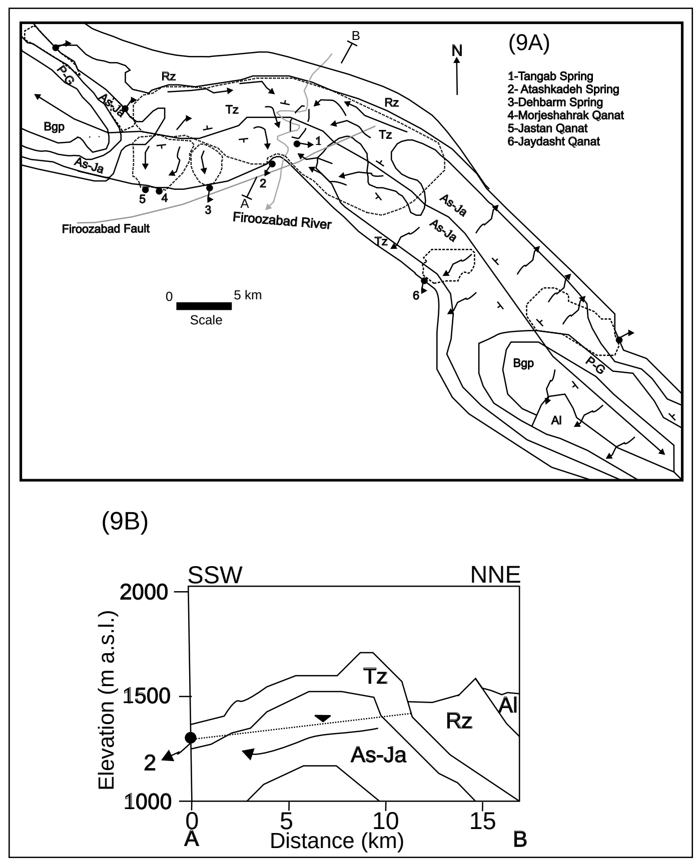


Figure 9. Hydrogeologic maps and regional flow pattern (A) and geologic cross sections (B) of Podenow Anticline. Legend is referenced in Figure 5.

river is similar to plunge apex subgroup, except that the river is the only local base level of the anticline. The combination subgroup has complex geometric properties and depends on the type of configuration between river, plunge apex, and limbs.

Consequently, various configurations of geological parameters result in different regional flow patterns. The main controlling factor is the lowest outcrop of the aquifer. This point is the best probable place for outflow position. Together with the overall geometry of the aquifer (*i.e.*, geometry of impermeable bedrock) this parameter makes it possible to predict the flow direction, at least in a general sense. The presence of discontinuities such as fractures, faults, an incised river, or the outcrop of an impermeable layer inside the catchment area often induces deviation from this simple model. This explains why 42 cases of 72 examined belong to combination subgroups of the model.

In Zagros, perennial high discharge rivers, originating from the non-karstic rocks, traverse the karst formations and develop deep valleys. The gradients of rivers in valleys are low and these rivers act as regional base levels. It is likely that the karst water of each limb area drains into the river as springs or seeps into the riverbed. A typical example of this subgroup is not found in any of the 72 case studies. Most of the rivers flow on the plain parallel to the strike of the karstic anticline or turn on the plain between the plunge apexes of two adjacent anticlines instead of cutting though the karstic formation. Rivers traverse only five anticlines in the study areas, and it seems that the low frequency of cases where rivers incise anticlines and special geometry of subgroups is the main reason for this missing case in this subgroup.

In Zagros, the transfer of karst water from the donor limb to receiver limb is a rare case because it requires special tectonic settings. With respect to the receiver limb, the donor limb must be relatively elevated so that the hydraulic gradient is steep enough to change the direction of flow towards the receiver limb. Tectonic displacements uplift not only the donor limb, but the plunge apexes as well. Therefore, the local base level is located at the foot of receiver limb instead of the plunge apexes. Consequently, no case representative of subgroup with hydraulic connectivity between limbs and discharge from plunge apexes was found in any of the 72 anticlines under study.

Conclusions

Aquifer geometry and discharge location are linked to the catchment area and flow direction. It has been theoretically shown that there are eight configurations of aquifer geometry and discharge zones (Fig. 1). The validity of conceptual models was tested by using the Zagros Region anticlines. Based on the presence or absence of hydraulic continuity between the northern and southern limbs, the anticlines of Zagros are classified into two main groups. Out of 72 anticlines, 64 have no hydraulic connectivity between their northern and southern limbs. Because the impermeable formations below the crest of the anticlines are significantly higher than the feet of the anticlines, both limbs are hydraulically independent. The large number of cases with no hydraulic connectivity indicates that folding and sandwiching of karst formations between two thick impermeable formations is the prominent factor controlling the regional direction of flow, forcing the karst water of each limb area toward its foot. The numerous cases with no hydraulic connectivity are expected because folding is one of the main characteristics of the Zagros Region. Groups with or without hydraulic connectivity are each classified into four subgroups based on the location of discharge zones, mainly along one or both plunge apexes, limb, river, and combination of plunge apexes, limb and river. The discharge zones can be in the form of springs, seepage into river, adjacent alluvium and/or successive karstic anticline, or adjacent syncline.

The main discharge zones are both located in limbs or as combination of limbs and other type of discharge zones. In most anticlines, karst water discharges from several discharge zones, rather than one.

The main controlling factor of the discharge zone location is the local base level, not the regional one. Numerous local base levels are created by differential erosion and tectonic settings in the study area. Faults and later differential erosion outcrop the underlying impermeable formation, generating several independent blocks of karst aquifers, each block having its own discharge zone. Karst waters are in direct contact with different lithologies such as alluviums and impermeable formations creating numerous discharge zones. Consequently the configuration of discharge zone, and folding and geometry clearly define the regional flow in aquifers.

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Ira Sasowsky and Melisa Bishop. Empirical study of conduit radial cross-section determination and representation methods on cavernous limestone porosity characterization. *Journal of Cave and Karst Studies*, v. 68, no. 3, p. 130–136.

EMPIRICAL STUDY OF CONDUIT RADIAL CROSS-SECTION DETERMINATION AND REPRESENTATION METHODS ON CAVERNOUS LIMESTONE POROSITY CHARACTERIZATION

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Radial cross sections are constructed during cave mapping in order to illustrate karst groundwater conduit (cave passage) morphology. These sections can also be employed in studies of porosity distribution and paleohydrology. Cave surveyors usually estimate left, right, up, and down (LRUD) distances from a survey station to the conduit wall, and these four values are used to construct the radial cross section, and occasionally integrated along the length of the passage to determine cave volume. This study evaluates the potential errors caused by LRUD estimation, as well as the effects of differing geometric approximations of passage shape. Passage dimensions at 18 stations of diverse size and morphology in Scott Hollow Cave, West Virginia were first estimated for LRUD and then precisely surveyed using a laser rangefinder taking 16 radial measurements. Results show that, depending upon the purpose of a survey, a reasonable approximation of passage shape might be made with fewer (four or eight) measurements. In cases where only four lengths are determined, approximation of the passage as an ellipse or rectangle provides a more accurate morphology and area than if portrayed as a quadrilateral. In the former case, average area errors were on the order of ±10%, as opposed to −45% in the latter. Surveyor estimates of LRUD give an average overestimate of 27%. Length errors compound, however, when areas are calculated. This results in an average cross-section area error (as quadrilateral) of 57% when using estimates instead of measurements. This may be problematic for such analyses as calculation of fluid storage volumes or paleodischarges.

Introduction

Accurate cave maps serve as the foundation for many studies of karst geology, hydrology, and biology, because most limestone cave passages are active or abandoned karst groundwater conduits. Refinement of survey and mapping techniques through the years and the proliferation of survey reduction software have made it easier to produce high quality representations of caves (Dasher, 1994). There are many different approaches to mapping (Dasher, 1994), but the usual strategy is to lay out a three-dimensional line of survey through the cave, referenced to a known point on the land surface. This establishes the humanly explorable length of the cave, position of the cave in space, and the topology of the conduits. In order to produce other than a simple line map of the cave, it is also necessary to determine passage width and height, or radial cross-section dimensions, at each survey station. To accomplish this, distances are recorded as left, right, up, and down (LRUD) values from the survey station to the cave wall, and thereby provide thickness to the spine created by the three dimensional survey line (Fig. 1a, b). These values can then be used to represent cave size/shape in the ways indicated in Table 1. In addition to allowing good representations of the cave, accurate radial cross sections are essential for many scientific purposes. They allow paleodischarge calculations when taken in conjunction with paleoflow indicators such as scallops (Curl, 1974), evaluation of cave origin and geologic controls (phreatic/vadose) when analyzed for morphology (*e.g.*, Palmer 1981, 1984; White, 1988), and determination of overall cave volume (and rock bulk porosity) when integrated along the length of the cave (Worthington *et al*., 2000). It should be noted that in the case of volume and porosity, results are limited to discovered and proper (Curl 1964, 1966) caves. There will always be undiscovered or un-explorable porosity in the rock mass.

In spite of all of the above reasons to determine accurate radial cross sections, this aspect usually receives the least attention during a cave survey. In most cases the LRUD dimensions are not actually measured, but are estimated to the nearest whole foot or meter. This is done for the sake of expediency. Moreover, while there is a literature on the techniques of cave surveying and the sources of error therein (summarized in Dasher, 1994), scant attention has been paid to errors due to estimation of LRUD, or due to the approximations of passage cross-sectional shape based on only four distances.

In order to examine the quality of LRUD estimations and passage radial cross-section representations, we conducted precise radial surveys at a variety of stations in a cave (Fig. 1). We then compared the LRUD values estimated by surveyors to those that we measured. We also examined variation of cross-sectional area calculation caused by using different geometric approximations with the LRUD values, and by using additional radial measurements.

STUDY LOCATION

Scott Hollow Cave (Monroe County, West Virginia; Fig. 2) contains 43.4 km (27.0 miles) (Gulden, 2006) of mapped passage, and was chosen for this study due to the wide variety of passage types present. Monroe County lies at the transition between the Appalachian Plateau and the Valley and Ridge geomorphic provinces, and the cave is developed within rocks of the Mississippian age Greenbrier Group and the underlying Maccrady Shale. The cave is situated in the western arm of the Sinks Grove Anticline (Davis, 1999), and contains passages of both phreatic and vadose origin, as well as modifications by breakdown, speleothem growth, and fluvial sedimentation.

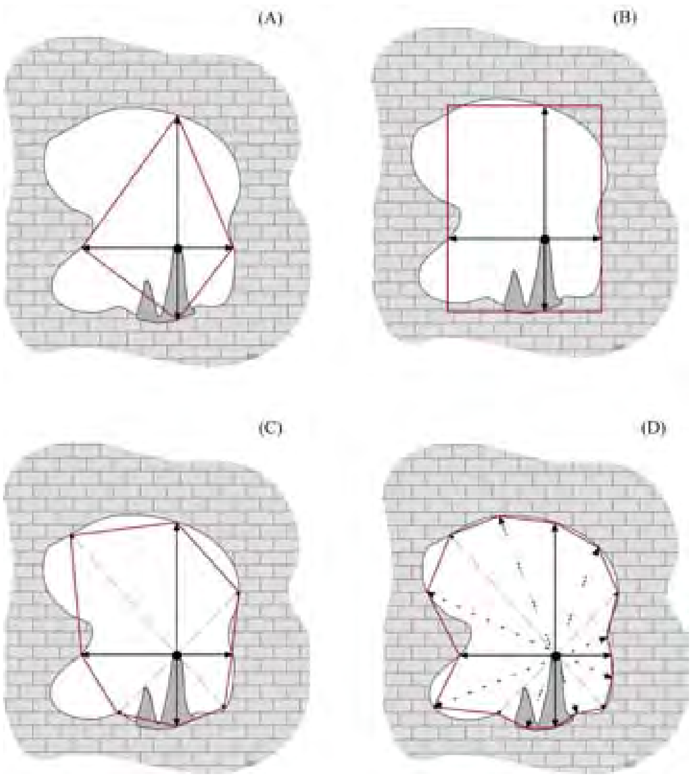

Figure 1. Determination of cave passage cross-sections. In standard surveying methods the distances from the survey station (on top of stalagmite in this example) to the left-right-up-down (LRUD) passage boundaries are measured or estimated as shown by arrows (A, B). An approximation of passage shape may then be made as a polygon using LRUD locations as vertices for a quadrilateral (A), or as a rectangular bounding box using LRUD to establish lines that are either vertical or horizontal (B), or as an ellipse using the sums L+ R and U + D (not shown). If additional radial measurements are collected, an octahedron using eight points as vertices (C) or hexadecagon with sixteen radial points may be made (D). In each case cross-section area of the passage may be calculated using geometric formulae.

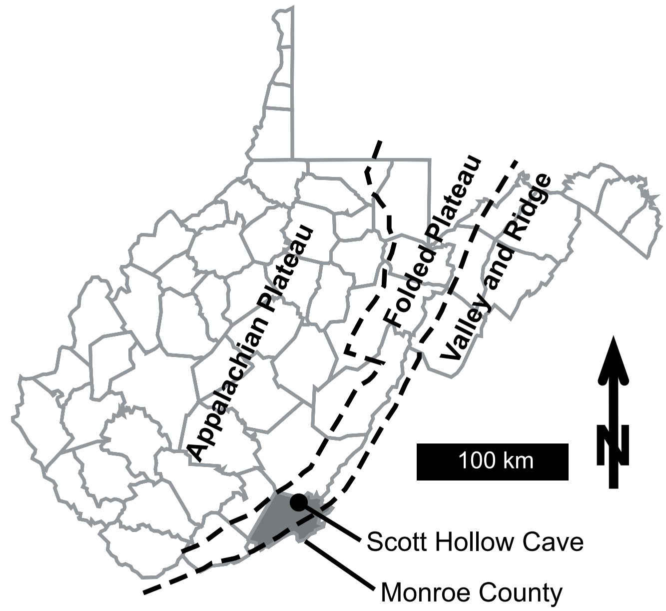

Figure 2. Location of Monroe County, West Virginia and Scott Hollow Cave, with respect to physiographic provinces. Province boundaries after Kulander and Dean (1986).

METHODS

For this investigation, a series of radial cross-section surveys were conducted in several passages of Scott Hollow Cave. The locations of the 18 survey stations are shown in Fig. 3. These stations were chosen to encompass a variety of sizes and morphologies. At each location a specially designed survey data sheet was used. By convention, the survey was conducted facing into the cave. Between two and five surveyors were present at a given station. The names of each surveyor, location, passage type, date, time, and the survey number were recorded. Then, each surveyor present made a private estimation of LRUD (in feet) which was recorded for later comparison with the laser measurements.

After this, a laser rangefinder, the Leica Disto Classic5, was used to precisely measure radial distances to passage walls. This device measures distances up to 200 m and has an accuracy of ±1.5 mm. In order to conveniently make numerous precise measurements at each station, a transit head was modified from horizontal rotation to vertical rotation and mounted on a tripod to secure the rangefinder (Fig. 4). The head was aligned with the general trend of the cave passage at the survey station at the discretion of the operator. Intervals at 22.5º were marked on the transit head to allow for 16 radial measurements at equiangular steps (Fig. 1d). Distance measurements were taken in units of meters referenced to the rear of the instrument. Because the instrument measurement point was not centered on the rotation axis of the transit head, an offset of −0.106 m was programmed into the rangefinder to produce the correct measurement while surveying.

After the 16 measurements were obtained, a sketch of the cross-section was made indicating the station point and other detailed features of the cave passage. Various types of passages

Table 1. Methods by which passage cross-section dimensions can be used to represent a cave.

Method	Description
Plan View Maps	Passage width by scale drawing
	Passage height by notation (number in circle)
	Passage height, width, and shape by inclusion of selected passage cross-section drawings
Longitudinal Cross Sections	Passage height by scale drawing
Overall Cave Shape and Size	Perspective (or block) diagrams of cave (an artist uses the data to draw by hand an illustration of the cave)
	Physical (usually clay) models of cave (sculptor uses data to create representation of cave)
	Three-dimensional digital models (cross sections at each station are modeled from LRUD data, and then passage dimensions between stations are interpolated to construct a tube or prism approximating the passage shape)

were measured, including large and small trunk conduits, small keyhole-shaped canyons, and very large canyons. Rooms, which present special morphological problems for surveying, were excluded from consideration.

Measurements from each survey station were used to construct five geometric representations for each passage cross-section shape. By simply joining the ends of four, eight, and 16 measurement vectors, quadrilateral, octagon, and hexadecagon representations were made (see Fig. 1a, c, d). Polygons so constructed using vectors radiating at equal angles from a central point have been informally called radar polygons. Within this study these three polygon types are geometrically irregular in that they do not contain equal angles between their sides, though. Additionally, two other geometric representations were made using the four LRUD measurements to create rectangles and ellipses. In the former case this was done by using the L+R and U+D sums as values for the sides of a rectangle. In the latter case these values served as the axes of the ellipse.

Measurements and estimations from each survey station were entered into Excel data sheets to calculate the areas of each cross-section, and to allow for various comparisons. Areas for the quadrilateral, octagon, and hexadecagon were calculated by summing the areas of triangles defined by the measurement vectors. For example, in the case of the hexadecagon 16 triangles are present (Fig. 1d). The area of each triangle was found by taking one half the sine of the known angle (22.5º) times the length of the two known sides (adjacent radial measurements). Additionally, areas for rectangular and ellipse representations (using measured LRUD) were calculated. Areas (for quadrilateral, rectangle, and ellipse representations) based on estimations of LRUD were then compared to areas calculated from measured values in order to evaluate potential error that occurred from estimating the LRUD.

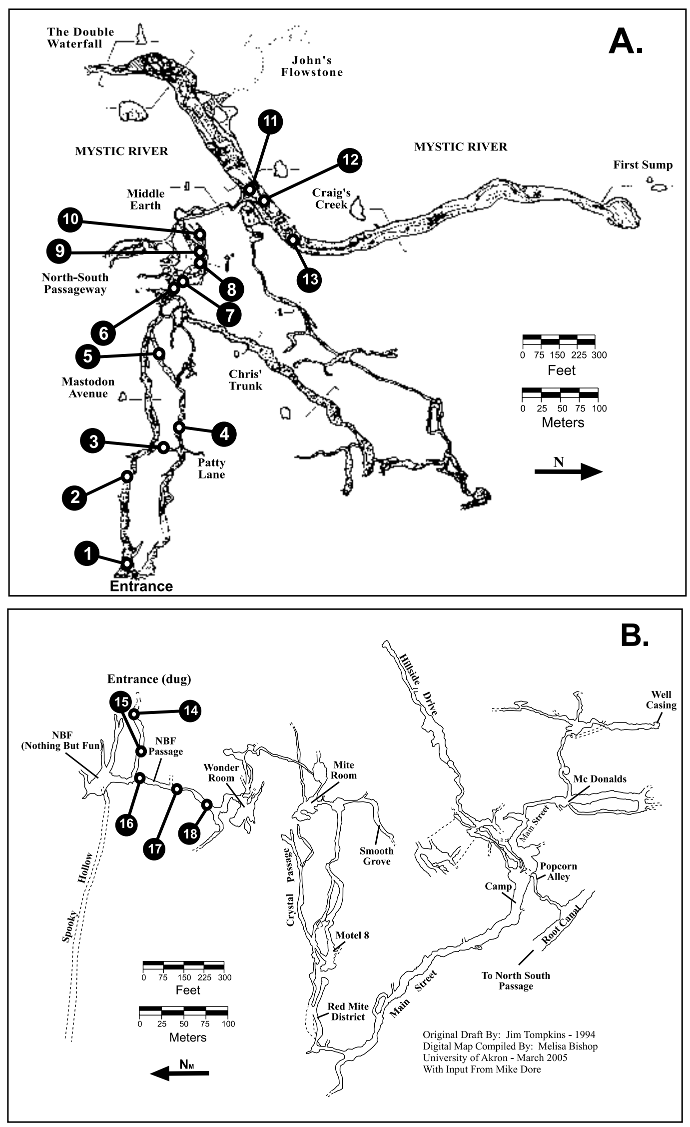

Figure 3. Maps of selected portions of Scott Hollow Cave showing locations of radial survey stations. Base maps courtesy Mike Dore.

RESULTS AND ANALYSIS

REPRESENTATION OF MORPHOLOGY

Figure 5 shows cross sections of all of the stations at the same scale, each represented with several different geometric approximations. The hexadecagon (column A) uses the greatest number of measurements (16) resulting in the most detailed, and hence most realistic, shape. This is apparent, for example, at stations 7, 11, 12 and 13. However, in several cases shape does not change substantially with the use of more radial points. Because of their diverse genesis and geologic controls, conduit cross sections have varying shapes and complexities (see examples in White, 1988). There are also many factors (irregularity, placement of survey station, *etc*.) which affect the number of points which are required to make a suitable representation. These factors are beyond the consideration of the present paper.

Depending upon the purpose of a survey, a reasonable approximation of passage shape might be made with four or eight measurements. For example, if the desired outcome is a general representation of overall cave pattern, then detail beyond measured LRUD is unnecessary. This decision would need to be taken by a surveyor on a case-by-case basis. It is also possible that the surveyor might selectively choose points to measure based upon morphology at the station (rather than measuring at a set angle interval). Even a surveyor with minimal experience could make a useful selection of such points, by briefly examining the shape and complexity of the conduit. This would then reduce the overall amount of data collected, and reduce survey time. The structure of the resulting dataset, however, would be irregular, producing complexity in later data analysis and representation.

Columns D and E of Figure 5 show two other geometric representations, which are simplifications of the passage that would typically be used in a digital cave model. Such generalizations allow for ease in data processing and in rendering of images. For the cases shown in Figure 5, there is significant variation from the detailed passage morphology (represented in column A). In a subsequent section, the effects of these approximations on cross-section area calculations will be evaluated.

Accuracy of surveyor estimations of LRUD

Five surveyors with experience levels varying from novice to expert made 104 estimates of LRUD distances in the course of this study. There was no obvious difference in estimate quality between surveyors, and the limited sample size does not permit detailed analysis of this relationship. Therefore, the estimates are analyzed *en masse*. Figure 6 compares surveyor estimates of LRUD to laser measured LRUD distances. The data would appear as a straight line with slope of one if all estimates were accurate. The best fit line shows that, on average, an overestimate of distance is made. The scatter of points shows that magnitude of errors increases in larger passages, as would be expected. However, percent errors (a comparison of measured to estimated values) do not increase (Fig. 7).

For this study, the average absolute error for length estimates (regardless of positive or negative sign) was 27% of the laser measured value. Underestimates are made along with overestimates, however, so these offset each other if signed (non-absolute) values are averaged. This results in a 17% (positive) overall average error for distance estimates. This is a considerable error compared to those usually found for length, azimuth, and inclination measurements in a cave survey, which are typically less than 1%. This error could then propagate to the calculation of passage cross-section areas, and overall karst porosity.

Figure 4. Equipment used for precise radial surveys. Device shown in use within Scott Hollow Cave (A). Disto laser measurement device by Leica is mounted on a tripod using a modified transit head (B, C). Arrangement allows both for leveling of device, and rotation through full 360 degrees of measurement.

Variability of cross section area due to estimation of LRUD

Passage cross-section area, which is of interest for reasons mentioned in the introduction, was calculated with radial length values. Using the LRUD estimates or measurements, several alternative geometric representations of the cross section may be made. The simplest is a quadrilateral constructed by joining the endpoints of the LRUD (Fig. 5, column C), and this was employed by us to appraise variability of calculated cross-section area caused by errors in LRUD length estimates (Fig. 8). As with the LRUD length errors, errors in calculated area tend to increase with passage size, and occur both as positive and negative discrepancies. However, the average error in calculated area was 57%, as opposed to the 27% error value for length measurements. This increase is because length measurements are multiplied to find area, producing a compound error.

Comparison of area based on alternative geometric representations using LRUD

As an alternative to the quadrilateral representation discussed in the preceding section, the left-right (LR) and up-down (UD) segments may be summed, and these values were used to construct rectangular or elliptical generalizations (Fig. 5, columns D and E, respectively). Commercial cave mapping

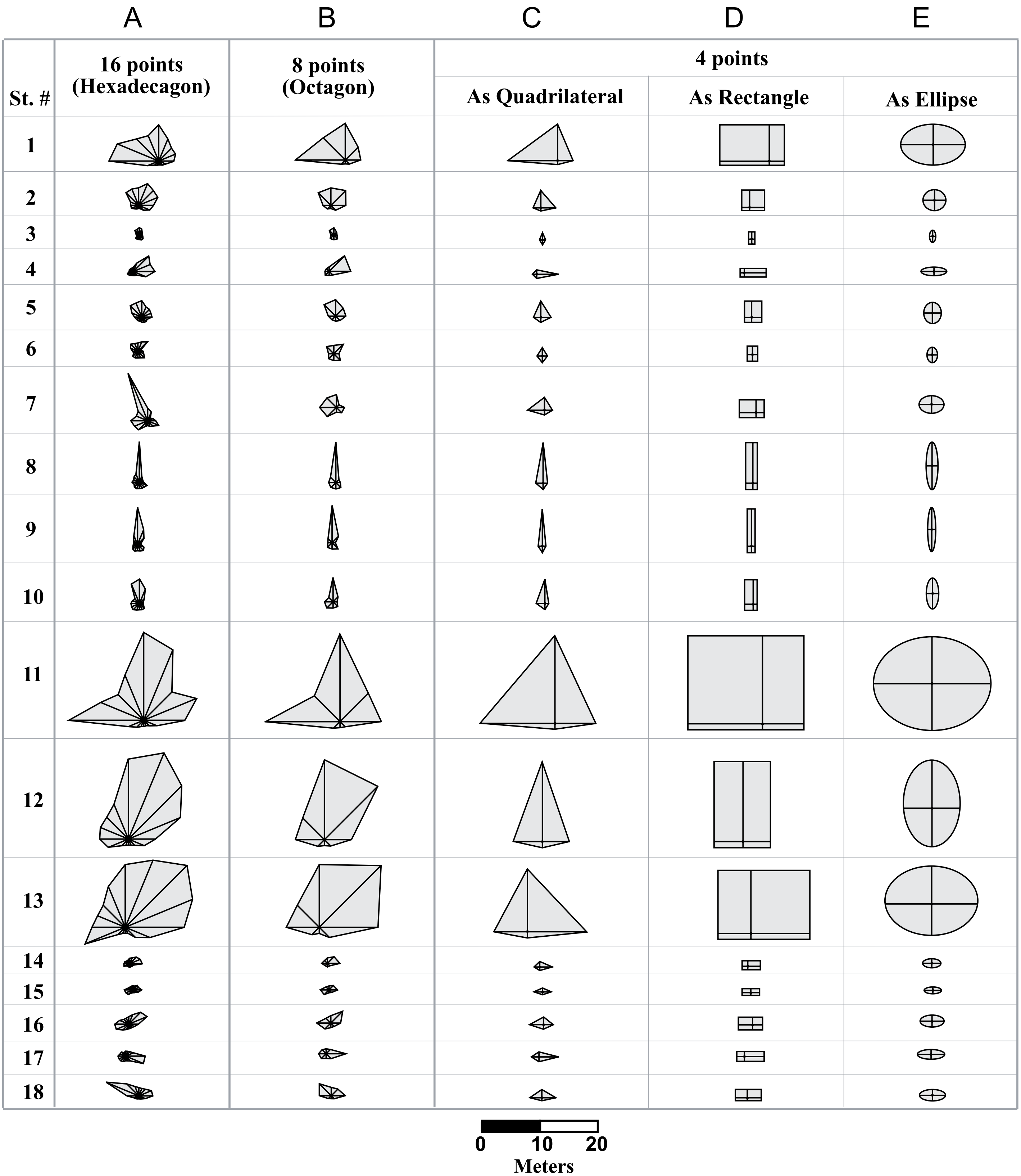

Figure 5. Graphical representation of surveyed cross sections for all stations. Thin black lines indicate up, down, left, right, or other radial distance measurements from survey station

software (*e.g.*, Compass, Walls, WinKarst) as well as advanced geometric visualization software (*e.g.*, EVS, GoCad, ArcGIS), may be employed to make such renderings. Depending upon the morphology of the conduit, different generalizations may provide a better or worse fit. For example, phreatic conduits having smooth perimeters would be most accurately modeled using the ellipse. To evaluate the aptness of the quadrilateral, rectangle, and ellipse generalizations, these areas were compared to those of the (non-regular) hexadecagon for each of the 18 stations (Fig. 9). Within the scope of this investigation, we consider that the hexadecagon provides the definitive passage cross section. The quadrilateral gave the least accurate value of cross-section area, underestimating in every case but two, with a range of −64% to +12% and a median error of −45%. The ellipse and rectangle provide more suitable values, with scatter on both sides of the hexadecagon value, and median errors of −11% and +10% respectively.

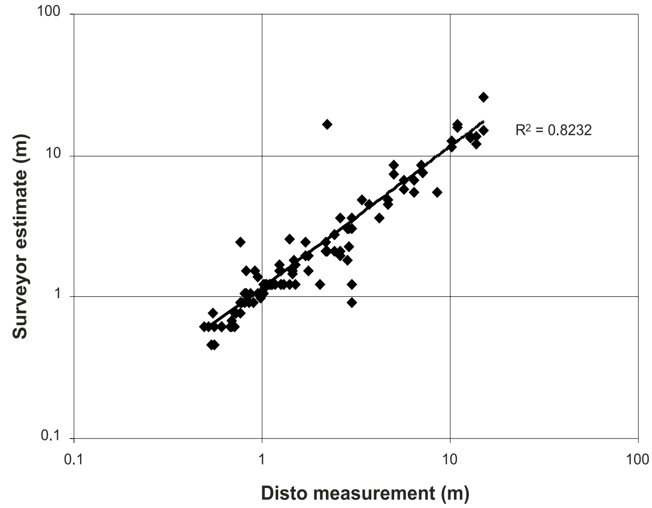

Figure 6. Comparison of LRUD distances as measured by Disto (x-axis) to surveyor estimates (y-axis). One hundred four estimates made by five different surveyors are included. Linear regression (solid line) using all points is given.

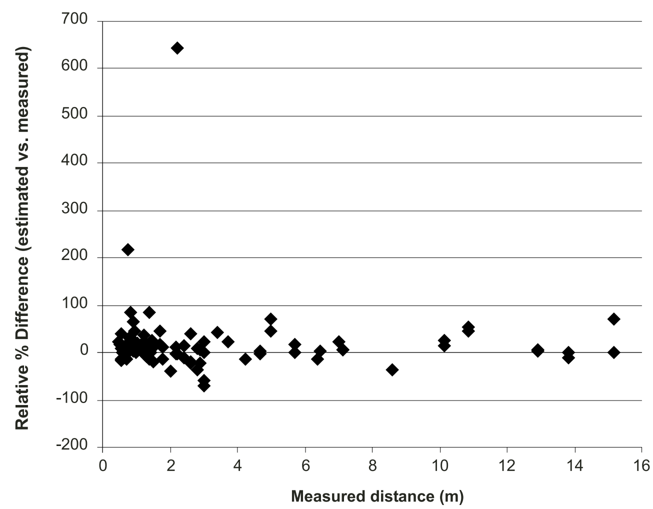

Figure 7. Relationship between measured LRUD distances and percent error in surveyor estimations of same. One hundred four comparisons are given. Seventy-three of the estimates exceeded the measured value (by an average of 32%). Thirty-one of the estimates were less than the measured value (by an average of 16%). Therefore, in this analysis, surveyors were about twice as likely to overestimate LRUD distances as to underestimate them. In addition, overestimates were worse (2×) in terms of percentage error. Surprisingly, there is no relation between the measured distance and the percent error of estimates.

DISCUSSION AND CONCLUSIONS

The data collected for this study allow evaluation of two sources of potential error associated with standard techniques for determination of cave passage cross sections. These errors arise from (a) estimation, rather than measurement, of LRUD distances, and (b) the insufficiency of four orthogonal lengths to define complex shapes.

For the passages that were examined, morphology of the conduits was not well-represented using only LRUDs (Fig. 5). This demonstrates that for applications where it is important to show passage shape, it is essential that the surveyor either provide a hand-drawn cross section, and/or make additional radial measurements beyond the four standard LRUDs. Simple canyons or tubes can be represented with solely four measurements, but where complexity exists due to breakdown, passage intersections, or other factors, increasing the number of measurements makes a noticeable difference in representation of morphology.

With regard to the practice of estimating rather than measuring LRUDs, it was found that estimates made by surveyors are grossly accurate, but poor for analytical use, and far below typical survey standards for at least 1% accuracy. An average overestimate of 27% was found for all distance determinations. The magnitude of errors increased with larger passage sizes, but the percent errors did not increase. Length errors compound, however, when areas are calculated. This results in an average cross-section area error of 57% (as quadrilateral), which is problematic for such things as calculation of fluid storage volumes or paleodischarges.

Finally, a comparison of the use of different geometries to calculate cross-section area shows that representation as a quadrilateral results in a median overestimation of about 45%. Alternatively, only 10% error (+ or −) is associated with representing the conduit as a rectangle or ellipse. Passage shape obviously plays a role in how good the area representation is; simpler cross sections can be more accurately represented by a smaller number of measurements. Because conduit shape results from such factors as lithology, structure, and hydrologic history, it follows that certain caves will be more accurately represented by LRUD only, along with simplistic geometries. It might be possible in future work to quantify this effect by studying errors present in passages of different rock types, hydrologic origin, *etc.*

The data and analyses presented above illustrate the variety of factors that can affect the measurement and representation of cross-section data for cave passages. For the majority of cave maps, which are made for the purposes of navigation and for documenting exploration, estimation of LRUD probably provides a suitable estimate of true passage dimensions. With only these four measurements, the ellipse and rectangle provide the most accurate passage shape and area representations. Where more accurate measures of passage shape and area are required, the use of 16 radial measurements can be employed. This requires additional equipment and time, but may be justified where such accuracy is needed for scientific purposes. Nevertheless,

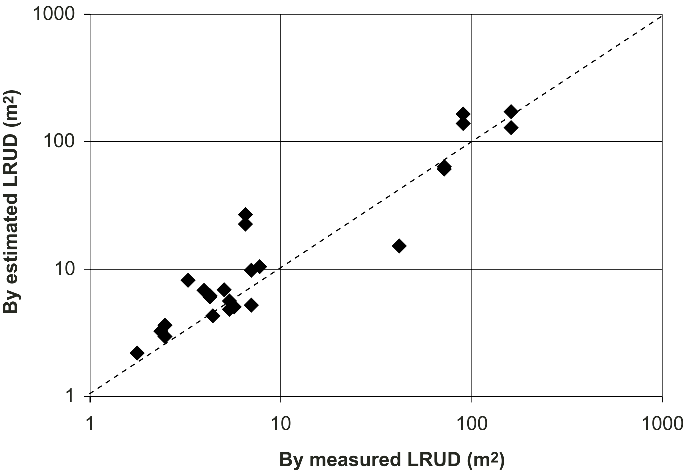

Figure 8. Comparison of conduit cross-section areas (m²) calculated using measured vs. estimated LRUD values (as quadrilateral). Log-log scale is used in order to facilitate viewing of data. Dashed line illustrates the theoretical relationship that would exist if all LRUD estimates were accurate.

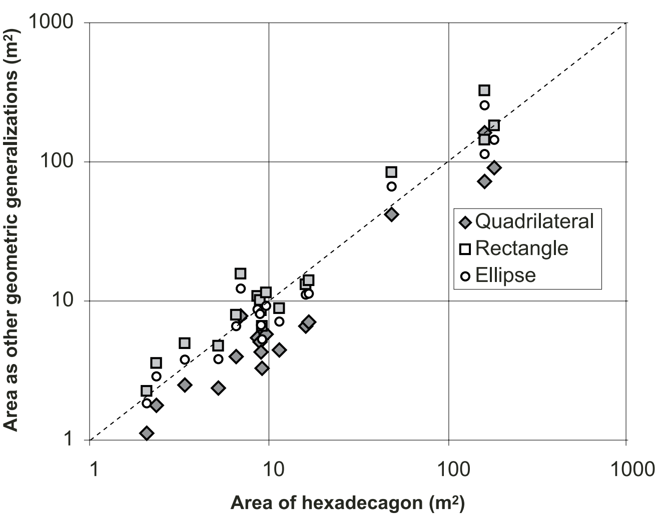

Figure 9. Comparison of passage cross-section areas (m²) based on geometric generalizations (quadrilateral, rectangle, and ellipse) of measured LRUD values to areas based on 16 radial measurements (hexadecagon). The hexadecagon is the most accurate. The quadrilateral provides the least appropriate area, almost always under-representing the value. Log-log scale is used in order to facilitate viewing of data.

there are many other limitations to the accurate representation of karst porosity. These particularly include rooms, which are not amenable to accurate description using the line and LRUD paradigm of most surveying approaches.

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EVALUATION OF THE EFFECT OF OVEN ROASTING AT 340° C, BLEACH, 30% H_2O_2, AND DISTILLED/DEIONIZED WATER ON THE $\delta^{13}C$ VALUE OF SPELEOTHEM CARBONATE

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Organic compounds derived from plants are found in many cave formations, which are collectively termed speleothems. Both the carbon in the organic compounds and the carbon in the speleothem $CaCO_3$ have distinct ratios of the stable isotopes of carbon (^{12}C and ^{13}C) that are expressed as $\delta^{13}C$ values. Values of $\delta^{13}C$ in the organic compounds are lower than $\delta^{13}C$ values of speleothem calcium carbonate and could affect the $\delta^{13}C$ values of speleothems with high organic matter concentrations, if the organic compounds were not removed. Four treatments conventionally used to destroy organic matter in carbonates prior to geochemical analysis were evaluated in this study. The treatments were oven roasting at 340° C, soaking in bleach, soaking in 30% H_2O_2, and soaking in distilled deionized water. There is no statistically significant difference between results from untreated and treated samples. These results suggest that the treatments do not affect the $\delta^{13}C$ value of speleothems' calcium carbonate. The treatments might be helpful in removing organic matter in speleothems that have high concentrations of organic matter. However, most speleothems have low organic carbon concentrations that do not affect the $\delta^{13}C$ value of the speleothem, even if left untreated. Ultimately these treatments only need to be applied to speleothems with unusually high concentrations of organic matter.

INTRODUCTION

Naturally occurring carbon consists almost entirely of two stable isotopes, ^{13}C and ^{12}C, and the ratio of these isotopes in different materials is expressed in terms of $\delta^{13}C$ values relative to the PDB standard, a sample of $CaCO_3$ from a fossil belemnite in the Cretaceous-age Pee Dee Limestone Formation of South Carolina. Paleoenvironmental studies have used $\delta^{13}C$ values of carbon derived from plants as proxies to determine the photosynthetic pathway of ancient vegetation (*e.g.*, Huang *et al.*, 2001, Dorale *et al.*, 1992, Ambrose and Sikes, 1991.) Three types of photosynthetic pathways have been recognized in modern vegetation. One is C_3 or Calvin-Benson (normal) photosynthesis, which results in $\delta^{13}C$ values of plant tissue between −22 and −35‰ (average = −26.5‰) relative to PDB. A second pathway is C_4 or Hatch-Slack photosynthesis (mostly found in tropical grasses adapted to hot and/or arid environments), which results in $\delta^{13}C$ values of plant tissue between −6 and −19‰ (average = −12.5‰) vs. PDB (Bowen, 1988). A third photosynthetic pathway is C.A.M. (Crassulan Acid Metabolism) used by desert succulents, resulting in $\delta^{13}C$ values of plant tissue between −10 and −20‰ (average = −18.0‰) vs. PDB (Attendorn and Bowen, 1997). Because the dominant plant type in a landscape is primarily a result of climate (Huang *et al.*, 2001), the difference in the average $\delta^{13}C$ values of these three kinds of plants makes carbon derived from them a useful proxy for determining the photosynthetic pathway of ancient vegetation, and thus for interpreting paleoclimate.

The C isotopic composition of plants is believed to affect the $\delta^{13}C$ value of coeval speleothem calcite, where speleothem is the term given to deposits such as stalagmites, stalactites, and flowstones formed by dripping water in caves. Speleothems, especially those found in limestone caves, commonly consist of calcium carbonate ($CaCO_3$). Some of the carbon in calcium carbonate speleothems comes from carbon dioxide (CO_2) generated in the soils above caves, where respiration by plant roots and decomposition of plant debris produce CO_2. The $\delta^{13}C$ of the CO_2 in the soil is primarily the result of the photosynthetic pathway (C3, C4, CAM) used by the plants. Because the $\delta^{13}C$ of the dissolved calcium carbonate that is contributed to a speleothem from the overlying bedrock is believed to be constant over the speleothem's growth history, the changes in the $\delta^{13}C$ of speleothem calcium carbonates have long been believed to be the result of changes in the types of plants growing on the surface above a cave. Thus, the $\delta^{13}C$ values of speleothems have been used as proxies for paleovegetation in many paleoenvironmental studies (*e.g.*, Desmarchelier *et al.*, 2000, Hellstrom *et al.*, 1998, Dorale *et al.*, 1992, Brook *et al.*, 1990). More recent work has shown that the $\delta^{13}C$ values of carbonate speleothems can also be affected by factors other than changes in the dominant vegetation over a cave. These include changes in ecosystem productivity controlling soil P_{CO2} (Genty *et al.*, 2003), changes in the $\delta^{13}C$ values of atmospheric CO_2 (Baskaran and Krishnamurthy, 1993), and changes in water/rock interactions (McDermott, 2004). In addition to these controls, factors involving precipitation of calcium carbonate in nonequilibrium may also affect the $\delta^{13}C$ value of speleothem calcium carbonate (Mickler *et al.*, 2004).

In addition to C in $CaCO_3$ itself, speleothems also commonly contain C in organic matter, including humic substances (large organic molecules) and other organic residues that are formed from the decomposition of plant litter (dead plant material) in soil (Gascoyne, 1992, Shopov *et al.*, 1994, Baker *et al.*, 1996, Baker *et al.*, 1997). The $\delta^{13}C$ values of humic substances and other organic compounds in many soils have been shown to reflect the $\delta^{13}C$ values of the plants from which they are derived (Nissembaum and Schallinger, 1974, Ambrose and Sikes, 1991, Lichtfouse *et al.*, 1995). The $\delta^{13}C$ values of humic substances are generally much lower than the $\delta^{13}C$ values of the $CaCO_3$ in which they are found (Elkins and Railsback, 2002). This difference raises concern that failure to remove organic C from speleothem carbonate might lead to erroneously low apparent $\delta^{13}C$ $CaCO_3$ values and thus to misinterpretation of the speleothem $\delta^{13}C$ record.

Various treatments have been used to remove organic matter from biogenic carbonate, such as coral, prior to geochemical analysis. This study will evaluate the effect of four such treatments by comparing the $\delta^{13}C$ values measured with and without treatment of speleothem calcite. The four treatments are: 1) oven roasting at 340° C (Boiseau and Juillet-Leclerc, 1997), 2) distilled /deionized water (DDW) (Mitsuguchi *et al.*, 2001), 3) 30% H_2O_2 (Boiseau and Juillet-Leclerc, 1997) and 4) sodium hyperchlorite (bleach) (Gaffey and Bronnimann, 1993).

Three general results are possible. In the first case, if the $\delta^{13}C$ values of treated speleothems with high organic carbon contents are greater than $\delta^{13}C$ values of untreated samples, then the treatments will seemingly have been successful at removing organic matter. In the second case, if the $\delta^{13}C$ values of treated speleothem samples show no significant difference from $\delta^{13}C$ values of untreated samples, either the treatments will seemingly have had no effect, or there will have been so little organic matter that effective treatment caused no significant change in measured $\delta^{13}C$. In the third and least likely case, if the $\delta^{13}C$ values of treated speleothem samples are less than $\delta^{13}C$ values of untreated samples, then the treatment methods will seemingly have altered the $\delta^{13}C$ values of the speleothem calcium carbonate, counter to the intent of researchers that apply such methods.

Methods

Material

Twelve speleothems from a wide range of geographic locations were chosen for our study (Tables 1–3). Three stalagmites, two stalactites and two flowstones, all of which were recrystallized, were chosen from Caverns of Sonora in west Texas. One recrystallized stalagmite from Egypt, one stalagmite from Reflection Cave in Belize, one stalagmite from Pettijohn's Cave near LaFayette, Georgia, two recrystallized speleothems of unknown type from Carthage, Tennessee and one stalactite and one stalagmite from unknown localities were also used.

A total of 32 samples weighing 3 to 9 g were cut from the speleothems (Tables 1–3) using a diamond impregnated bandsaw blade. The samples were ground to a fine powder using a mortar and pestle.

Treatments

Sub-samples weighing 10 mg were taken from each of the 32 untreated powdered samples and set aside for $\delta^{13}C$ analysis. Four sets of 40 mg sub-samples were weighed out of the 32 untreated powdered samples (a total of 128 sub-samples). One set of sub-samples was spread over clean watch glasses and roasted at 340° C in an oven for 24 hours. Samples in the remaining sets were placed in separate 40 ml amber vials (96 vials total). One set of vials was filled with 40 ml of DDW, another with 40 ml of bleach, and another with 40 ml of 30% H_2O_2. Samples were left in the solutions for 24 hours.

After treatment, the supernatant from each of the vials was carefully decanted to ensure that as few grains were lost as possible. Each vial was then filled with 40 ml of DDW. Vials sat for 10 minutes until all carbonate grains settled to the bottom. The water was then carefully decanted to insure that as few grains as possible were lost. This process was repeated 10 times to insure that none of the organic matter that might have been removed from the calcium carbonate in treatment and released into the supernatant remained in the samples. The wet samples were left in the vials and dried in an oven at 60° C for 24 hours.

$\delta^{13}C$ Analysis

Sub-samples weighing 10 mg were taken from each of the 128 treated samples and 32 of the untreated samples and reacted with 100% phosphoric acid at 50º C. The evolved CO_2 was isolated using a cold finger under vacuum at the University of Georgia Stable Isotope Lab and measured on a Finnigan MAT 252 stable isotope mass spectrometer. The standard used for isotopic analysis was Iceland spar and has a $\delta^{13}C$ value of −4.7‰ (vs. PDB). Two samples of gas extracted from solid Iceland spar were analyzed on the mass spectrometer 13 times, and the precision of the analysis was ± 0.1‰.

Organic Analysis

Sub-samples weighing 2 g were placed in 40 ml amber vials and reacted with 40 ml of 1 N HCl at room temperature to dissolve the calcite. After two days, some carbonate grains remained at the bottom of some of the vials. An additional 2–3 ml of 1 N HCl was added to all the vials, which resulted in complete dissolution of the remaining grains. No precipitated organic matter was observed on the bottom of the vials.

The resulting supernatants (with the organic matter freed in solution) were analyzed for total organic carbon (TOC) concentration on an OI 1010 carbon analyzer at the University of Ottawa's G.G. Hatch Isotope Laboratory following the method described by St-Jean (2003). During this process, an aliquot of the sample was siphoned into a reaction vessel at 100°C. Drops of phosphoric acid were added to the sample, releasing the total inorganic carbon (TIC), which was passed in a helium carrier through nafion and chemical traps to remove water and then on to a non-destructive infrared detector (NDIR) tuned to CO_2. With the TIC removed, sodium persulfate was added to oxidize the TOC to CO_2. The effluent was directed to the NDIR for determination of the TOC concentration. Standards for this analysis were sucrose1, potassium phthalate and citric acid.

Table 1. Characteristics of samples used in this study.

Sample ID	Sample Location	Speleothem ID and Type	Mineralogy	TOC Concentration of Calcite (ppm)
C.S.1-T	Sonora, Texas	C.S.-1 (stalagmite)	Calcite	165.9
C.S.-1Mi	Sonora, Texas	C.S.-1 (stalagmite)	Calcite	184.8
C.S.-1Mo	Sonora, Texas	C.S.-1 (stalagmite)	Calcite	170.1
C.S.-1b	Sonora, Texas	C.S.-1 (stalagmite)	Calcite	144.9
C.S.-2i	Sonora, Texas	C.S.-2 (stalagmite)	Calcite	123.9
C.S.-2o	Sonora, Texas	C.S.-2 (stalagmite)	Calcite	126.4
C.S.-3d	Sonora, Texas	C.S.-3 (stalagmite)	Calcite	168.4
C.S.-3L	Sonora, Texas	C.S.-3 (stalagmite)	Calcite	140.7
C.S.-T1	Sonora, Texas	C.S.-T1 (stalactite)	Calcite	130.2
C.S.-T2	Sonora, Texas	C.S.-T2 (stalactite)	Calcite	123.9
C.S.-F.D.	Sonora, Texas	C.S.-F (flowstone)	Calcite	113.4
C.S.-F.Ma	Sonora, Texas	C.S.-F (flowstone)	Calcite	65.1
C.S.-F.Mb	Sonora, Texas	C.S.-F (flowstone)	Calcite	52.5
C.S.-F.Mc	Sonora, Texas	C.S.-F (flowstone)	Calcite	56.7
C.S.-F.L	Sonora, Texas	C.S.-F (flowstone)	Calcite	48.3
C.S.-F2a	Sonora, Texas	C.S.-F 2 (flowstone)	Calcite	159.6
C.S.-F2b-R	Sonora, Texas	C.S.-F 2 (flowstone)	Calcite	161.7
C.S.-F2c-R	Sonora, Texas	C.S.-F 2 (flowstone)	Calcite	163.8
Reflx-T	Reflection Cave, Belize	Reflx (stalagmite)	Calcite	252.4
Reflx-L	Reflection Cave, Belize	Reflx (stalagmite)	Calcite	239.4
Reflx-B	Reflection Cave, Belize	Reflx (stalagmite)	Calcite	218.4
MR-68o	Carthage, Tennessee	MR-68 (type uncertain)	Calcite	182.7
MR-68m	Carthage, Tennessee	MR-68 (type uncertain)	Calcite	212.1
MR-68i	Carthage, Tennessee	MR-68 (type uncertain)	Calcite	231.4
Car-Mro	Carthage, Tennessee	Car-Mr (type uncertain)	Calcite	224.7
Car-Mri	Carthage, Tennessee	Car-Mr (type uncertain)	Calcite	224.7
P.J.Y.	LaFayette, Georgia	P.J. (stalagmite)	Calcite	203.7
P.J.O.	LaFayette, Georgia	P.J. (stalagmite)	Calcite	239.4
E.E.-12D	Wadi Sannur, Egypt	E.E.-12 (stalagmite)	Calcite	102.9
E.E.-12L	Wadi Sannur, Egypt	E.E.-12 (stalagmite)	Calcite	104.4
Unknown-1	Unknown	Unknown-1 (stalactite)	Calcite	184.8
Unknown-2	Unknown	Unknown -2 (stalagmite)	Aragonite	193.2

Results

The $\delta^{13}C$ values of the treated speleothem carbonate show no statistically significant difference from those of the untreated samples (Tables 1–3, Fig. 1). We follow standard statistical procedure in reporting the average of the differences between paired samples to one more significant figure than the original $\delta^{13}C$ values (Tables 1–3). The average difference between the oven-roasted samples and corresponding untreated samples is 0.00‰ (Fig. 2). The average difference between samples treated with bleach and corresponding untreated samples is 0.06‰. The average difference between the samples treated with 30% H_2O_2 and corresponding untreated samples is 0.02‰. The average difference between samples treated with DDW and corresponding untreated samples is 0.03‰ (Fig. 2). Applying *t*-tests show the mean differences between the treated and untreated samples are not significantly different from zero ($p > 0.93$ and thus very far from statistical significance for all four treatments) (Tables 1–3).

Discussion

The treatments to remove organic carbon had no statistically significant effect on the $\delta^{13}C$ values of the carbonates studied (Figs. 1 and 2). As noted in the Introduction, this may be because the treatments are ineffective at removing organic carbon.

Table 2. Carbon isotope results[a].

Sample ID	$\delta^{13}C$ by Conventional Treatment	$\delta^{13}C$ with Roasting at 340°C	$\delta^{13}C$ with Bleach Treatment	$\delta^{13}C$ with H_2O_2 Treatment	$\delta^{13}C$ with DDW Treatment
C.S.1-T	−7.9	−7.9	−7.9	−7.9	−7.9
C.S.-1Mi	−8.7	−8.7	−8.8	−8.8	−8.8
C.S.-1Mo	−8.2	−8.2	−8.1	−8.2	−8.2
C.S.-1b	−6.8	−6.8	−6.9	−6.8	−6.7
C.S.-2i	−5.9	−5.9	−5.9	−5.9	−5.9
C.S.-2o	−6.1	−6.2	−6.0	−6.1	−6.0
C.S.-3d	−8.0	−7.9	−8.0	−7.9	−7.9
C.S.-3L	−6.5	−6.5	−6.7	−6.6	−6.5
C.S.-T1	−6.4	−6.2	−6.2	−6.3	−6.3
C.S.-T2	−5.7	−5.8	−5.9	−5.8	−5.7
C.S.-F.D.	−5.1	−5.3	−5.4	−5.1	−5.1
C.S.-F.Ma	−2.7	−2.7	−3.1	−2.2	−2.7
C.S.-F.Mb	−2.6	−2.4	−2.5	−2.5	−2.5
C.S.-F.Mc	−2.4	−2.4	−2.7	−2.3	−2.4
C.S.-F.L	−2.2	−2.3	−2.3	−2.2	−2.2
C.S.-F2a	−7.5	−7.5	−7.6	−7.6	−7.4
C.S.-F2b-R	−7.6	−7.6	−7.7	−7.6	−7.6
C.S.-F2c-R	−7.7	−7.6	−7.8	−7.6	−7.6
Reflx-T	−12.1	−12.0	−12.0	−11.9	−11.9
Reflx-L	−11.2	−11.2	−11.4	−11.1	−11.3
Reflx-B	−10.6	−10.5	−10.4	−10.6	−10.3
MR-68o	−8.6	−8.4	−8.7	−8.6	−8.6
MR-68m	−10.3	−10.3	−10.1	−10.3	−10.4
MR-68i	−11.1	−11.1	−11.0	−11.1	−11.1
Car-Mro	−10.6	−10.7	−10.7	−10.7	−10.6
Car-Mri	−10.6	−10.5	−10.7	−10.6	−10.3
P.J.Y.	−9.7	−9.6	−9.7	−9.7	−9.7
P.J.O.	−11.2	−11.2	−11.4	−11.0	−11.3
E.E.-12D	−5.0	−5.0	−4.9	−5.0	−4.9
E.E.-12L	−4.9	−5.1	−5.0	−4.8	−4.9
Unknown-1	−8.8	−8.8	−8.8	−8.7	−8.8
Unknown-2	−9.2	−9.1	−9.2	−9.2	−9.2

[a] $\delta^{13}C$ values are all in ‰ with respect to the PDB standard. Location, mineralogy, and TOC concentration of samples are given in Table 1.

One possible reason for them to be ineffective might be the size of humic molecules relative to the size of the $CaCO_3$ particles in which they are housed, and with the non-porous nature of that $CaCO_3$. If humic acid molecules are 1 to 10 nm in size and the $CaCO_3$ enclosing them is pulverized to 1 µm particles, most humic acid molecules will lie well inside any $CaCO_3$ particle and thus be immune to treatment prior to dissolution of that $CaCO_3$. Only permeability through micropores (pores less than 1 µm in size) would allow access by attacking fluids. It thus may not be reasonable to expect pretreatments to affect molecules or particles with sizes orders of magnitude smaller than the grain size.

The failure of the various treatments to yield $\delta^{13}C$ values significantly different from untreated values also probably results from the C isotope systematics of spelean carbonate, for three reasons. First, speleothems contain little organic carbon compared to the organic contents of brachiopod shells, many mollusk shells, and many limestones (Fig. 3). The skeletal carbonate nearest to spelean carbonate in organic content is coral aragonite, and Boiseau and Juillet-Leclerc (1997) found that H_2O_2 treatment of coral aragonite was more likely to cause a decrease in $\delta^{13}C$ because of dissolution of post-biotic cement than it was to cause the expected increase by removing significant organic carbon. Secondly, speleothems have $\delta^{13}C$ $CaCO_3$ values lower than those of marine carbonates, so that $\delta^{13}C$ of the bulk material is changed less by incorporation of organic carbon with low $\delta^{13}C$ values (Fig. 3). Thirdly, at least some speleothems

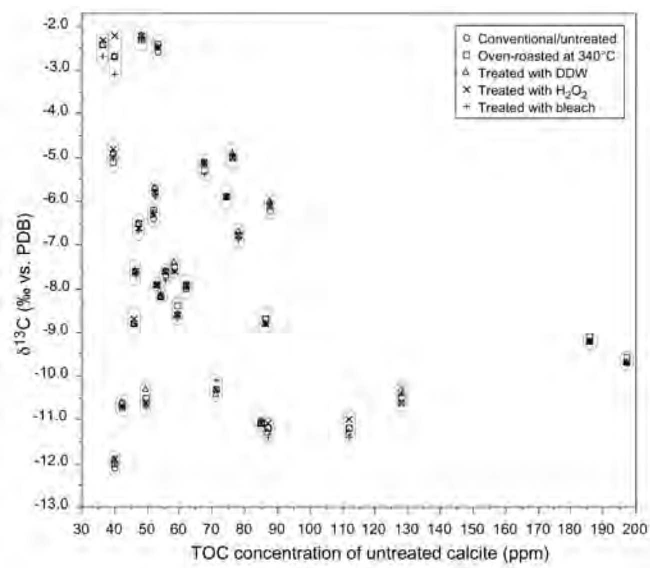

Figure 1. $\delta^{13}C$ of 32 carbonate samples, each analyzed with no treatment and with four different treatments, plotted against concentration of total organic carbon in each sample. Ovals and loops enclose the five symbols for any one sample. Uncertainty of $\delta^{13}C$ values plots within vertical extent of symbols. General overlap of symbols illustrates that treatments have little effect on measured $\delta^{13}C$.

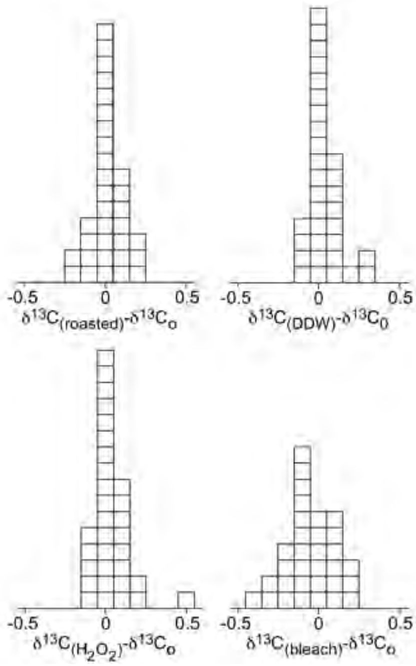

Figure 2. Frequency of differences between $\delta^{13}C$ untreated and corresponding treated speleothem carbonates. Plots show no more than a 0.5‰ change in the difference of $\delta^{13}C$ values of speleothem carbonate after treatments have been applied.

incorporate organic C processed by C_4 photosynthesis, so that the $\delta^{13}C$ of incorporated organic carbon need not cause a large decrease in $\delta^{13}C_{bulk}$ (Fig. 3). As a result of these considerations, $\delta^{13}C_{bulk}$ of speleothem carbonates can only be expected to be at most 0.05‰ less than $\delta^{13}C_{CO3}$, whereas $\delta^{13}C_{bulk}$ of mollusk shells, brachiopod shells, and limestones can be more than 1.0‰ less than the $\delta^{13}C$ of the carbonate itself (Fig. 3).

Conclusions

Conventional techniques to remove organic material from carbonates prior to isotopic analysis had no significant effect on the $\delta^{13}C$ value of the speleothems studied. These treatments could therefore be useful in removing organics from speleothems with higher organic matter content without concern that the treatments might alter the $\delta^{13}C$ value of the calcium carbonate in which the organic is contained. However, the speleothems used in this study, and by analogy most speleothems used in geologic studies, do not contain enough organic matter to affect the $\delta^{13}C$ values of speleothems even if they are left untreated. Therefore, pretreatment of speleothem samples is unnecessary unless the speleothem has unusually high organic carbon content.

Table 3. Oxygen isotope results[a].

Sample ID	$\delta^{18}O$ by Conventional Treatment	$\delta^{18}O$ with DDW Treatment	$\delta^{18}O$ with Roasting at 340°C	$\delta^{18}O$ with Bleach Treatment	$\delta^{18}O$ with H_2O_2 Treatment
C.S.1-T	–4.5	–4.8	–4.6	–4.5	–4.5
C.S.-1Mi	–5.8	–5.7	–5.8	–5.7	–5.8
C.S.-1Mo	–5.9	–5.8	–5.9	–6.1	–5.8
C.S.-1b	–5.3	–5.4	–5.4	–5.3	–5.3
C.S.-2i	–5.1	–5.2	–5.3	–5.3	–5.0
C.S.-2o	–5.3	–5.1	–5.3	–5.1	–5.2
C.S.-3d	–5.8	–5.9	–5.8	–5.7	–5.7
C.S.-3L	–4.9	–4.9	–5.0	–5.0	–5.0
C.S.-T1	–5.0	–5.2	–5.0	–5.0	–4.9
C.S.-T2	–4.9	–5.1	–5.0	–5.0	–5.1
C.S.-F.D.	–5.1	–5.0	–4.9	–5.0	–5.0
C.S.-F.Ma	–5.0	–4.9	–4.8	–5.0	–4.9
C.S.-F.Mb	–4.8	–4.7	–4.8	–4.7	–4.8
C.S.-F.Mc	–4.5	–4.6	–4.6	–4.6	–4.3
C.S.-F.L	–4.5	–4.5	–4.5	–4.4	–4.5
C.S.-F2a	–4.4	–4.3	–4.5	–4.3	–4.3
C.S.-F2b-R	–4.8	–4.8	–4.8	–4.9	–4.8
C.S.-F2c-R	–5.5	–5.4	–5.5	–5.6	–5.5
Reflx-T	–4.6	–4.5	–4.6	–4.6	–4.4
Reflx-L	–4.2	–4.4	–4.4	–4.4	–4.3
Reflx-B	–4.9	–4.8	–5.0	–4.9	–5.0
MR-68o	–4.0	–4.1	–4.2	–4.2	–4.1
MR-68m	–4.6	–4.4	–4.5	–4.4	–4.4
MR-68i	–4.2	–4.5	–4.3	–4.4	–4.2
Car-Mro	–4.2	–4.2	–4.4	–4.3	–4.3
Car-Mri	–5.0	–5.1	–5.5	–5.0	–5.0
P.J.Y.	–4.1	–4.2	–4.3	–4.4	–4.1
P.J.O.	–4.2	–4.2	–4.5	–4.3	–4.2
E.E.-12D	–11.4	–11.4	–11.2	–11.5	–11.4
E.E.-12L	–10.1	–10.2	–10.1	–10.2	–10.1
Unknown-1	–3.0	–3.1	–3.2	–3.1	–3.0
Unknown-2	–4.8	–4.9	–5.0	–4.9	–4.9

[a] $\delta^{18}O$ values are all in ‰ with respect to the PDB standard. Location, mineralogy, and TOC concentration of samples are given in Table 1.

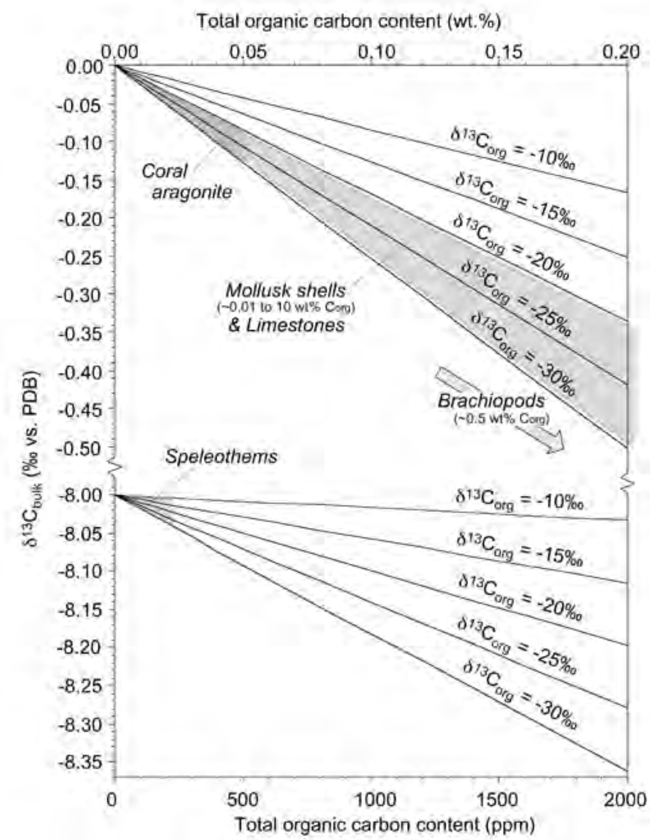

Figure 3. $\delta^{13}C_{bulk}$ of a hypothetical marine carbonate with $\delta^{13}C_{CO3}$ = 0.00 and of a hypothetical spelean carbonate with $\delta^{13}C_{CO3}$ = 8.00, as a function of total organic carbon content with various values of $\delta^{13}C_{org}$. Field for coral aragonite is from Boiseau and Juillet-Leclerc (1997), field for mollusk shells is from Weiner et al. (1983), field for limestones is from Pratt (1984) and Pancost et al. (1998, 1999), arrow for brachiopods is from Jope (1971, 1977), and field for speleothems is from this paper.

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Yongli Gao, Robert Tipping, and E. Calvin Alexander Jr. Applications of GIS and database technologies to manage a karst feature database. *Journal of Cave and Karst Studies*, v. 68, no. 3, p. 144–152.

APPLICATIONS OF GIS AND DATABASE TECHNOLOGIES TO MANAGE A KARST FEATURE DATABASE

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This paper describes the management of a Karst Feature Database (KFD) in Minnesota. Two sets of applications in both GIS and Database Management System (DBMS) have been developed for the KFD of Minnesota. These applications were used to manage and to enhance the usability of the KFD. Structured Query Language (SQL) was used to manipulate transactions of the database and to facilitate the functionality of the user interfaces. The Database Administrator (DBA) authorized users with different access permissions to enhance the security of the database. Database consistency and recovery are accomplished by creating data logs and maintaining backups on a regular basis. The working database provides guidelines and management tools for future studies of karst features in Minnesota. The methodology of designing this DBMS is applicable to develop GIS-based databases to analyze and manage geomorphic and hydrologic datasets at both regional and local scales. The short-term goal of this research is to develop a regional KFD for the Upper Mississippi Valley Karst and the long-term goal is to expand this database to manage and study karst features at national and global scales.

INTRODUCTION

Several Geographic Information Systems (GIS)-based Karst Feature Databases (KFDs) have been established in many karst regions and countries (Cooper *et al.*, 2001; Florea et al., 2002; Lei *et al.*, 2001). However, the absence of comprehensive database models and standard metadata impeded the data compatibility and management (Gao *et al.*, 2005a). A KFD has been developed in Minnesota in the past few years (Gao et al., 2002; Gao *et al.*, 2005a; Gao *et al.*, 2005b). The development, implementation, and data analyses of the Minnesota KFD are described in detail in the first author's Ph.D. dissertation (Gao, 2002). This paper discusses the last two phases of the process to develop the Minnesota KFD: Building and Implementing Applications and Database Monitoring and Maintenance.

Based on a survey from potential users of the Minnesota KFD, the applications built for the database need to have the following features: easy to use interfaces, compatible with Microsoft Access and ArcView GIS, reliable concurrency control and security, and network and Web accessible. In Minnesota, similar applications already exist in Minnesota Geological Survey's (MGS) County Water-well Index (CWI) Database Management System (DBMS). These applications are used by many users to access and maintain information about Minnesota's millions of water wells. The applications built for the KFD build on the lessons learned from MGS's CWI project.

One of the advantages of a relational database is the capability of data queries. Query languages can be used in a relational DBMS to modify the structures of a database, to update data in the relations, and to extract useful information needed from the DBMS. The best known query language in relational databases is Structured Query Language (SQL). SQL is also called SEQUEL (Structured English Query Language) and was first designed in a relational database system called System R at IBM (Elmasri and Navathe, 1994). It is now used in most commercial relational DBMSs. Data queries were integrated into the applications to facilitate the functionality of the user interfaces. Stand alone data queries were also used to manipulate transactions of the database by the database administrator (DBA).

The DBA utilized the DBMS applications along with data queries and data logs to maintain the performance, consistency, and security of the KFD. Regular users can also use these applications to monitor the performance of the database.

BUILDING APPLICATIONS

Figure 1 illustrates two sets of applications built for the KFD. The five applications (data entry, data edit, data lookup, data report, and code maintenance) shown on the left side in Figure 1 are built in Microsoft Access. The five applications (digitizing, visualization, location verification, spatial transformation, and map generation) shown on the right side are built in ArcView GIS.

One set of applications, shown as the left portion of Figure 1, was written in Visual Basic programming language and linked to the KFD under Microsoft Access DBMS. These user interfaces are used to process karst feature records from paper-file formats. The other set of interfaces, shown as the right portion of Figure 1, was written in ArcView Avenue programming language and linked to the KFD in an ArcView environment. These interfaces are used to process karst feature records surveyed and stored on topographic maps. Both kinds of applications allow users to enter, edit, and query karst feature data stored in the KFD.

Most of the karst feature datasets of Minnesota were paper files and/or digitized from locations indicated on USGS 1:24,000 topographic maps. Figure 2 is a paper-file record of a spring (ID number is MN85:A0261) on the Lewiston USGS topographic quadrangle in Winona County. This spring was visited and recorded on April 26, 1986. This spring was also marked on a USGS 1:24,000 topographic map as shown on Figure 3. Since some existing karst feature datasets are in either paper-file format or marked on topographic map, two kinds of applications were created to enter and manipulate these two different formats of datasets.

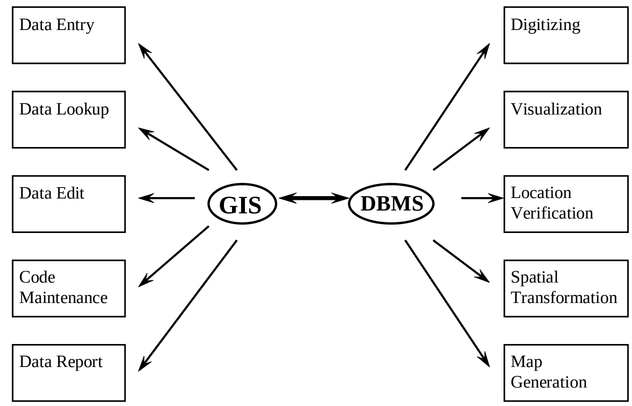


Figure 1. Applications built for the GIS-based KFD of Minnesota (updated from Gao et al. 2002).

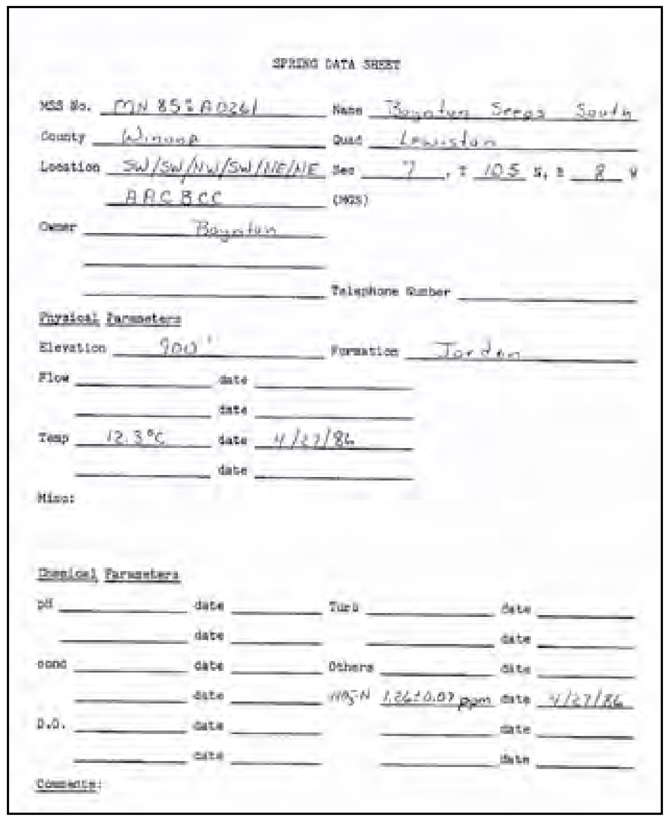
IMPLEMENTING APPLICATIONS IN MICROSOFT ACCESS

The main interface screen in Microsoft Access is shown in Figure 4. The top four command buttons link to four applications: Edit Data, Enter New Data, Lookup Data, and Maintain Code Tables. These four applications correspond to four of the five Microsoft Access applications listed in Figure 1. The fifth application, Data-Report, is embedded in Data-Lookup and Data-Edit applications.

All the applications are written in Visual Basic programming language and Structured Query Language (SQL). Figure 5 describes some commonly used graphical objects in the KFD applications. These graphical objects are called controls in Microsoft Access. These tools interact with the main database through codes written in Visual Basic or SQL.

Label is one of the simplest controls. Label is used to identify the meaning of other tools and usually not associated with programming codes. In Figure 5, the label FEATURE is used to describe that the combo box next to the label is linked to feature types. Combo box is often connected to a lookup table or code table through SQL. Users can click the small arrow to the right of a combo box to display items stored in the lookup table. In Figure 5, the combo box is associated with the code table FEATURE. Users can enter one of the karst feature types displayed by the combo box. Text box simply displays or lets a user enter data into the text box. The text box in Figure 5 asks the user to type in the MSSID for a karst feature. Command button is usually used to initiate an action or a set of actions. In Figure 4, if a user clicks the command button labeled by QUIT, it will close all the applications and quit. Clicking any of the other four buttons in Figure 4 would start the corresponding application as described by the label text next to it. In Figure 5, the Command Button, Save Record, would save a new or altered record into the KFD.

The interface of an application is also called form or report in Microsoft Access. Form can also be used to display and modify data records stored in the database. Report in Microsoft Access is used to present data records in a printable format. A



SPRING DATA SHEET

MSS No. MN 85:A0261 Name Boynton Spr. South
County Winona Quad Lewiston
Location SW/SW/NW/SW/NE/NE Sec 7, T 105 N, R 8 W
BACBCC (MGS)
Owner Boynton

Telephone Number

Physical Parameters
Elevation 900' Formation Jordan
Flow date
date
Temp 12.3°C date 4/27/86
date
Misc:

Chemical Parameters
pH date Turb date
date date
cond date Others date
date NO3-N 1.26±0.07 ppm date 4/27/86
D.O. date date
date date
Comments:

Figure 2. A karst feature recorded on a paper data sheet.

report looks like a form but it's usually read-only and formatted for output. One application interface in Microsoft Access can include many interfaces, which means a form or report can have a series of subforms or subreports. Subforms and subreports are usually controlled by tab controls in the primary form or report. In Figure 5, there are a series of subforms connected by tab controls. If a user clicks the tab control, Sinkholes, a new interface comes into the view and displays attributes for a sinkhole or asks the user to enter some attributes for a specific sinkhole.

Figure 6 illustrates a data-entry interface for karst features in paper-file format. BASE INFO and POSITIONING in Figure

6 correspond to the top-level karst feature index table of the database structure. The tabs (Sinkhole – Remarks) at the bottom section of Figure 6 are linked to the lower level data tables specific for each karst feature and its owner's address and additional remarks through sub-form interfaces. These sub-form tab controls correspond to the lower level tables in the karst database structure. Figure 6 illustrates information about the spring (shown in Figure 2) entered through the data entry interface.

Figure 7 and Figure 8 are karst feature Data-Edit and Data-Lookup interfaces, respectively. The Data-Edit interface displays attribute values for a specific karst feature record allowing authorized users to modify these attribute values and even delete incorrectly assigned karst feature records. The Data-Lookup interface looks almost identical to the Data-Edit interface. However, Data-Lookup interface is read-only and limited to search and display attribute values of a karst feature record. The Data-Edit, Data-Lookup and Data-Entry interfaces (Figure 6) have very similar layouts which are compatible with the structure of the relational model of the karst feature DBMS.

The search button in both Data-Edit and Data-Lookup interfaces is connected to a smaller interface to search a specific karst feature record to be accessed by the Data-Edit or Data-Lookup applications. Figure 9 is such an interface that searches a karst feature record by asking users to enter its Relate ID or a combination of a feature's county name, feature type, and numerical ID.

The print-log button in both Data-Edit and Data-Lookup interfaces is connected to a report interface to print out a formatted report sheet of a specific karst feature record. Figure

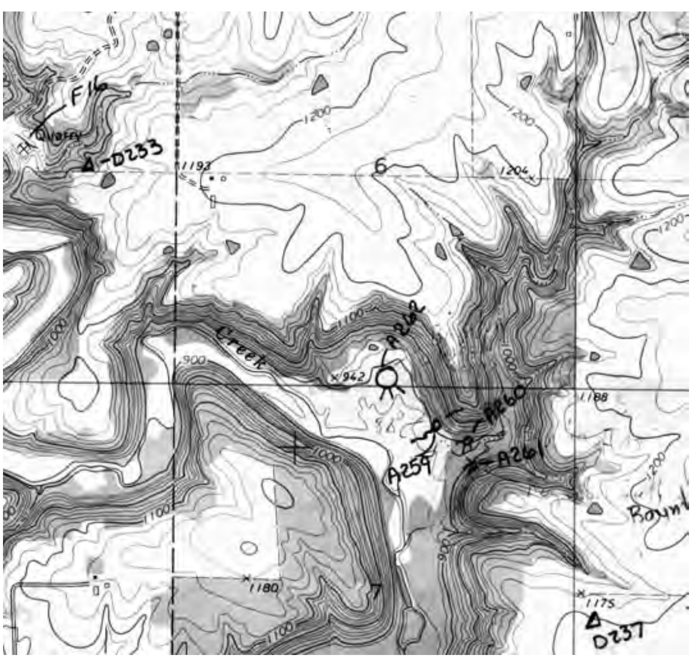


Figure 3. Karst features compiled on USGS 1:24,000 topographic maps. This example is from the Lewiston Quadrangle, Minnesota – Winona Co., 7.5-minute series topographic map, 1974. The area of section 6 is 1 square mile.

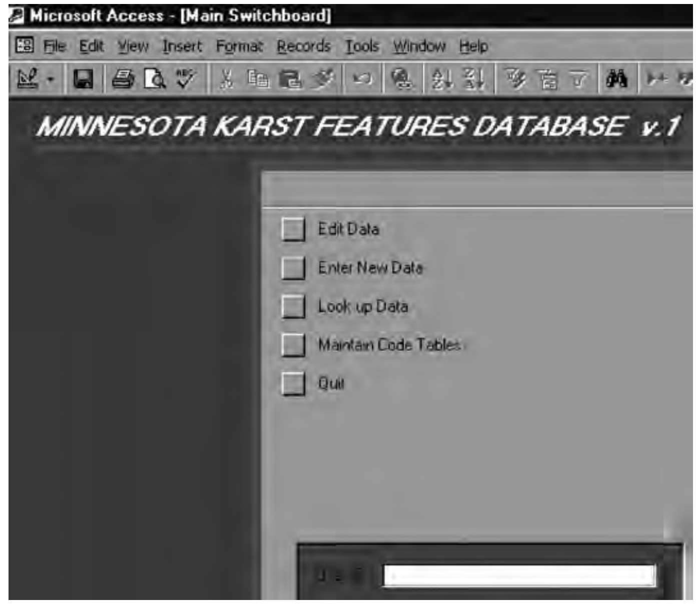


Figure 4. Main interface for the applications built for the karst feature DBMS in Microsoft Access.

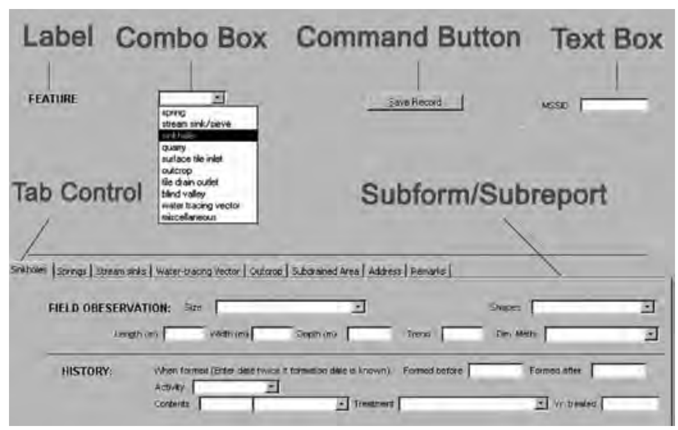


Figure 5. Most commonly used controls in the application interfaces of karst feature DBMS in Microsoft Access.

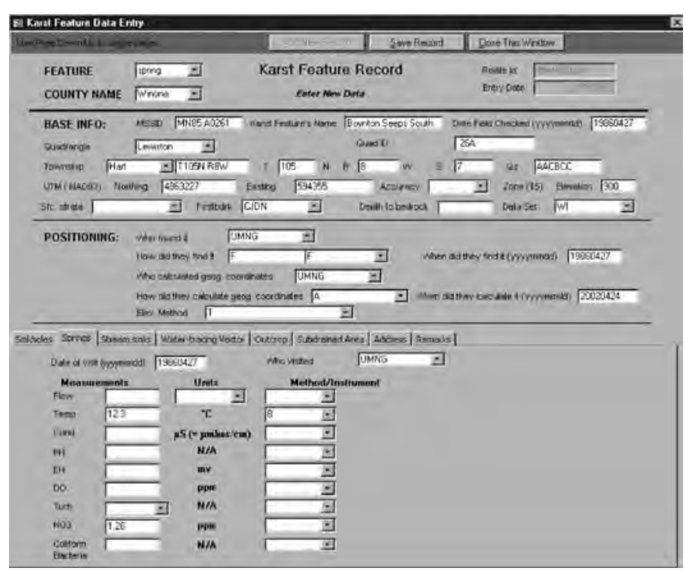


Figure 6. Data-entry interface written in Visual Basic programming language under Microsoft Access.

10 shows a two-pages report for a sinkhole whose Relate ID is 25D0000044. The first page contains information stored in the data tables of karst feature index, remarks, and owner's address. The second page prints out information specific for sinkhole record stored in the sinkhole data table. This sinkhole is also demonstrated in the search interface (Figure 9) and displayed in both Data-Edit (Figure 7) and Data-Lookup (Figure 8) interfaces. Notice that all the codes used in the data tables are converted to their full descriptions to make the report sheet more readable and understandable to the general public.

Figure 11 displays an interface to maintain code tables. Many of the code tables listed in Appendix D of Gao (2002) are subject to change with new information obtained for the karst feature DBMS. Some records in the code tables might get outdated and need to be removed in the future. This interface would allow authorized users to add a new record, delete an outdated record, and modify an existing record for any of the code tables used in the KFD. In Figure 11, records in the GCMCODE table are shown in Code-Table-Maintenance interface.

The Data-Entry, Data-Edit, Data-Lookup, and Code-Table-Maintenance interfaces are directly linked to the main interface. The Search and Report interfaces are accessible through the Data-Edit and Data-Lookup interfaces.

Implementing Applications in ArcView GIS

The applications in ArcView can access data in the KFD through Data Sources Open Database Connectivity (ODBC). The main application interface in ArcView GIS is shown in Figure 12. The structure of applications in ArcView GIS is different from the one in Microsoft Access. It consists of two windows. The left window acts as a control interface and the right window is a visualization window to display locations of karst features and maps or images related to locations or some attribute values of individual karst features. These images or maps are used to verify attributes of existing karst features or digitize new karst features and save them into the KFD. The controls in the main interface are similar to those in the interfaces in Microsoft Access. Authorized users utilize these controls to activate specific applications to control what to display in the visualization window.

As shown in Figure 1, the five applications in ArcView GIS are digitizing, visualization, location verification, spatial transformation, and map generation. In addition, applications in ArcView GIS have some comparable functions to those in Microsoft Access. Digitizing is a simplified Data Entry application based on a karst feature's locations on a map instead of its own geographic coordinates. Some basic feature attribute values can be displayed or changed by using controls such as Feature Attributes, Change MSSID #, and those combo boxes as shown on Figure 12 and Figure 13. The control Find Feature functions the same as the search interface in Microsoft Access to find and to display a specific karst feature based on its county number and numerical ID. However, applications in ArcView GIS can only access and modify a limited number of attributes for a karst feature record. These applications are designed for

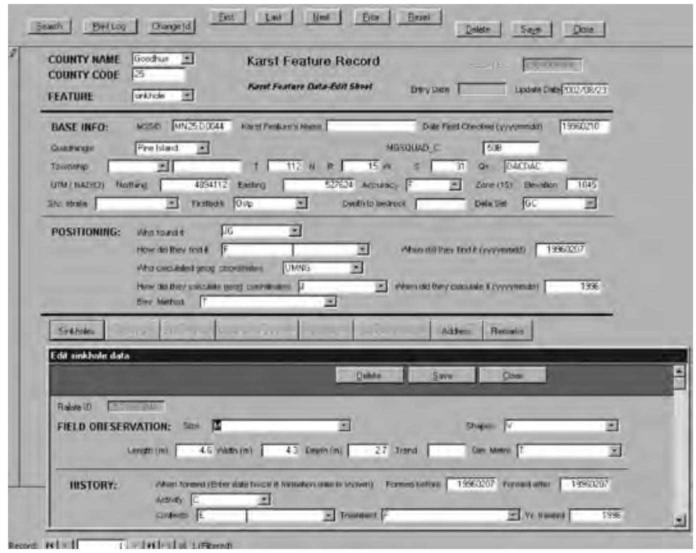


Figure 7. Data-edit interface written in Visual Basic programming language under Microsoft Access.

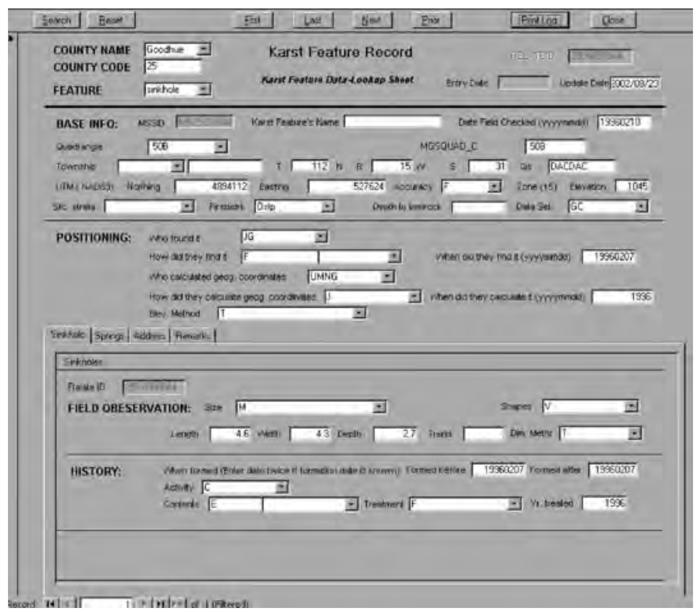


Figure 8. A Data-lookup interface written in Visual Basic programming language under Microsoft Access.

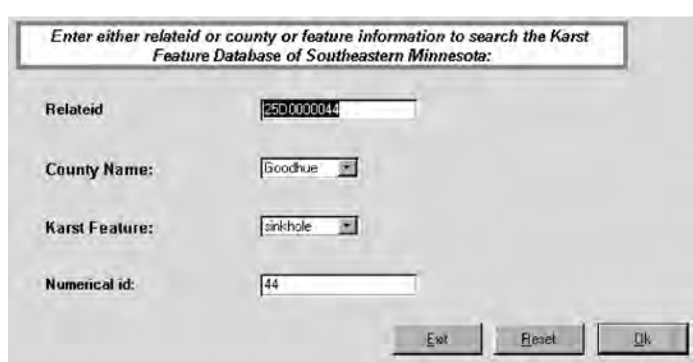


Figure 9. Search interface used to search specific karst feature record for Data-Edit and Data-Lookup applications.

Figure 10. Report interface used to print out a karst feature record from Data-Edit and Data-Lookup applications.

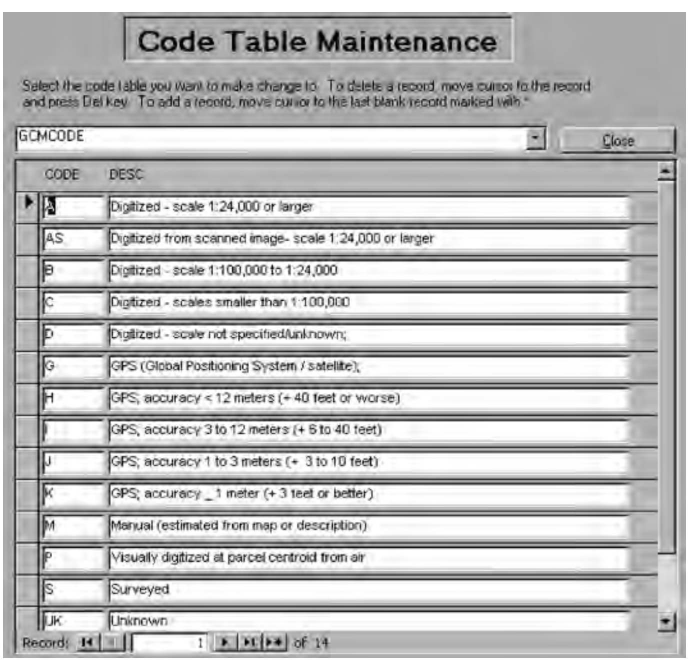


Figure 11. Code Table Maintenance interface written in Visual Basic programming language under Microsoft Access

point features such as sinkholes, springs, stream sinks and they cannot be used for line and polygon features.

The Add Feature and Digitize Location controls in Figure 12 and 13 can be used consecutively to digitize a karst feature based on its location on a USGS topographic map or an aerial photograph. Georeferenced digital raster graphic (DRG) and digital orthophoto quadrangle (DOQ) are used to match karst feature's location and topographic setting. A DRG is a scanned image of a U.S. Geological Survey (USGS) standard series topographic map (U.S. Geological Survey, 2001). The image inside the map neatline is georeferenced to the surface of the earth and fit to the Universal Transverse Mercator (UTM) projection. A DOQ is a computer-generated image of an aerial photograph in which displacements caused by camera orientation and terrain have been removed (U.S. Geological Survey, 1996). If a user clicks the save button on the interface, a karst feature's location information such as geographic coordinates, quadrangle, township, and range will be automatically entered into the database.

There are many visualization controls users can manipulate to decide what to display on the visualization window. Users can select what quadrangle of DRG or DOQ is to be displayed from the combo box Select Quad Name. The control button Find Feature can be used to find a specific karst feature record and its corresponding DRG and DOQ based on its geographic coordinates. Figure 12 demonstrates that users can find the spring entered through Microsoft Access interface (Figure 6) and its corresponding DRG through the main interface in ArcView GIS. Geographic themes such as county, quadrangle, and township are added to the visualization window by default to define and to verify the political boundaries of karst feature records. The visualization window in Figure 13 shows all these themes along with karst features, DRG, and DOQ in Wykoff Quadrangle, Fillmore County. In the main interface of Figure 13, Full-screen Crosshairs and Enable Map Tips at the bottom of the main interface are enabled to display a crosshair and karst feature label when the mouse pointer moves close to a karst feature. In this example, a sinkhole's label D2129 is displayed to identify this feature as a sinkhole in Fillmore County with Relate ID 23D0002129 (Label is composed by the code of a feature type plus the last four digits of the Relate ID).

Users can verify locations of many karst features based on their position on DRG and DOQ. Many karst features were mapped and marked on topographic maps. Many closed depressions on topographic maps and aerial photos can be identified on DRGs and DOQs in ArcView GIS. Once the location of a karst feature is seen to be incorrect, authorized users can move it by using the Adjust Location control in the main interface (Figure 12). Figure 14 illustrates that sinkhole locations in an area of Wykoff Quadrangle were verified and adjusted based on information from a DOQ. The locations of topographically closed depressions on DRG and DOQ are almost identical in this example. The sinkhole locations were placed, whenever possible, where the two maps agreed. The DOQ and DRG can be superimposed on the computer screen. Both maps are important and features visible on one map may be invisible on the other. When the locations of a topographically identified karst

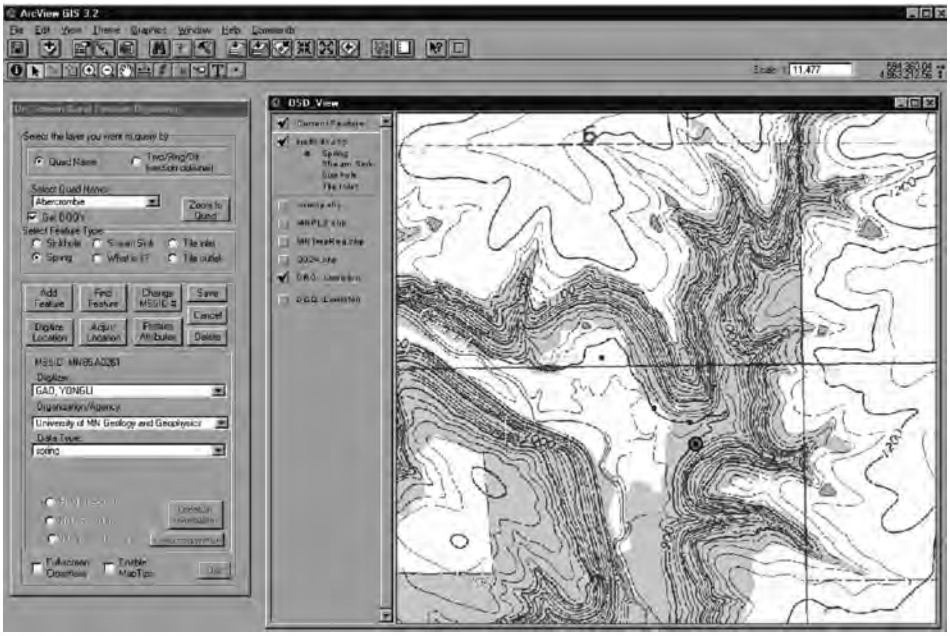


Figure 12. Main interface written in ArcView Avenue programming language under ArcView 3.2 environment. The background DRG in the visualization window is from the USGS Lewiston Quadrangle, Minnesota – Winona Co., 7.5 minute series topographic map, 1974.

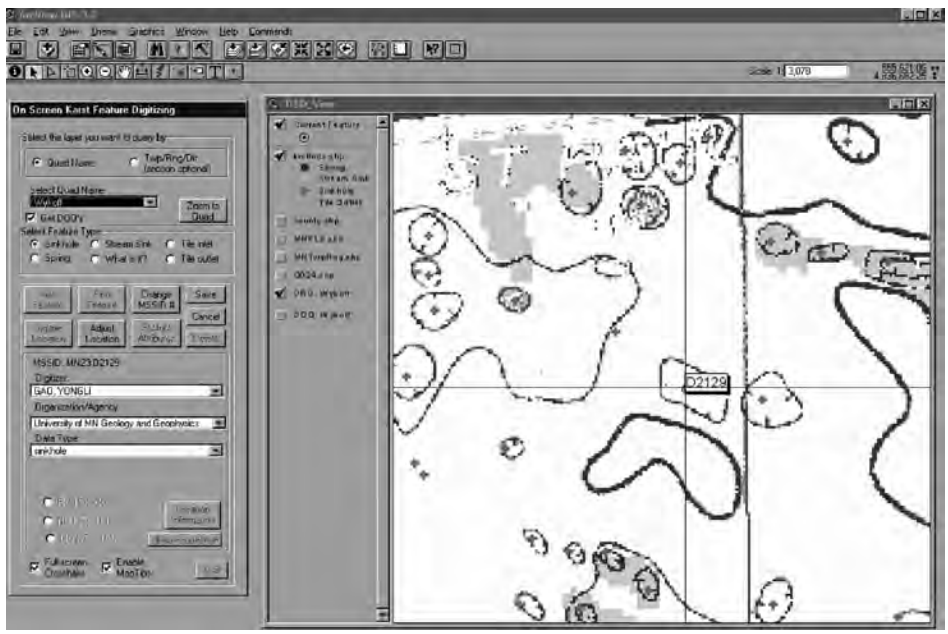


Figure 13. Karst feature visualization through application interfaces in ArcView GIS. The background map in the right window is from the USGS Wykoff Quadrangle, Minnesota – Fillmore Co., 7.5 minute series topographic map, 1965.

feature don't match between DOQ and DRG, the DOQ is usually more reliable since this technology is relatively new and the topographic maps used for DRG are much older than the aerial photos used for DOQ. Some of the newly located sinkholes using a Global Positioning System (GPS) unit appear to be in the same locations as the closed depressions shown on DOQs.

In addition to all the tools discussed above, users can use all the available ArcView tools to visualize and analyze karst feature distribution in Minnesota. For instance, bedrock geology and surficial geology themes can be added to the visualization windows to verify or to define some geologic attribute values of any karst feature record.

DATA QUERIES

The karst feature DBMS uses five different kinds of SQL queries: select query, delete query, append query, update query, and make table query.

The select query is the most commonly used query in relational DBMS. The basic form of select query is a SELECT FROM WHERE block (Elmasri and Navathe, 1994). It has the following form:

```
SELECT <attribute list>
FROM <table list>
WHERE <criteria>
```

This form means select a list of attributes from a list of tables based on some criteria to retrieve information from the database. For example, the following query was used to retrieve

A B

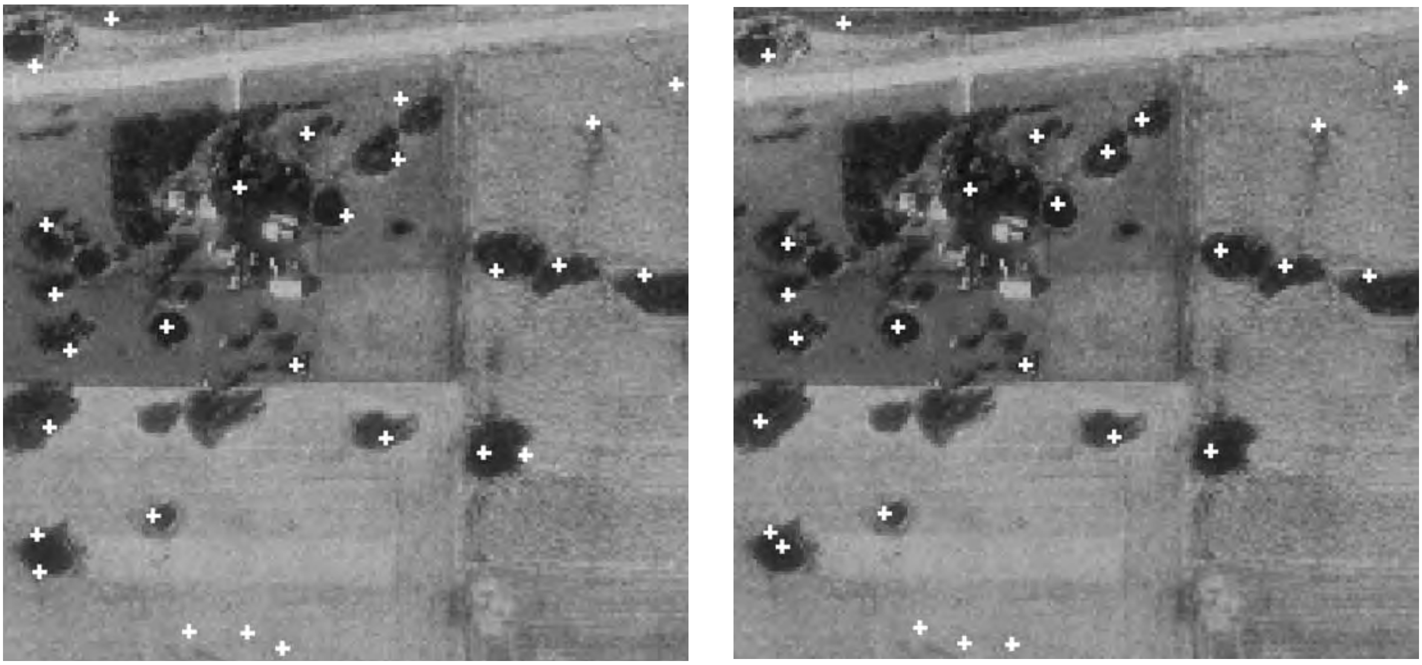


Figure 14. Verified and adjusted sinkhole locations on a DOQ in an area of Wykoff Quadrangle, Fillmore County using Location-Verification and Spatial Transformation tools in ArcView GIS. (A) sinkhole locations before spatial transformation. (B) sinkhole locations after spatial transformation. The cross on the aerial photo reflects sinkhole locations on the land surface.

attributes of all the features whose geographic coordinates do not exist in the karst feature index table. Select kfix.* means to retrieve all the attributes in the table kfix.

```
SELECT kfix.*
FROM kfix
WHERE (kfix.utme = 0 or kfix.utmn = 0);
```

This query was used to identify all of the numbered features which had no location in the KFD so that the missing locations could be supplied.

If a select query retrieves information from more than one table, some tables need to be joined together to combine data records from different tables. The following query retrieves RELATEID, UTME, UTMN, and Shapes of all the large sinkholes in Goodhue County.

```
SELECT kfix.RELATEID, kfix.UTME, kfix.UTMN, kfsk.SHAPES
FROM kfix INNER JOIN kfsk ON kfix.RELATEID = kfsk.RELATEID
WHERE ((kfix.COUNTY_C=”25”) AND ((kfsk.SIZE)=”L”));
```

In Microsoft Access, both tables and queries could be joined together. The query above has an inner join statement which joins the karst feature index table and sinkhole table. When it finds matches of RELATEID in both tables, it combines those two records from the two tables and displays them as one record in the query's results. For an inner join statement, if one table or query doesn't have a matching record in the other table or query, neither record appears in the query's results. Other join types such as left outer join or right outer join can select all the records from one table or query whether or not it has matching records in the other table or query.

The select query also includes functions such as COUNT, SUM, MIN, MAX, and AVG and more clauses such as GROUP BY, HAVING, and ORDER BY to make more complicated selections. The following query retrieves the number of karst features and counties in which more than 100 karst features exist from the karst feature index table. The results of the query are sorted by county code.

```
SELECT Count(kfix.FEATURE) AS NUMBER_OF_FEATURES, kfix.COUNTY_C
FROM kfix
GROUP BY kfix.COUNTY_C
HAVING COUNT(*) > 100
ORDER BY kfix.COUNTY_C;
```

The delete query removes some records from a table based on certain criteria. The following query would remove any sinkholes in Winona County whose numeric IDs are greater than 1000. Since cascading delete is enforced between karst feature index table and lower level data tables, deleting a record from the index table would delete corresponding records in the related tables as well.

Delete Query:

```
DELETE *
FROM kfix
WHERE RELATEID < “85D0009999” and RELATEID
```

```
>= “85D0001000”;
```

The append query inserts a set of records into a data table. The following query inserts all records from kfix85 into the table kfix. It loads the most recent Winona County sinkhole data set, which is converted as table kfix85, into the karst feature index table, kfix.

```
INSERT INTO kfix
SELECT kfix85.*
FROM kfix85;
```

The update query is used to modify attribute values of some selected records. The following query modifies all the karst features’ labels (FEAT_LABEL) to match their RELATEID. The Mid function is used in this statement to combine the third character and the last four digits from the RELATEID to form a feature’s label.

```
UPDATE kfix SET kfix.FEAT_LABEL = Mid([RELATEID],3,1)+Mid([RELATEID],7,4);
```

The make table query is used to convert the results of a query into a table in Microsoft Access. The following query selects all the karst features of Winona County in the karst feature index table and converts it to be an index table in the Winona County DBMS.

```
SELECT kfix.* INTO kf85ix IN ‘kf85.mdb’
FROM kfix
WHERE (((kfix.RELATEID)<’85d0009999’ And (kfix.RELATEID)>=’85d0000001’));
```

In the karst feature DBMS, combinations of different SQL queries provide the fundamental information needed for the applications built on the KFD. The SQL query is also an essential tool for DBMS monitoring and maintenance.

DBMS Monitoring and Maintenance

After a DBMS is set up, it needs to be monitored closely to maintain its performance, consistency, and security. The KFD of Minnesota was originally put on a Windows NT server and switched to a Windows XP Citrix server in MGS. Authorized users can access the DBMS by connecting to the server as a Citrix client.

Table 1 lists four levels of users to access the KFD. The database administrator (DBA) is responsible for authorizing users to access the database and monitoring its use. The DBA has exclusive access to the DBMS to modify the structure and applications of the DBMS and recover lost or misplaced data due to hardware and software failures and human errors. Power users are authorized to access and update attribute values of karst features and code tables through all the application interfaces in both Microsoft Access and ArcView GIS. Regular users can access the DBMS through all application interfaces except code table maintenance application in Microsoft Access. They are not authorized to modify code tables used in the KFD. Guest users access the DBMS through read-only applications such as the Data-Lookup interface in Microsoft Access and the visualization interface in ArcView GIS. General public can access and download karst feature index files through MGS’s website. The GIS-based karst feature index files are generated from the DBMS on a regular basis to make the most up to date karst feature information accessible to the general public.

Database consistency and recovery are accomplished by creating data logs for the database. Data logs record entry, update, and delete dates for all the karst features in the DBMS. Original attribute values related to location and topographic setting of a karst are also saved in the data logs when it’s updated or deleted. When hardware and software failure or human error occurs, the DBA can retrieve critical attribute values and put them back to the KFD. The karst feature DBMS is backed up to magnetic tapes and CD-ROMs at MGS on a regular basis. New and updated karst features are usually printed out as report sheets. Backup files and report sheets will be used for DBMS recovery if the karst DBMS is completely corrupted.

Conclusions

The KFD of Minnesota is a relational GIS-based DBMS. Microsoft Access and ArcView were used to develop application tools for the working database. Existing county and sub-county karst feature datasets have been assembled into the KFD capable of analyzing the entire data set. Data tables are stored in a Microsoft Access DBMS and linked to corresponding ArcView applications. The current KFD of Minnesota was moved from a Windows NT server to a Windows XP Citrix server accessible to researchers and planners through networked interfaces.

This working database also provides guidelines and management tools for future study of karst features in Minnesota. An inventory of current karst features has been put on MGS’s website (http://mgsnt4.mngs.umn.edu/karst) to be accessible to the general public. The working database is still incomplete and more data will be put in the database in order to implement more complex statistical and hydrogeological models. More tools need to be built to make the data modules more powerful and interactive. Existing applications will be upgraded to process linear and polygon karst features. The methodology of designing this DBMS is applicable to develop GIS-based databases to analyze and manage geomorphic and hydrologic datasets at both regional and local scales. The KFD of Minnesota is being expanded to manage and study karst features in the Upper Mississippi Valley Karst (Gao *et al.* 2005c).

Acknowledgements

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Table 1. Karst feature DBMS users and their authorized privileges.

DBMS User	Authorized Privilege
Database Administrator (DBA)	Grant and revoke privileges to other users and user groups Maintain DBMS consistency and security
Power User	Access the DBMS through all application interfaces
Regular User	Access the DBMS through all application interfaces except code table maintenance application in Microsoft Access
Guest User	Access the DBMS through read-only application interfaces
General Public	Access karst feature index files through MGS's website (http://mgsnt4.mngs.umn.edu/karst/)

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CAVE FAUNA OF THE BUFFALO NATIONAL RIVER

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The Buffalo National River (within Baxter, Marion, Newton, and Searcy counties, Arkansas) is completely underlain by karstic topography, and contains approximately 10% of the known caves in Arkansas. Biological inventory and assessment of 67 of the park's subterranean habitats was performed from 1999 to 2006. These data were combined and analyzed with previous studies, creating a database of 2,068 total species occurrences, 301 animal taxa, and 143 total sites. Twenty species obligate to caves or ground water were found, including four new to science. The species composition was dominated by arthropods. Statistical analyses revealed that site species richness was directly proportional to cave passage length and correlated to habitat factors such as type of water resource and organics present, but not other factors, such as degree of public use or presence/absence of vandalism. Sites were ranked for overall biological significance using the metrics of passage length, total and obligate species richness. Fitton Cave ranked highest and is the most biologically rich cave in this National Park and second-most in all of Arkansas with 58 total and 11 obligate species. Recommendations include continuation of physical and biological inventories, increased protection of high-ranking sites, and increased public education/outreach.

Introduction

The Buffalo National River (BNR), located in northwest Arkansas within Marion, Newton, and Searcy counties, is a 387-km^2 (95,730-acre) park with extensive recreational and natural resources (Fig. 1). The BNR hosts a rich diversity of biota, including the animals endemic to this watershed, including the milliped *Auturus florus* (Causey, 1950, Robison and Allen, 1995) and the dipluran *Occasjapyx carltoni* (Allen, 1988). Two-thirds of the total BNR watershed (3,471 km^2 [857,607 acres]) consists of karst terrane (Scott and Hofer, 1995) (Fig. 2). There are approximately 350 caves on the BNR (defined as a naturally occurring void in the rock with a length and/or depth of at least 15 m (50 ft), with the length of passage greater than twice the width of the entrance whether or not the entrance is natural). With approximately 3,900 caves on USDI National Park Service (NPS) lands, the BNR contains 9% of all known caves on NPS lands (Steele, 2002). Yet, this National River lacked a comprehensive inventory of its cave resources, which hinders the protection of these resources from encroaching development, looting, and habitat degradation. The physical and biological inventory of the karst resources began in the 1970s with contracts to the Cave Research Foundation. This study expanded the biological component, and sought to describe the abundance and diversity of animal life in subterranean habitats of the BNR. Furthermore, this study explored the relationship of biodiversity metrics to habitat variables to discern any patterns in subterranean diversity within the BNR.

Methods

Biological inventories of macrofauna were performed from November 1999 to December 2005. During this five-year study, at least 139 inventory events were performed and at least 67 caves and other karst features were inventoried (Fig. 3). Sites were georeferenced in Universal Transverse Mercator coordinates using the North America Datum 1983 with a global positioning system handheld unit (Garmin III Plus GPS), and the estimated position error was recorded (range of 1 – 20 m). At each site, the specific habitat variables were determined (Table 1).

Macrofauna were counted visually with helmet-mounted lights, using snorkeling gear and dive lights for deep pools. Bioinventories were discontinued any time endangered bats of any species were encountered. Collections were limited to those fauna that were impossible to identify in the field and performed under the following permits: NPS Collecting permit PSN-101, Federal Fish and Wildlife Permits PRT-834518, TE834518-1, TE834518-2, and TE834518-1; and Arkansas Game and Fish Commission Educational Collecting Permits 1082 and 1476. Voucher specimens were collected primarily by hand, aspirator, and dipnet (and occasionally by bait trap), and preserved in 75–90% ethanol, and brought back to the University of Arkansas at Fayetteville (UAF) for identification and cataloging. Specimens were identified at UAF by Graening and Slay, by J. Barnes (UAF Dept. of Entomology), or sent to taxonomic specialists, including the following: K. Christiansen (Grinnell College) and J. Battigelli (Earthworks Research Group) for collembolans; H. Hobbs III (Wittenburg University) for decapods; J. Holsinger (Old Dominion University) for amphipods; J. Lewis (Lewis and

Figure 1. Location of Buffalo National River (black polygon) in Arkansas with county boundaries shown in gray.

Associates, LLC.) for isopods; W. Shear for diplopods; J. Battigelli for Acari; W. Muchmore (University of Rochester) for pseudoscorpions; H. Robison (Southern Arkansas University) for fishes; S. Peck (Carleton University) for coleopterans; J. Cokendolpher (Museum of Texas Tech University) and D. Ubick (California Academy of Sciences) for opilionids; L. Ferguson (Longwood College) and M. Muegge (Texas Cooperative Extension) for diplurans; A. Hampton (Castleton College) for planarians; T. Cohn (University of Michigan) for orthopterans; and G. Walsh for gastropods.

The species' occurrence data and habitat characteristics were entered into a relational database (Access 2003, Microsoft, Inc.) and combined with historical data from 1935 to 1999, primarily the Cave Research Foundation project inventory of 98 sites in BNR (Lindsley and Welbourn, 1977; Welbourn and Lindsley 1979). Data were also used from the following previous studies: Black and Dellinger, 1938; Baker, 1949; Dearolf, 1953; Brandon and Black, 1970; Youngsteadt and Youngsteadt, 1978; Schram, 1980; Schram, 1982; Brown and Willis, 1984; Chaney, 1984;

Figure 2. Surficial geology of Buffalo National River (park boundary in white), adapted from a digital map created by the Arkansas Geologic Commission.

Willis and Brown, 1985; Graening and Brown, 2000; Graening *et al.*, 2001; Peck and Thayer, 2003; Shear, 2003; Barnes, 2004; and Graening *et al.*, 2005. Unpublished data sources were also used: cave files of the Association for Arkansas Cave Studies (D. Taylor, data manager); Arkansas Natural Heritage Database (Arkansas Natural Heritage Commission, C. Osborne, data manager); cave files of the Buffalo National River (NPS, C. Bitting, data manager); field notes of A. Brown, L. Willis, and S. Todd (all three with the University of Arkansas at Fayetteville); taxonomic database of collembola of K. Christiansen (Grinnell College); annual status reports from 1981 to 2005 of endangered bat surveys of M. Harvey (Tennessee Technological University) and R. Redman (Arkansas Soil and Water Commission); cave database of J. Roth (Oregon Caves National Monument); and unpublished data from the M.S. thesis of Slay (University of Arkansas at Fayetteville).

Statistical analyses (using JMP 5 software, SAS Institute, Inc.) and geographical information system analyses (using ArcView 3.2 software, ESRI, Inc.) were performed to discern any relationships between the richness of cave fauna and habitat factors such as geologic setting and watershed, level of disturbance, *etc*. Statistics used included linear and logistic regression, *t*-test, and the chi-square test. One-way analysis of variance (ANOVA, or *F*-test) was used to determine if there was a statistical difference between the group mean values. To determine differences between groups, a post-hoc comparison was performed using the Tukey-Kramer Honestly Significant Difference Test.

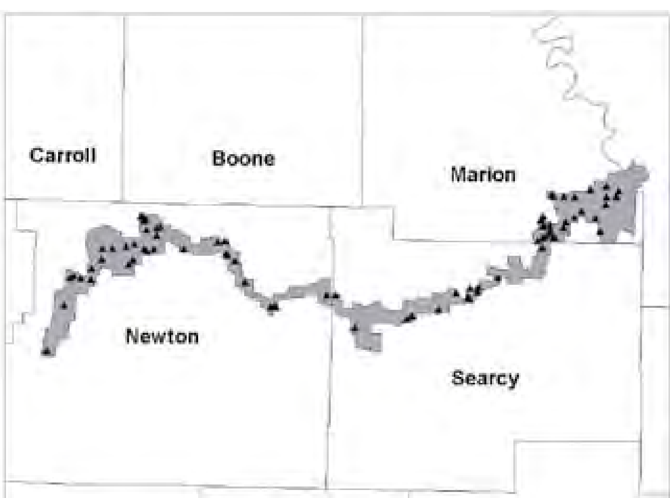

Figure 3. Location of sites (black triangles) in the BNR (gray polygon) bioinventoried in this study.

Results

Bioinventory Data

The bioinventory data generated during this study were pooled with historical data to produce a data set as follows: 143 sites (31 only partially inventoried); 443 inventory events: 139 in this study, 131 by the Cave Research Foundation, 169 by M. Harvey, and 4 by N. and J. Youngsteadt; 2,068 occurrence records; and 301 taxa. Appendix 1 summarizes the faunal list. Of 143 cave habitats with at least partial inventory data, the mean species per habitat (alpha diversity) was 11, with a maximum of 58 (Fitton-Fitton Spring Cave complex), a median of five, and a mode of one. The Fitton-Fitton Spring Cave complex was the richest with 58 taxa, and second was Square Cave with 51 taxa. Regional species richness (gamma diversity) was difficult to estimate, but at least 20 species obligate to ground water (stygobites) or caves (troglobites) and at least 280 other, non-cave-adapted taxa occurred on the BNR (Appendix). The Fitton Cave-Fitton Spring Cave complex had the most obligates per cave with a count of 11; other notable sites were Coon Cave with eight, Van Dyke Cave with seven, and John Eddings Cave with six. There were numerous anecdotal reports by recreational cavers of cavefish (Amblyopsidae) and cave crayfish (Cambaridae), but these reports could not be confirmed. The pooled faunal occurrences (n = 2,068) were examined for most abundantly occurring species, irrespective of habitat. Overall, arthropods dominated the cave habitats, especially crickets, mosquitoes, spiders, and springtails. The most common invertebrate taxon was cave crickets of the genus *Ceuthophilus* with 112 site occurrences, and second was cave orb weaver (*Meta americana*) with 27 occurrences. The most common vertebrates were eastern pipistrelle bat (*Pipistrellus subflavus*) with 60 occurrences and cave salamander (*Eurycea lucifuga*) with 53 occurrences. In aquatic habitats, crustaceans dominated (including 32 occurrences of the isopods of the genus *Caecidotea*).

Habitat Correlates

Surficial geology was determined for 91 solution caves, 16 mines, 13 bluff shelters, 10 pits, 9 sinkholes and 3 springs by site reconnaissance and by applying GIS analyses on the Arkansas Geologic Commission's digital version of the 1976 Geologic

Table 1. Habitat variables determined for the BNR biological macrofauna inventory.

General Feature	Habitat Variables
Type of Site	Bluff Shelter, Cave, Sinkhole, Well, Quarry, Spring, Mine, Crevice/Talus
Degree of Public Use[a]	None, Light, Moderate, Heavy
Vandalism[b]	Yes / No
Presence of Organics[c]	Yes / No
Presence of Bat Guano	Yes / No
Subterranean Water Resource	Perennial Stream, Intermittent Stream, Drip Pools Only, Dry, Unknown
Gated Site Entrance	Yes / No
Surficial Geologic Unit	. . .

[a] Primarily recreational caving.

[b] Defined as evidence of looting, presence of litter, campfire smoke residue, graffiti, animal injury, or damage of geologic resources.

[c] Defined as guano or other feces, leaf litter, woody debris, *etc*.

Map of Arkansas, scale 1:500,000 (Fig. 2). Sixty-two caves were formed in Mississippian-aged limestone of the Boone formation (including St. Joe member), four in Mississippian-aged limestone of the Pitkin Formation, eight in Ordovician-aged limestones / dolomites of the Fernvale, Plattin, and Joachim formations, 64 in Ordovician-aged limestone (Everton formation), and three in Silurian-aged limestone of the St. Clair Formation. Of the 143 inventoried sites, mean total passage length was 226 m (742 ft); the longest cave in the data set was the Fitton Cave – Fitton Spring Cave complex at over 13,411 m (43,999 ft) of combined, mapped passages, and the shortest were springs and shelters at 3 m (10 ft) (Table 2). Site passage length did not significantly differ by geologic category, according to a one-way ANOVA (n = 133, F ratio = 0.441, p = 0.780). Furthermore, a one-way ANOVA of surface geology categories with species richness as the response variable revealed no significant differences in species richness between geologic categories (n = 142, F ratio = 1.470, p = 0.215). However, linear regression revealed that species richness of a site was directly proportional to its passage length (m) (richness = 0.004 × length + 9.783, n = 133, $R^2 = 0.164$, t = 9.77, $p < 0.001$). According to this linear model, approximately one more taxon is added to the site's richness for every additional 250 m of cave passage (Fig. 4).

Other habitat characteristics were compared to site richness. Most caves did not have appreciable organics (100 of 143) and most did not have bat guano (112 of 143), but species richness was significantly greater when organics were present (n = 143, F = 31.171, $p < 0.001$) and when bat guano was present (n = 143, F = 22.731, $p < 0.001$). Species richness was significantly different between habitat types (n = 143, F = 2.847, p = 0.018); Tukey-Kramer HSD determined that caves were significantly more rich than bluff shelters, but comparisons of other habitat types were not significantly different. The water resource type was relatively evenly distributed between categories, and species richness differed significantly between water resource types (n = 138, F = 4.395, p = 0.006). Tukey-Kramer HSD determined that sites with perennial streams were significantly richer than dry sites, but comparisons of other water resource types were not significantly different. Degree of public use for most sites was light (Table 1) (85 of 143), and site richness was significantly different between degree of use categories (n = 138, F = 5.061, p = 0.001), with sites with moderate use significantly more rich than sites with light use. Given the correlation between richness and passage length, this result was not totally unexpected, as disturbed sites (defined as the combined categories of heavy use and moderate use [Table 1]) were significantly

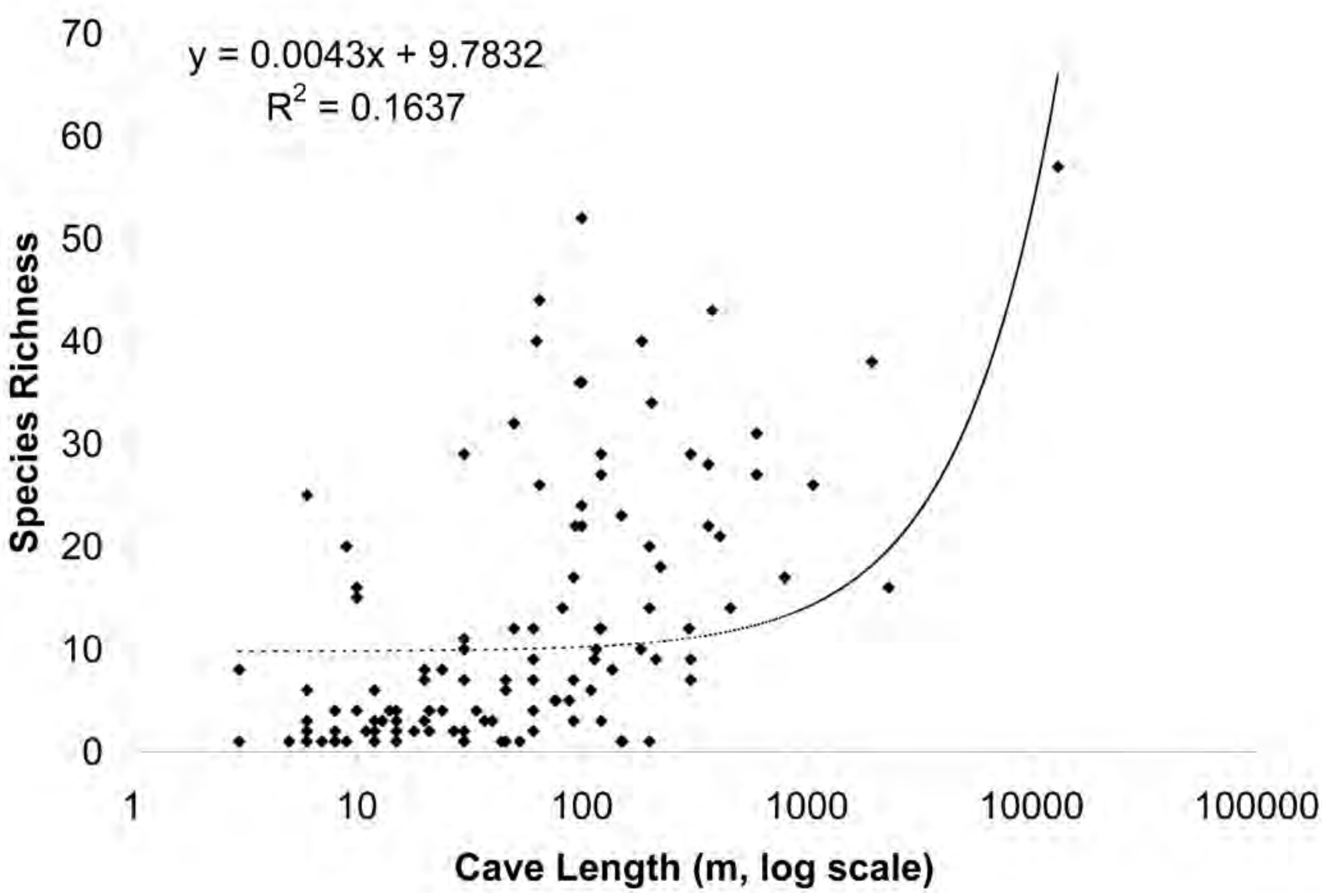

Figure 4. Significant linear relationship between total passage length of a site (shown on log scale) and the species richness of the site.

Table 2. Ranking of the top 20 most biologically significant caves on the BNR, with and without Fitton Cave and Fitton Spring Cave combined.

Site Name	No. of Obligates	No. of Species	Length (m)	Score	Rank
Fitton Cave / Fitton Spring Cave	11	58	13,411	284	1st
Fitton Cave	8	48	13,106	242	1st
John Eddings Cave	6	35	1,952	139	2nd
Coon Cave	8	37	185	131	3rd
Van Dyke Spring Cave	7	37	63	115	4th
Fitton Spring Cave	7	26	305	113	5th
Tom Barnes Cave	4	38	381	98	6th
Earl's Cave	5	35	98	95	7th
In-D-Pendants Cave	4	30	600	94	8th
Tom Watson's Bear Cave	3	15	2,316	93	9th
Forest Trail Ridge Cave	4	42	65	90	10th
Corkscrew Cave	5	19	412	89	11th
Cave Mountain Cave	3	26	1,067	89	12th
Summer Cave	4	29	365	88	13th
Copperhead Cave	4	17	800	85	14th
Stockman Cave	5	20	200	84	15th
Square Cave	2	52	100	82	16th
Pretty Clean Cave	3	27	600	81	17th
Willis Cave	4	22	366	81	18th
Back o' Beyond Cave	4	27	122	78	19th
Len House Cave	3	28	366	77	20th

Sites were scored according to the following formula: (number of obligate species × 10) + (number of total species) + (square root of length in meters).

longer than undisturbed sites (combined categories of light use and no use [Table 1]) (n = 134, $t = 2.709$, $p = 0.008$). Species richness was significantly greater when the site was gated (n = 143, $F = 151.106$, $p < 0.001$), but this may be another nested effect because all long caves on the BNR are gated, and we demonstrated earlier that longer caves have greater richness. Logistic regression revealed that gated caves were significantly longer than ungated caves (n =133, $X^2 = 12.015$, $p < 0.001$). Most sites were not vandalized (111 of 143); however, those that were vandalized had greater richness (n = 143, $F = 11.357$, $p < 0.001$). Again, due to the correlation between richness and length, this result was not totally unexpected. Vandalized caves were significantly longer than caves not vandalized (n = 136, $t = -2.700$ $p = 0.008$). Contingency analysis of vandalism by degree of public use revealed a significant relationship (n = 143, Pearson $X^2 = 49.570$, $p < 0.001$). Most sites had light or no use with no vandalism, but those sites rated moderate and heavy use were more likely to be vandalized.

Discussion

The BNR is one of the most biologically important karst areas of the Ozark Plateaus ecoregion. Several species with federal status under the Endangered Species Act rely upon subterranean habitats of the BNR: the endangered gray bat (*Myotis grisescens*) and Indiana bat (*M. sodalis*) utilize caves for hibernation and reproduction, and the endangered Ozark big-eared bat (*Corynorhinus townsendii ingens*) has occasionally been reported in crevice and solution caves. At least 20 subterranean-obligate species exist on the BNR, including three new species of troglobitic diplurans and one troglobitic springtail that await taxonomic description (Table 3). However, this bioinventory effort is not complete, and much taxonomic work remains to be done. Continuation of biologic and geologic inventories is highly recommended in order to accurately assess and manage these karst resources.

The 143 sites analyzed in this study were ranked in order of biological importance to facilitate and focus management decisions. The richness of obligate species is often used to rank the importance of the world's caves (*e.g.* Culver and Sket, 2000; Graening *et al.*, 2004), so this criterion was used. Total cave passage length is one metric of habitat size, and passage length was significantly correlated to richness in this study and in other Arkansas caves (Graening *et al.*, 2004). For this reason, length was used as another criterion for biological significance ranking. The third criterion was total species richness, which is a common measure of biological significance (*i.e.*, alpha diversity). The caves that had been bioinventoried thoroughly (117 out of 143) were ranked according to these three criteria if they had a minimum of at least two obligate species, at least 60 m of cave passage, and at least 15 total taxa (Table 2). The Fitton Cave / Fitton Spring Cave complex ranked highest with 58 species, 11 of which were stygobites or troglobites. This cave complex is the second-most biologically rich cave in Arkansas - Blanchard Springs Caverns is first with 96 documented taxa (Graening *et al.*, 2004).

The Buffalo River watershed is subject to several ecosystem stressors, primarily land conversion and water quality degradation. Conversion of forest to pasture is occurring at an average annual rate of approximately 15 km^2 per year (3,707 acres per year) (Scott and Hofer, 1995). Since the establishment of BNR in 1972, more watershed has been deforested than is protected within the boundaries of the National River. Scott and Hofer (1995) report that water quality and land use monitoring in the Buffalo River watershed demonstrates a correlation between deforestation and confined animal feeding operations activities and increased turbidity, nutrient and fecal bacterial concentrations in tributary streams. The Arkansas Department of Pollution Control and Ecology designated 11 kilometers of the Buffalo River as impaired by nonpoint source pollution. In response to concerns over degrading water quality, USDA Natural Resources Conservation Service initiated a Watershed Protection Water Quality Enhancement Project and the NPS has developed a Water Resources Management Plan for the Buffalo River watershed. The BNR is afforded some protection through federal Wild and Scenic River designations and State of Arkansas Extraordinary National Resource Waters and Natural and Scenic Waterway designations.

Another potential stressor is recreational use of the subterranean resource which occurs from the nearly one million people who visit the BNR each year who take part in hiking, canoeing, caving, and other recreational activities. BNR's longest cave is also its most popular, with approximately 100 permit trips issued per year. Our study demonstrated that the longest caves are also the most biologically rich, and this constitutes a significant management challenge because the longest caves are also the most attractive for recreational caving. A high degree of recreational use and vandalism was observed in the longest caves, making the potential impact of trespass, archaeological looting, and vandalism in caves of the BNR of special concern. For example, in 2005, a vandal shot approximately 200 hibernating endangered bats (*Myotis grisescens*) in Cave Mountain Cave, ranked 12th in biological significance (27 May 2005 edition of NPS' The Morning Report).

The Arkansas Cave Resources Protection Act of 1989 affords limited protection to caves, and subterranean fauna are protected by Arkansas Game and Fish Commission Regulation No.1817 – Wildlife Pet Restrictions and the federal Endangered Species Act of 1973. The Federal Cave Resources Protection Act protects caves designated as significant on federal lands by allowing federal land managers to keep cave locations and names confidential and assign a penalty of up to $10,000 for abuses. All caves on NPS lands have been designated significant. Access to certain caves is restricted through a permitting system, while access to other caves is unrestricted. Permits to enter the restricted caves may be acquired from BNR headquarters. Approximately 100 recreational caving permits per year and five scientific study permits per year are issued. Over 1,000 recreational caving trips per year are undertaken in caves that do not require a permit (C. Bitting, NPS, unpublished data).

The NPS has invested approximately $0.6 million in protection of karst resources on the BNR, including the following expenditures: endangered bat species monitoring and research at approximately $20,000 per year for at least four years; 27 cave gates at approximately $9,000 each; and monitoring, research, and educational products at approximately $13,000 per year for the last 20 years. The NPS has also developed a park-wide cave resources management plan and a plan specifically for Fitton Cave. We recommend increasing protection of sites that ranked high in this analysis, and the improvement of public outreach regarding wise use of subterranean resources.

ACKNOWLEDGMENTS

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Table 3. Cave-obligate Animals of BNR. At least 20 species are known to be limited to, or adapted to, groundwater habitats (stygobites) or caves (troglobites) on the BNR.

Taxon	Common Name	Global Rank	State Rank	No. of Sites
Vertebrates				
Eurycea spelaea	grotto salamander	G4	S4	25
Arachnids				
Apochthonius sp.	cave false scorpion	GU	SU	7
Crosbyella distincta	cave harvestman	G1G2	SNR	1
Hesperochernes occidentalis	cave false scorpion	G4G5	SNR	10
Porrhomma cavernicola	Appalachian cave spider	G4G5	SNR	3
Crustaceans				
Brackenridgia sp.	cave pill bug	GU	SU	1
Caecidotea ancyla	cave isopod	G3G4	S1?	2
Caecidotea antricola	cave isopod	G5	SNR	4
Caecidotea dimorpha	cave isopod	G1G3	S1?	2
Caecidotea macropropoda	Bat Cave isopod	G2G3	SNR	1
Caecidotea stiladactyla	cave isopod	G3G4	S1?	6
Stygobromus alabamensis	Alabama cave amphipod	G4G5	SNR	8
Stygobromus ozarkensis	Ozark cave amphipod	G3G4	S1	5
Other Invertebrates				
Causeyella dendropus	cave millipede	GNR	SNR	1
Japygidae	undescribed cave dipluran	GU	SU	3
Litocampa sp. nov. # 1	undescribed cave dipluran	GU	SU	2
Litocampa sp. nov. # 2	undescribed cave dipluran	GU	SU	3
Pseudosinella sp. nov.	undescribed cave springtail	GU	SU	1
Spelobia tenebrarum	cave dung fly	GNR	SNR	3
Tricladida	cave flatworm	GU	SU	3

Note: Also shown are the global and state (or subnational) heritage status ranks assigned by The Nature Conservancy and NatureServe: 1- critically imperiled; 2 – imperiled; 3 – vulnerable; 4 – apparently secure; 5 – demonstrably secure; GU – unranked; and NR – not rankable (NatureServe, 2006).

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Appendix 1. Taxonomic list of all known fauna from subterranean habitats within the BNR.

Site names were assigned the following code numbers, alphabetically: 1 = Attic Cave; 2 = Baby Toad Cave; 3 = Back o' Beyond Cave; 4 = Bat Cave; 5 = Bear Pit; 6 = Bear Wallow Tube Cave; 7 = Beaver Den Shelter; 8 = Beechwood Mine; 9 = Bennett Mines; 10 = Big Bluff; 11 = Blowing Bear Cave; 12 = Blue Bluff Cave; 13 = Boat Creek Mine; 14 = Bolin Cave; 15 = Bonanza Mine; 16 = Broken Ladder Pit; 17 = Broken Stalactite Cave; 18 = Cave Mountain Cave; 19 = Chert Cave; 20 = Chuck's Forest Trail Cave; 21 = Cob Cave; 22 = Cold Spring; 23 = Coon Cave; 24 = Copperhead Cave; 25 = Corkscrew Cave; 26 = Crane Cave; 27 = Debbie's Delight; 28 = Den Cave; 29 = Dirt Cave; 30 = Dixie Girl Mine; 31 = Dogman Cave; 32 = Dome Room Shelter; 33 = Eagle Aerie Cave; 34 = Earl's Cave; 35 = Eden Falls Cave; 36 = Elephant Cave; 37 = Fallout Cave; 38 = Fire Place Cave; 39 = Fitton Cave; 40 = Fitton Spring Cave; 41 = Flat Cave; 42 = Flea Cave; 43 = Flowstone Façade Cave; 44 = Fool's Crawl; 45 = Forest Trail Pit; 46 = Forest Trail Ridge Cave; 47 = Fox Den Mine; 48 = Friday the 13th Cave; 49 = Gaddy Cave; 50 = Greasy Fissure Cave; 51 = Greenbriar Cave; 52 = High Water Shelter; 53 = Huchingson's Waterfall Cave; 54 = Icebox Cave; 55 = Indian Creek Cave; 56 = Indian Rockhouse Cave; 57 = Indian Rockhouse Sink Cave; 58 = In-D-Pendants Cave; 59 = John Eddings Cave; 60 = Keeton Sinkhole; 61 = Keyhole Cave; 62 = Kneebacker Cave; 63 = Ladder Cave # 2; 64 = Leatherwood Sink Cave; 65 = Len House Cave; 66 = Little Den Cave; 67 = Long Ear Mine; 68 = Magic Bean Cave; 69 = Mickey Mouse Pit; 70 = Middle Creek Spring Cave; 71 = Mike's Maze; 72 = Milk Cow Cave; 73 = Morning Star Mine # 05; 74 = Morning Star Mine # 06; 75 = Morning Star Mine # 07; 76 = Morning Star Mine # 15; 77 = Mr. Clean Cave; 78 = Natural Bridge Cave; 79 = Novack Spring Cave; 80 = Novak's Shed Cave; 81 = One Note Pit; 82 = Oven Bird Cave; 83 = Overlook(ed) Cave; 84 = Pa Pa Shelter Cave; 85 = Pack Rat Shelter; 86 = Pam's Blower Cave; 87 = Panther Cave; 88 = Paul's Paradise; 89 = Perry Cave; 90 = Peter Cave; 91 = Plum Field Pit; 92 = Prelunch Pit Stop; 93 = Pretty Clean Cave; 94 = Pretty Junkyard Spring Cave; 95 = Rat's Nest Cave; 96 = Rattlesnake Cave; 97 = Red Roof Shelter; 98 = Reddell Bluff Grotto; 99 = Roadcut Solution Hole; 100 = Rush Landing Spring Cave; 101 = Rush Spring; 102 = Saltpeter Cave; 103 = Sandstone Cave; 104 = Seashell Dome Cave; 105 = Shack Cave; 106 = Silver Hill Cave; 107 = Silver Hill Pit; 108 = Sinkhole Icebox; 109 = Six Shooter Cave; 110 = Sixteen Mine; 111 = Skull Pit; 112 = Small Arch Cave; 113 = Small Cave; 114 = Sneeds Creek Cave; 115 = Spider Cave; 116 = Springhouse at Steel Creek Ranger Cabin; 117 = Square Cave; 118 = Squirrel Pit; 119 = Steel Creek Campground Cave; 120 = Steeve's Mine; 121 = Stockman Cave; 122 = Stovepipe Cave; 123 = Summer Cave; 124 = Switchback Cave; 125 = Sycamore Cave; 126 = Toga Toga Cave; 127 = Tom Barnes Cave; 128 = Tom Watson's Bear Cave; 129 = Toney Bend Mine # 2; 130 = Toney Bend Mine # 3; 131 = Triangle Cave; 132 = Turtle Crack; 133 = Unnamed Mine at T17N = R15W = S12; 134 = Van Dyke Spring Cave; 135 = Villines Spring Cave; 136 = Walnut Cave; 137 = Waterfall Pit # 1; 138 = Waterfall Shelter; 139 = Wild Goose Cave; 140 = Willis Cave; 141 = Winding Staircase # 1; 142 = Winding Staircase # 2; and 143 = Wishbone Spring.

PHYLUM ANNELIDA
CLASS CLITELLATA
ORDER HAPLOTAXIDA
Family Lumbricidae
Genus undetermined (undet.), earthworm. Marion County (Marion): 83, 87, 102, 113, 129, 130. Newton County (Newton): 66, 77, 118, 119, 127. Searcy County (Searcy): 58, 91, 117.

ORDER Undet.
Hirudinea, leech. Newton: 134.

PHYLUM ARTHROPODA
CLASS ARACHNIDA
ORDER ACARINA
Family Cheyletidae
Cheyletus tenuipilis, mite. Newton: 55.
Family Ereynetidae
Ereynetes sp., mite. Newton: 59.
Family Histiomidae
Histiostoma sapromyzarum, mite. Newton: 5.
Family Ixodidae
Genus undet., tick. Searcy: 117.
Family Laelapidae
Genus undet., mite. Marion: 4, 23. Newton: 40, 65, 134.
Family Nanorchestidae
Nanorchestes sp., mite. Newton: 25.
Family Oribatulidae
Oribatula tibialis, mite. Newton: 118.
Genus undet. Marion: 67. Searcy: 117.
Family Parasitidae
Genus undet., mite. Marion: 23. Newton: 65, 134.
Family Podocinidae
Podocinum sp., mite. Newton: 79.
Family Pygmephoridae
Genus undet., mite. Newton: 42.
Family Rhagidiidae
Rhagidia sp., mite. Marion: 23. Newton: 34, 65, 134, 136. Searcy: 37.
Genus undet. Marion: 46, 73, 83, 102, 129, 130. Newton: 54, 104, 119. Searcy: 58, 117.
Family Trombiculidae
Genus undet., mite. Marion: 23, 46.

ORDER ARANEAE
Family Araneidae
Meta americana, cave orb weaver. Marion: 31, 56, 70, 87, 92, 102, 123. Newton: 25, 34, 35, 51, 53, 65, 78, 79, 104, 115, 119, 121, 128, 134, 136, 140, 142, 135. Searcy: 58, 91.
Family Dictynidae (funnel-weaving spider)
Cicurina brevis. Newton: 134.
Cicurina davisi. Newton: 134.
Cicurina sp. Marion: 23.
Family Linyphiidae
Centromerus latidens. Marion: 45.
Meioneta sp. Marion: 23.
Porrhomma cavernicola, Appalachian cave spider, G4G5. Marion: 4. Newton: 25, 65.
Family Lycosidae
Lycosa sp., wolf spider. Marion: 123. Newton: 7, 49, 104, 115, 121, 127, 128.
Family Nesticidae
Eidmannella pallida, cave spider. Newton: 134.
Family Pisauridae
Dolomedes sp., fishing spider. Marion: 129, 130. Newton: 116, 119. Searcy: 117.
Family Symphytognathidae
Maymena ambita, spider. Marion: 20. Newton: 34.
Family Theridiidae
Genus undet., spider. Searcy: 3.

ORDER OPILIONES
Family Phalangiidae
Bishopella sp., harvestman. Newton: 18.
Family Phalangodidae
Crosbyella distincta, cave harvestman, G1G2. Newton: 39.
Crosbyella sp., cave harvestman. Marion: 23, 110, 123. Newton: 18, 34, 39, 59, 65, 119, 121, 127, 128, 78, 134, 140. Searcy: 26.
Family Sabaconidae
Sabacon cavicolens, harvestman. Marion: 123. Newton: 77, 93.
Sabacon sp. Marion: 20, 23, 46, 67, 73, 74, 75, 83, 94, 102, 129, 130. Searcy: 117.
Family Sclerosomatidae
Leiobunum flavum, harvestman. Searcy: 3
Leiobunum sp. Marion: 45, 46, 73, 75, 102, 129. Newton: 34, 53, 59. Searcy: 3, 117.

ORDER PSEUDOSCORPIONES
Family Chernetidae
Hesperochernes occidentalis, cave false scorpion, G4G5. Marion: 23, 45, 123. Newton: 34, 40, 65, 134, 136. Searcy: 26, 37, 58, 117.
Family Chthoniidae
Apochthonius sp., cave false scorpion. Marion: 4, 23. Newton: 18, 34, 40, 134, 136

CLASS CHILOPODA
ORDER LITHOBIOMORPHA
Family Lithobiidae (centipede)
Genus undet. Marion: 67, 73, 102, 129, 130. Newton: 135. Searcy: 117.

CLASS DIPLOPODA
ORDER CHORDEUMATIDA
Family Paradoxosomatidae
Oxidus gracilis, hothouse millipede, G5. Newton: 119, 121, 127. Searcy: 122.
Family Trichopetalidae
Causeyella dendropus, cave millipede. Newton: 39.
Causeyella sp. Marion: 20, 23, 46, 83. Newton: 39, 40, 53, 78, 104, 127, 134, 140. Searcy: 37, 58, 117, 122.
Scytonotus granulatus, millipede, G5. Marion: 20.
Trigenotyla parca, cave millipede, G1G2. Newton: 18, 65.

ORDER POLYDESMIDA
Family Paradoxosomatidae
Undet. millipede. Newton: 127
Family Polydesmidae
Pseudopolydesmus minor, millipede. Newton: 59.
Pseudopolydesmus sp. Marion: 94.

CLASS INSECTA
ORDER ARCHAEOGNATHA
Family Machilidae (jumping bristletail)
Genus undet. Marion: 67, 130. Searcy: 117.

ORDER COLEOPTERA
Family Cantharidae (soldier beetle)
Genus undet. Marion: 46. Searcy: 117.
Family Carabidae (ground beetle)
Brachinus americanus. Newton: 118.
Platynus parmarginatus. Newton: 25
Platynus tenuicollis. Marion: 123. Newton: 18, 40, 59, 135.
Platynus sp. Marion: 102, 49, 77, 118, 127, 131, 134. Newton: 93. Searcy: 117.
Family Chrysomelidae (leaf beetle)
Genus undet. Newton: 128
Family Coccinellidae (lady beetle)
Genus undet. Newton: 119
Family Cryptophagidae
Cryptophagus sp., silken fungus beetle. Newton: 18
Family Curculionidae (weevil)
Genus undet. Marion: 130
Family Dytiscidae (predaceous diving beetle)
Agabus sp. Newton: 43, 135

Hydaticus sp. Newton: 43
Family Elateridae (click beetle)
Genus undet. Marion: 46
Family Histeridae (hister beetle)
Genus undet. Searcy: 117.
Family Leiodidae (round fungus beetle)
Ptomaphagus cavernicola. Marion: 23, 45, 123. Newton: 18, 24, 34, 39, 65, 78
Ptomaphagus shapardi. Newton: 39
Ptomaphagus sp. Marion: 45, 46, 67, 73, 75, 83, 130. Newton: 54, 104, 118, 127, 136, 140. Searcy: 58, 117
Family Scarabaeidae (scarab beetle)
Genus undet. Searcy: 117.

Family Staphylinidae (rove beetle)
Atheta troglophilia, Rove Beetle, G1. Newton: 18
Athetini sp. Newton: 59
Bisnius cephalotes group. Marion: 123
Quedius erythrogaster. Newton: 25
Quedius sp. Marion: 45, 46, 67, 83, 102, 129, 130. Newton: 7, 34, 39, 54, 65, 104, 118, 127, 134, 136, 140. Searcy: 58, 117.

ORDER COLLEMBOLA (springtails)
Family Entomobryidae
Pseudosinella aera. Marion: 4.
Pseudosinella argentea. Marion: 4, 23, 45. Newton: 18, 34, 65, 136.
Pseudosinella collina. Marion: 4.
Pseudosinella folsomi. Newton: 18, 59.
Pseudosinella sp. nov., undescribed cave springtail. Newton: 134
Pseudosinella violenta. Marion: 23.
Tomocerus flavescens, golden springtail, G5? Marion: 23, 45, 70. Newton: 25, 34, 59, 65, 134, 136. Searcy: 3
Tomocerus lamelliferus. Marion: 4.
Tomocerus sp. Marion: 46, 67, 73, 74, 75, 83, 102, 129, 130.
Tomocerus sp. Searcy: 58, 117.
Genus undet. Newton: 104, 119, 135.
Family Hypogastruridae
Hypogastrura antra. Newton: 34
Genus undet. Marion: 129, Newton: 118.
Family Isotomidae
Folsomia nivalis. Marion: 23.
Isotoma notabilis, remarkable springtail. Marion: 45.
Proisotoma ballistura antigua. Marion: 45.
Family Onychiuridae
Onychiurus pseudofimetarius. Newton: 93.
Onychiurus sp. Newton: 18.
Genus undet. Marion: 46.
Family Sminthuridae
Arrhopalites clarus, springtail, G4. Newton: 18, 34, 39, 59, 65, 77, 136.
Arrhopalites pygmaeus, pygmy springtail. Marion: 4, 23. Newton: 18, 24, 34, 134.
Lepidocyrtus sp. Newton: 65.
Ptenothrix ptenothrix marmorata. Newton: 134.
Sminthurides hyogramme. Newton: 5.
Genus undet. Marion: 46, 67, 73, 74, 75, 83, 130. Newton: 5. Searcy: 117.

ORDER DERMAPTERA
Family Labiduridae (earwig)
Genus undet. Newton: 59. Marion: 123.

ORDER DIPLURA
Family Campodeidae
Litocampa sp. nov. # 1, undescribed cave dipluran. Marion: 123. Newton: 39.
Litocampa sp. nov. # 2, undescribed cave dipluran. Newton: 39, 40. Searcy: 3.
Litocampa sp., cave dipluran. Marion: 17, 23, 46, 75, 83, 129, 130. Newton: 34, 54, 59, 104, 121, 127, 134, 136, 140. Searcy: 58, 37, 117, 122.
Family Japygidae
Cenojapyx sp. nov., undescribed cave dipluran. Marion: 31. Newton: 93.
Genus undet. Marion: 129. Newton: 39, 121.

ORDER DIPTERA
Family Calliphoridae
Calliphora sp., blow fly. Newton: 118.
Family Cecidomyiidae
Peromyia sp. Newton: 5.
Genus undet. Marion: 67, 73, 74, 75. Newton: 5.
Family Chironomidae (bloodworm)
Genus undet. Marion: 31, 67, 74. Newton: 49.
Family Culicidae (mosquito)
Anopheles punctipennis. Newton: 128.
Genus undet. Marion: 70. Newton: 34, 39, 65, 119, 121, 127, 134, 140. Searcy: 3, 58.
Family Drosophilidae (pomace fly)
Genus undet. Newton: 59.
Family Empididae (balloon fly)
Tachypeza sp. Newton: 39.
Family Heleomyzidae (fly)
Aecothea specus. Marion: 23, 94.
Amoebaleria defessa. Marion: 83, 94. Newton: 24, 39, 128. Searcy: 3.
Heleomyza brachypterna. Newton: 25.
Genus undet. Marion: 4, 46, 47, 67, 73, 74, 75, 102, 123, 129. Newton: 35, 40, 43, 49, 77, 79, 86, 93, 127, 131, 135, 140. Searcy: 91, 117, 122.
Family Mycetophilidae (fungus gnat)
Exechiopsis sp. Newton: 128.
Macrocera nobilis. Marion: 6, 46, 73, 83, 129. Newton: 39, 77, 127. Searcy: 58, 117.
Genus undet. Marion: 20, 23, 67, 74, 75, 102, 113, 130.
Family Phoridae (humpbacked fly)
Megaselia cavernicola. Marion: 4, 23, 70. Newton: 34, 65, 134.
Genus undet. Marion: 46, 67, 73, 74, 75, 83, 129, 130. Newton: 127. Searcy: 117.
Family Psychodidae (moth fly)
Genus undet.. Marion: 75, 83, 129. Newton: 104. Searcy: 117.
Family Sciaridae (dark-winged fungus gnat)
Corynoptera sp. Newton: 59
Genus undet. Marion: 46, 67, 73, 74, 75, 83, 129, 130. Newton: 39. Searcy: 117.
Family Sphaeroceridae (small dung fly)
Leptocera caenosa. Newton: 59.
Spelobia tenebrarum, cave dung fly. Marion: 94. Newton: 24, 25.
Telomerina flavipes. Newton: 59.
Genus undet. Marion: 46, 67, 73, 74, 83, 102, 129, 130. Newton: 104. Searcy: 58, 117.
Family Tipulidae (crane fly)
Pedicia sp. Newton: 131
Genus undet. Marion: 20, 46, 67, 73, 74, 75, 83, 102, 129, 130. Newton: 49, 119. Searcy: 117.

ORDER EPHEMEROPTERA
Family Leptophlebiidae (mayfly)
Paraleptophlebia sp. Newton: 39, 55.

ORDER HEMIPTERA
Family Reduviidae (tread-legged bug)
Genus undet. Marion: 23, 45.

ORDER HETEROPTERA
Family Gerridae (water strider)
Gerris remigis. Marion: 94. Newton: 40, 59, 135.

ORDER HOMOPTERA
Family Cicadellidae (leafhopper)
Genus undet. Newton: 118.

ORDER HYMENOPTERA
Family Braconidae
Genus undet., parasitic wasp. Marion: 67, 73, 74, 75, 129. Newton: 136
Family Formicidae
Camponotus americanus, carpenter ant. Marion: 130
Tapinoma sessile, ant. Marion: 123
Genus undet. Marion: 46, 67, 83, 130. Newton: 34, 39, 131. Searcy: 117.

Family Sphecidae (mud dauber)
Genus undet. Searcy: 3
Family Vespidae (wasp)
Genus undet. Marion: 73, 97, 129. Searcy: 98.

ORDER LEPIDOPTERA
Family Pyralidae (moth)
Genus undet. Newton: 127.
Family Undet. Marion: 45, 67, 73, 74, 75, 83, 102, 123, 129, 130. Newton: 49, 93, 119. Searcy: 58, 117.

ORDER MEGALOPTERA
Family Corydalidae (hellgrammite)
Genus undet. Newton: 39, 104.
Family Myrmeliontidae (ant lion)
Genus undet. Newton: 14.

ORDER NEUROPTERA
Family Chrysopidae (lacewing)
Genus undet. Newton: 39.

ORDER ORTHOPTERA
Family Acrididae (grasshopper)
Genus undet. Searcy: 117. Newton: 118.
Family Raphidophoridae (cave cricket)
Ceuthophilus gracilipes. Marion: 6, 31, 46, 67, 73, 74, 75, 83, 92, 94, 102, 113, 123, 129, 130. Newton: 24, 35, 39, 40, 43, 49, 59, 77, 79, 99, 104, 116, 118, 119, 128, 135. Searcy: 3, 58, 91, 117, 122.
Ceuthophilus silvestris, woodland camel cricket. Marion: 45. Newton: 25
Ceuthophilus sp. Marion: 13, 15, 17, 23, 38, 46, 47, 50, 56, 70, 87, 102, 109, 112, 130, 132, 133. Newton: 2, 7, 12, 19, 29, 32, 34, 35, 40, 42, 48, 51, 53, 54, 59, 60, 61, 63, 64, 65, 66, 69, 71, 72, 78, 79, 80, 81, 88, 93, 95, 103, 115, 119, 120, 121, 125, 126, 127, 128, 131, 134, 136, 138, 140, 142. Searcy: 3, 11, 26, 36, 37, 89, 90, 96, 106, 107, 139
Family Tettigoniidae
Pterophylla camellifolia, Northern True Katydid. Newton: 68
Genus undet. Searcy: 117.

ORDER PHASMIDA (walking stick)
Family Diapheromeridae
Diapheromera sp. Newton: 111
Family Phasmatidae
Genus undet. Searcy: 117.

ORDER PLECOPTERA
Family Chloroperlidae
Alloperla sp., Green Stonefly. Newton: 39
Family Leuctridae (stonefly)
Zealeuctra sp. Newton: 40

ORDER PSOCOPTERA
Family Psyllipsocidae
Psyllipsocus ramburii, cave barklice. Marion: 45, 46, 67, 74, 75, 83, 102. Newton: 34, 65, 127. Searcy: 58.

ORDER SIPHONAPTERA
Family undet., flea. Newton: 18, 34, 65,

ORDER THYSANURA
Family Lepismatidae (silverfish)
Genus undet. Marion: 45, 83. Newton: 51, 119, 121.

ORDER TRICHOPTERA
Family Hydropsychidae (net-spinning caddisfly)
Homoplectra doringa. Newton: 39.

CLASS MALACOSTRACA
ORDER AMPHIPODA
Family Crangonyctidae
Stygobromus alabamensis sensu latu, Alabama cave amphipod, G4G5. Marion: 23, 70. Newton: 18, 24, 25, 48, 77, 128.
Stygobromus ozarkensis, Ozark cave amphipod, G3G4S1. Marion: 13. Newton: 39, 40, 59, 93.
Stygobromus sp. Marion: 75, 100. Newton: 104, 121, 136. Searcy: 3.
Family Gammaridae
Gammarus minus, epigean amphipod. Marion: 22, 101, 143. Newton: 43, 59

ORDER DECAPODA
Family Cambaridae
Orconectes neglectus neglectus, ringed crayfish, G5T4T5. Newton: 59.
Orconectes sp. Newton: 35, 39, 40, 53, 78, 93, 134, 135, 140.

ORDER ISOPODA
Family Armadillidiidae (sowbug)
Armadillidium nasatum. Marion: 73, 74, 130.
Armadillidium vulgare. Marion: 73, 74, 102, 130. Searcy: 117.
Family Asellidae
Caecidotea ancyla, cave isopod, G3G4S1? Newton: 40, 93
Caecidotea antricola, cave isopod, G5SNR. Newton: 34, 59, 65, 135.
Caecidotea dimorpha, Cave Isopod, G1G3S1? Marion: 123. Searcy: 122.
Caecidotea macropropoda, Bat cave isopod, G2G3. Newton: 128.
Caecidotea stiladactyla, cave isopod, G3G4S1? Marion: 70. Newton: 18, 35, 39, 59, 79.
Caecidotea sp. Marion: 23, 31, 33, 56, 100, 143. Newton: 24, 25, 43, 66, 104, 116, 121, 131, 134. Searcy: 3, 58.
Lirceus sp., epigean isopod. Marion: 56, 94. Newton: 24, 39, 40, 55, 119, 134, 135. Searcy: 58, 122.
Family Ligiidae (sowbug)
Ligidium sp. Newton: 104. Searcy: 58, 117.
Family Trichoniscidae
Amerigoniscus sp., cave sowbug. Marion: 20.

CLASS MAXILLOPODA
Order undet., copepod. Marion: 13.

CLASS OSTRACODA
Order undet., ostracod. Newton: 104.

CLASS SYMPHYLA
Order undet., pseudocentipede. Marion: 130.

PHYLUM CHORDATA
CLASS ACTINOPTERYGII
ORDER CYPRINIFORMES
Family Cyprinidae
Genus undet., minnow. Newton: 39, 59, 127, 135.

ORDER PERCIFORMES
Family Centrarchidae
Lepomis sp., sunfish. Newton: 39, 127, 134.

ORDER SCORPAENIFORMES
Family Cottidae
Cottus carolinae, banded sculpin, G5S4. Newton: 39, 40, 59, 134, 135.

CLASS AMPHIBIA
ORDER ANURA
Family Bufonidae
Bufo americanus, American toad, G5S5. Newton: 2
Family Hylidae
Hyla sp., tree frog. Searcy: 91
Pseudacris crucifer crucifer, Northern spring peeper, G5T5S5. Newton: 118
Pseudacris sp., chorus frog. Searcy: 91.
Family Ranidae
Rana catesbeiana, bullfrog, G5S5. Searcy: 58.
Rana clamitans melanota, green frog, G5T5S4. Marion: 123. Newton: 40.
Rana palustris, pickerel frog, G5S4. Marion: 75, 130. Newton: 39, 40, 43, 59, 93, 104. Searcy: 91.
Rana sphenocephala, Southern leopard frog, G5S5. Newton: 93
Rana sylvatica, wood frog, G5S4. Marion: 15, 45, 87, 130. Newton: 21.

Searcy: 117.
Rana sp. Newton: 7.

ORDER CAUDATA
Family Ambystomatidae
Ambystoma tigrinum, tiger salamander, G5S3. Newton: 69.
Family Plethodontidae
Eurycea longicauda melanopleura, dark-sided salamander, G5T4S4. Marion: 30, 67, 123, 130. Newton: 7, 24, 39, 40, 43, 48, 49, 59, 79, 127, 134, 135, 140.
Eurycea lucifuga, cave salamander, G5S4. Marion: 15, 20, 23, 27, 45, 46, 67, 70, 73, 83, 92, 94, 102, 108, 113, 123, 129, 130. Newton: 5, 24, 25, 34, 39, 40, 43, 48, 49, 62, 65, 68, 71, 78, 79, 93, 103, 105, 111, 116, 118, 120, 127, 128, 131, 134, 135, 136, 140. Searcy: 3, 11, 58, 91, 107, 117.
Eurycea multiplicata griseogaster, graybelly salamander, G4T4S4. Marion: 70. Newton: 79.
Eurycea spelaea, grotto salamander, G4S4. Marion: 15, 23, 56, 123, 129. Newton: 5, 24, 25, 39, 40, 48, 53, 54, 59, 66, 77, 93, 116, 119, 127, 134, 140. Searcy: 3, 58, 122.
Plethodon albagula, slimy salamander, G5S5. Marion: 13, 15, 23, 27, 31, 45, 47, 67, 70, 73, 74, 130. Newton: 5, 24, 25, 34, 39, 40, 43, 48, 59, 65, 66, 69, 77, 78, 79, 93, 118, 119, 127, 134, 140, 141. Searcy: 3, 91, 117.
Plethodon angusticlavius, Ozark zigzag salamander, G4S3. Marion: 46, 83, 87, 129, 130. Newton: 34, 40, 65, 79, 93, 116, 118, 127, 134, 142. Searcy: 91.
Family Salamandridae
Notophthalmus viridescens louisianensis, central newt, G5T5S5. Newton: 5, 118. Searcy: 91.

CLASS AVES
ORDER CICONIIFORMES
Family Cathartidae
Coragyps atratus, black vulture, G5S4. Newton: 10. Searcy: 139.

ORDER PASSERIFORMES
Family Tyrannidae
Sayornis phoebe, Eastern phoebe, G5S4. Marion: 4, 16, 56, 67, 70, 87, 102, 123, 129, 130. Newton: 1, 12, 14, 82, 118, 119. Searcy: 3, 117.

CLASS MAMMALIA
ORDER ARTIODACTYLA
Family Cervidae
Odocoileus virginianus, white-tailed deer, G5S4. Marion: 67.

ORDER CARNIVORA
Family Mephitidae
Mephitis mephitis, striped skunk, G5S4. Marion: 4.
Family Procyonidae
Procyon lotor, Northern raccoon, G5S4. Marion: 23. Newton: 39, 93, 121.
Family Ursidae
Ursus americanus, American black bear, G5S3. Marion: 6. Newton: 126, 128

ORDER CHIROPTERA
Family Vespertilionidae
Corynorhinus townsendii ingens, Ozark big-eared bat, G4T1S1. Marion: 4, 23, 76. Searcy: 124.
Eptesicus fuscus, big brown bat, G5S4. Marion: 123. Newton: 18, 39, 59. Searcy: 89, 90.
Myotis grisescens, Gray Bat, G3S2. Marion: 123. Newton: 18, 25, 39, 42, 55, 59, 135. Searcy: 3, 26, 37, 90.
Myotis leibii, Eastern small-footed bat, G3S1. Newton: 18.
Myotis lucifugus, Little Brown Bat, G5S3? Newton: 18, 39.
Myotis septentrionalis, Northern long-eared bat, G4S2. Marion: 15, 47, 70. Newton: 18, 25, 39, 140.
Myotis sodalis, Indiana bat, G2S2. Marion: 4. Newton: 18, 25, 39, 42, 55.
Myotis sp. Newton: 55, 93. Searcy: 26
Pipistrellus subflavus, Eastern pipistrelle, G5S4. Marion: 4, 15, 23, 31, 46, 47, 50, 87, 102, 109, 113, 123, 129, 130. Newton: 5, 9, 18, 19, 24, 25, 34, 35, 39, 40, 42, 48, 53, 54, 55, 59, 63, 65, 66, 69, 72, 79, 86, 93, 104, 111, 116, 118, 119, 121, 126, 127, 128, 134, 135, 140, 142. Searcy: 3, 26, 37, 58, 89, 90, 91, 117, 122.

ORDER INSECTIVORA
Family Soricidae (shrew)
Genus undet. Searcy: 91.

ORDER RODENTIA
Family Castoridae
Castor canadensis, beaver, G5S4. Marion: 22. Newton: 40, 134, 135.
Family Muridae
Mus musculus, house mouse, G5SE. Newton: 34.
Neotoma floridana, Eastern woodrat, G5S4. Marion: 4, 13, 16, 17, 23, 45, 46, 56, 83, 87, 94, 97, 102, 123, 130. Newton: 12, 14, 34, 35, 40, 48, 61, 64, 65, 69, 77, 84, 85, 93, 95, 119, 120, 121, 134, 135, 136. Searcy: 3, 26, 37, 58, 122, 137.

ORDER XENARTHRA
Family Dasypodidae
Dasypus novemcinctus, nine-banded armadillo, G5S4. Searcy: 91.

CLASS REPTILIA
ORDER SQUAMATA
Family Colubridae
Diadophis punctatus, ringneck snake, G5S4? Marion: 130. Searcy: 91, 117.
Thamnophis sp., garter snake. Searcy: 91.
Family Viperidae
Agkistrodon contortrix contortrix, Southern copperhead, G5T5S5. Searcy: 91.

ORDER TESTUDINES
Family Emydidae
Terrapene carolina triunguis, three-toed box turtle, G5T5S4. Marion: 132. Searcy: 91, 117. Newton: 5, 126.

PHYLUM MOLLUSCA
CLASS GASTROPODA
ORDER BASOMMATOPHORA
Family Carychiidae
Carychium exile, ice thorn snail, G5. Newton: 53.
Carychium sp. Newton: 104. Searcy: 58.

ORDER STYLOMMATOPHORA
Family Philomycidae
Megapallifera ragsdalei, Ozark mantleslug. Newton: 116. Searcy: 58.
Family Physidae
Physella gyrina, tadpole physa, G5SNR. Newton: 59, 135.
Family Polygyridae
Inflectarius inflectus, shagreen, G5S5. Marion: 45.
Patera perigrapta, engraved bladetooth snail. Marion: 20, 67, 73, 130. Newton: 10, 39. Searcy: 3, 117.
Family Zonitidae
Genus undet. Marion: 87. Newton: 34, 65. Searcy: 106

PHYLUM NEMATA
Class undet., roundworm. Newton: 141.

PHYLUM NEMATOMORPHA
CLASS GORDIACEA
ORDER GORDIOIDEA
Family Gordiidae
Gordius sp., Gordian worm. Newton: 48, 66, 141.

PHYLUM PLATYHELMINTHES
CLASS TURBELLARIA
ORDER TRICLADIDA
Family Dendrocoelidae
Dendrocoelopsis americana, cave flatworm, G3G4SNR. Newton: 119, 128.
Family undet.
Cave flatworm. Marion: 23, 31. Newton: 141.

ABSTRACTS FROM THE 2006 NATIONAL SPELEOLOGICAL SOCIETY CONVENTION BELLINGHAM, WASHINGTION

Biology

Ultraviolet Radiation Sensitivity in Cave Bacteria versus Surface Bacteria

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Previous studies have shown that subsurface bacteria are not more sensitive to ultraviolet (UV) light than surface bacteria. However, earlier studies from our lab have shown that cave bacteria are more sensitive to UV light than surface bacteria. In order to quantify starting material and to have a more quantitatively accurate assessment of differences between surface and cave bacteria exposed to UV light, we measured number of colony forming units per millimeter using cell counting and series dilution counts. Cave bacteria from Left Hand Tunnel in Carlsbad Caverns, New Mexico and surface bacteria from the surface above Carlsbad Caverns were grown on low nutrient (R2A) medium, were exposed to 0 seconds, 50 seconds or 100 seconds of UV light (200µWatts/cm2/s), were incubated at 15ºC for 6 days and colonies were counted. In addition, DNA repair capacity was quantified by exposing the organisms to various doses of UV-C radiation and measuring survivability. Results were compared to *Escherichia coli* and *Pseudomonas aeruginosa*. Gram status and pigmentation were also determined. Surface bacteria are predominately pigmented and gram positive, while the cave bacteria do not show either of these predominances. Preliminary results seem to agree with the earlier results from our lab, but survivability data suggest that cave microbes have not lost all of their capacity to repair UV-damaged DNA. Cave bacteria appear to have adapted to the absence of UV light in the cave environment and have lost traits that protect them from UV, such as thicker cell walls and pigmentation.

Scanning Electron Microscopy Analysis of Lechuguilla Cave Ferromanganese Enrichment Cultures

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Ferromanganese deposits (FMD) in Lechuguilla Cave (Carlsbad Caverns National Park) contain a diverse community of microorganisms with unique bacterial and mineralogical morphologies. To investigate whether similar morphologies are seen in culture, scanning electron microscopy (SEM) analysis was performed on sloppy agar gradient tubes containing a carpet tack (reduced Fe) and inoculated with FMD and punk rock from the EA Survey and PHD Room of Lechuguilla Cave in 1999. Cultures were incubated in a dark, 15ºC incubator for seven years. Some samples had reddish tubercles formed on the surface of the tack, while other regions had solid, mineral-like formations. Samples of aseptically extracted tubercles and mineral deposits were dried either by vacuum or ethanol/HMDS and sputter coated with gold-palladium (Au-Pd). With SEM we observed coccoid cells and biofilms in samples dried via both methods. Many cells appeared to have attachment-like structures. Cells ranged in diameter from about 0.5µm to about 1.5µm. Using energy dispersive spectroscopy, larger cell formations were found to have high Fe and oxygen (O) peaks and lower carbon (C) peaks. Conversely, smaller cells had C peaks greater than Fe peaks. In addition, ropy biofilms were seen coating many of the cells. Mineralogical formations, such as FeO stars found in samples taken from caves, were found also in the cultures. This preliminary study shows that punk rock material inoculated into Fe-gradient tubes is able to oxidize Fe to form mineralogical structures, similar to those seen in caves, and tubercles containing actively growing bacteria.

Diversity Comparisons between Microbial Mats and Endosymbiont Gut Communities Associated with the Cave-dwelling *Androniscus dentiger* (Isopoda: Oniscidae) from the Frasassi Caves, Italy

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Because symbiosis is a pervasive driver of evolution and adaptation, it is important to understand the functional relationships between symbiont and host. The 16S rRNA gene sequence diversity of microbial mats (as a food source) from the Frasassi Caves (Grotta Grande del Vento – Grotta del Fiume), Italy, and endosymbiont communities from the guts of *Androniscus dentiger* isopods were analyzed to test the hypothesis that constant ingestion of the microbial mats supplants gut community bacterial populations. Molecular analyses of microbial mats from sulfidic cave stream segments revealed the prevalence of *Epsilonproteobacteria* (45% of clones screened), and low taxonomic diversity overall based on the number of diagnosed taxonomic affiliations and nearly saturated rarefaction curve estimates of clone libraries. Other notable taxa included the *Deltaproteobacteria* (20%), *Bacteriodetes* (19%), *Verrucomicrobia* (5%), *Gammaproteobacteria* (3%), *Betaproteobacteria* (3%), *Chloroflexus* (2%), *Planctomycetes* (2%), and the candidate division OP-11 (1%). Members of the *Bacteriodetes* are commonly associated with animal gut flora, and some of the mat organisms are also closely related to other species identified from the deep-sea hydrothermal vents. Although the *A. dentig*er gut communities are currently being assessed, *Desulfotomaculum* spp. have been found in the gut of *Procellio scaber*, a cousin to *A. dentig*er. In the mats, only *Desulfocapsa thiozymogenes* was found and the isopods could be acquiring and retaining *D. thiozymogenes*. This is the first study to explore the possible ecological significance of microbial mat communities, not just as a food source for cave-dwelling organisms, but in the establishment of endosymbiotic communities.

Epsilonproteobacteria in Terrestrial Caves and Springs with Sulfidic Waters

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Recently an outburst of research has centered on testing the long-standing dogma that microbes are distributed everywhere because of their overwhelming abundance, metabolic tenacity, and small size aiding in widespread dispersal. Many biogeography studies, however, have been conducted in habitats with high connectivity (e.g., marine habitats), and there have been relatively few studies to characterize microbes living in habitats where dispersal is assumed to be limited. Hypothetically, microbes from the terrestrial subsurface, and specifically caves and karst settings, would have less opportunity to exchange genetic information because of barriers (e.g., hydrologic, geologic, or stratigraphic) to gene flow. Toward rigorously testing the concept of microbial biogeography, we studied *Epsilonproteobacteria* from sulfidic terrestrial habitats (6 caves and 12 springs). Based on the diversity of retrieved 16S rRNA sequences, we identified novel groups that immediately supplement the current knowledge of environmental *Epsilonproteobacteria*. At 99% sequence similarity, there were >35 lineages identified. Cave systems had more lineage diversity compared to springs, which tended to have <3 lineages present. High diversity, even within a site, may be explained by the fact that sequenced genomes from the *Epsilonproteobacteria* lack DNA mutation repair genes. This is an interesting evolutionary caveat because genetic variation may enhance the adaptability of these bacteria to geochemically changing or stressful conditions. In contrast, however, sequences from one lineage were retrieved from 8 geographically-disparate sites, suggesting that rampant mutation was not occurring and that modern geographic isolation may not be a driving factor in speciation.

Does Bad Taxonomy Serve Conservation Purposes? The Case of the *Cicurina cueva* Complex (Araneae: Dictynidae) in the Vicinity of Austin (Travis Co.), Texas

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Urban development in central Texas is a threat to many habitats, especially caves. About a dozen cave-restricted arthropod species are protected by the Endangered Species Act, while many others are classified as species of concern. The latter category includes *Cicurina cueva* Gertsch, an eyeless spider known from only two caves in the vicinity of Austin. A proposition for a new highway threatens the ecological integrity of Flint Ridge Cave, one of the two known localities for *C. cueva*. Correctly assessing the distribution and species limits of this taxon appears crucial for any conservation decisions. An intense sampling effort resulted in the collection of *Cicurina* spp. from ~70 caves in Travis, Hays, and Williamson counties. About 1kb of mtDNA (CO1) was sequenced for 170 spiders and the phylogenetic approach of Paquin & Hedin (2004) was used to assign species names to juveniles. Likelihood and Bayesian analysis gave similar results and extended the occurrence of *C. cueva* from two to ~20 adjacent caves. These results suggest that *C. cueva, C. bandida* and *C. reyesi* are the same biological entity. Furthermore, spermathecal variation is not correlated with geography or mtDNA phylogeny, providing further support for synonymy. The genetic structure of *C. cueva* populations shows restricted gene flow between caves. Inadequate taxonomy or lack of collections that artificially increases the biological uniqueness of caves or species rarity is not a sound basis for conservation purposes. Long-term strategies require adequate taxonomic basis and knowledge, which is still, unfortunately, largely deficient.

The Flux and Distribution of Organic Carbon in Caves - A Conceptual Model and Preliminary Data

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In general, there are three sources of organic carbon in cave waters. The first are sinking streams entering caves. These streams, in terms of carbon flux, are not very different from highly oligotrophic, unproductive desert streams - nearly all of the carbon comes from outside such as leaf fall in the desert and the transport of leaves into the cave in streams. The second source is exchange with groundwater. However, not all cave streams intersect groundwater and the direction of exchange is also unclear. These problems are also common to surface streams via the hyporheic. Finally, water percolating through soil and epikarst brings organic carbon into the cave. We focus our attention on the carbon brought in by sinking streams and epikarst percolation. Using Organ Cave in West Virginia and Postojna Cave in Slovenia as examples, we attempt to measure these fluxes. We also note differences in spatial distribution of the two fluxes, with sinking streams being very patchy in their effect relative to the comparatively ubiquitous percolating water. Finally we show that most of the organic carbon entering through percolating water is dissolved organic carbon, which is at least an order of magnitude greater than the flux due to copepods and other invertebrates coming in through drips. This is in spite of the fact that the flux of animals can be greater than one animal per drip per day. A careful consideration of carbon fluxes may require a modification of the commonly held view that caves are food poor.

A Biological Assessment of Caves in Lava Beds National Monument, California

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Lava Beds National Monument contains more than 500 lava tube caves and features, with more than 28 miles of passages that are home to a variety of cave-adapted organisms. We studied cavernicolous invertebrates in 29 caves between 2 June and 4 August 2005. Most of these caves had a dark zone varying from just above freezing to about 12 °C, where relative humidity varied from about 85 to 100%. In 193 biological samples, 1,511 specimens were recorded. Of the animals recorded, 22.6% were flies (Diptera), 19.3% were springtails (Collembola), 16% were spiders (Araneae), 12.2% were millipedes (Diplopoda), 11.7% were mites (Acari), and 5.3% were diplurans (Diplura). A variety of other animal taxa make up the remaining 12.9%.

Two common, large troglobitic invertebrates are the millipede *Plumatyla humerosa* and the dipluran *Haplocampa* sp. Common and nearly ubiquitous springtails of the family Tomoceridae (probably *Tomocerus* spp.) are important members of the Lava Beds cave community, and account for more than half of all springtails. Woodrats (*Neotoma* spp.) and bats (Vespertilionidae) are especially important in bringing nutrients into these caves, and bacteria and fungi growing on their feces provide energy to other cave animals.

Notable taxa include a terrestrial troglobitic isopod (Trichoniscidae), which was rarely encountered, and a troglobitic pseudoscorpion (Arachnida), which is almost certainly new to science. Richness of the taxa showed no discernable patterns with respect to their association with different lava flows, vegetation zones, or elevation.

The Aquatic Community of Tumbling Creek Cave (Taney County, Missouri): Results of a Decade of Monitoring

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A stratified sampling scheme was developed and initiated in 1996 to monitor The Tumbling Creek Cavesnail (Gastropoda: Hydrobiidae: *Antrobia culveri*), in Tumbling Creek Cave, Taney County, Missouri. An evident decrease in snail numbers in the late 1980s prompted concern for this snail endemic to a single cave in southwest Missouri. This report summarizes a decade of observations on the population status of the cavesnail and the other members of the cave stream community within the study transect. Thirty-two monitoring trips have provided data that support our concern that the cavesnail population has been decreasing. No snail has been seen in the transect area since the fall of 2002, although individuals still occur in an isolated area upstream from the study area. We hypothesize that surface land-management activities and the associated increase in erosion and subsequent silt deposition in the streambed have had a major negative impact on snail populations. However, populations of stygophilic and stygobitic crustaceans (amphipods and isopods) have fluctuated without distinct trends throughout the period of monitoring. Stygophilic limpets (*Ferrisia fragilis*) have experienced "boom and bust" population profiles during the study. Surface snails (*Physa* sp.), absent for several years, seem to be repopulating the cave stream. Surface land use within the cave recharge zone has been altered, surface restoration is in progress, and we continue to conduct cave stream monitoring trips twice yearly.

Caves of National Parks and Public Lands

Bugs, Lights, and Maps at Great Basin National Park

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Over the past five years, several projects have been conducted at Great Basin National Park to better understand and manage caves. In addition to Lehman Caves, which is open to the public, the park contains 45 additional caves, including the highest elevation, deepest, and longest caves in Nevada. From 2002–2004, 36 of these were mapped and inventoried for physical resources. In 2003, biological inventories were conducted at 10 caves, with two new species found. The results of these mapping and inventory trips, plus past data, were compiled into a Cave Resource Condition Report. Current cave projects include biological inventories of 15 additional caves and a relighting project in Lehman Caves to reduce lampflora and improve the cave lighting.

Mapping Surface Geology to Protect Cave and Karst Resources

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Jewel Cave is a vast cave system in the Mississippian Madison Formation in the southern Black Hills of South Dakota. Strong barometric winds in the cave have demonstrated that the 228 km presently known represent only about 3% of the total volume. Maps of cave passages overlain by detailed surface geologic maps have demonstrated a spatial relationship between cave passages and geologic contacts, providing a general indication of where undiscovered passages are likely to exist. Hydrologic connections from the surface into the cave are related to the surface exposure of two permeable subunits in the lower part of the overlying Minnelusa Formation. These infiltration zones are areas where the cave is susceptible to impacts from surface activities. Cave potential and vulnerability maps have been used as a predictive tool to anticipate where the undiscovered portions of the cave might be found and where potential impacts to the cave may occur. This information has been used to facilitate cave protection by land exchanges, mineral withdrawals, and recommendations for highway realignment.

Quantification of Bacterial DNA in Clastic Sediments and on Artificial Substrates in Mammoth Cave Aquifers

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Bacterial DNA concentrations in clastic sediments at the Charon's Cascade study site and in biofilms on artificial substrates at Eyeless Fish Trail, Mystic River, Owl Cave, Roaring River, and the Hawkins-Logsdon River confluence were determined with quantitative Real-Time PCR. Homogeneous fine sandy sediment like that found at Charon's Cascade can be found in streams throughout Mammoth Cave and affords a homogeneous substrate for comparative measurements of native bacterial DNA concentration wherever it has been deposited. Artificial substrates consisting of ceramic beads composed partially of crushed limestone were deployed in triplicate at five study sites to capture bacterial biofilm growth over a one year period in cave streams. Triplicate qRT-PCR reactions were performed to amplify eubacterial 16S SSU-DNA from each DNA extract and compared to a standard curve consisting of triplicate reactions on *E. coli* genomic DNA of accurately known concentration. Results were normalized by calculating the total yield of DNA per gram of sediment or substrate. Bacterial DNA concentrations in saturated sediments at Charon's Cascade averaged 1261 ng/g with a standard error of ±11%. Artificial substrates at Eyeless Fish Trail yielded 476 ± 81 ng/g, Mystic River yielded 6.3 ± 1.6 ng/g, Owl Cave yielded 3463 ± 258 ng/g, Roaring River yielded 1398 ± 114 ng/g, and Hawkins/Logsdon River yielded 5136 ± 2152 ng/g. The same technique can be used with DNA extracted from filters to determine the concentration of bacterial DNA in water over the range of 2-20,000 ng/L (parts per trillion).

The 2006 Memorandum of Understanding between the Bureau of Land Management, the National Speleological Society, and the Cave Research Foundation: Its Origins, Purpose and Possibilities

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The United States Bureau of Land Management (BLM) is a multiple-use land management agency administering more than 1.1 million km^2 of federal lands and resources in the Western states. Those resources include thousands of caves ranging from the small to the highly significant, and millions of acres of karst lands. The mission of the BLM has grown over the years, and has included positive input from the National Speleological Society (NSS) and Cave Research Foundation (CRF) back to the early 1960s, relating to cave and karst protection and management. The BLM's ability to manage land for its cave and karst resources is largely due to the long term partnerships we have enjoyed. For over four decades, the BLM has worked with the NSS and CRF, organizations dedicated to the preservation and scientific investigation of caves. These organizations have worked on national laws and found, mapped, and shared scientific knowledge about caves and karst lands. NSS and CRF volunteers helped develop Leave No Trace cave safety and ethics brochures and videos and have worked on conservation and restoration activities in and around caves. An Memorandum of Understanding (MOU) between the BLM, CRF, and the NSS is part of the ongoing long-term commitment to recognizing all aspects of speleology and the best management of our valued cave and karst lands. Other assistance agreements can be tiered off of the MOU, such as Cooperative Management Agreements, Cooperative Agreements, Challenge Cost Share Projects, and Volunteer Agreements.

New Cave Invertebrates: Inventory Results at Sequoia/ Kings Canyon National Parks

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From 2002 to 2004, park staff aided scientists from Zara Environmental in conducting a biologic inventory in 31 of the park's 240 known caves. As many as 50 different species were found in individual caves. The ranges of many species were extended, and 27 entirely new species were identified. Park staff are now planning a monitoring phase of this project in order to better understand these species.

Managing Multidisciplinary Cave and Karst Research at Carlsbad Caverns National Park

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There is a wide range of multidisciplinary cave and karst research being conducted in Carlsbad Caverns National Park. The park actively supports research by identifying research needs, streamlining environmental compliance, and obtaining funding for projects. In order to prevent the loss of institutional memory, the park has developed a system for tracking and archiving samples as well as keeping track of monitoring equipment and data in park caves. Geologic, mineralogic, and speleologic inventory data are collected during survey and exploration of all park caves and stored in a digital database to assist researchers in locating appropriate sample sites. Interim and final reports are tracked and archived so that it will be easy for park managers and future researchers to see what work has been done, what data are available, and identify research needs. This model for managing research has proved very successful to both park managers and researchers and could easily be applied to other parks, agencies, and groups managing large and small cave and karst projects.

Systematic Inventory and Survey of the Caves in Grand Canyon — Parashant National Monument, Arizona

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

Environmental DNA Analysis Techniques for Microbial Studies at Oregon Caves National Monument

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A variety of DNA analysis techniques were evaluated to provide a means for monitoring bacteria and fungi at Oregon Caves National Monument. Sediment samples from study quadrants clustered at the South End of the cave were taken directly from impacted tourist trails and from areas in the same quadrants some distance off the trails. DNA was extracted from the sediments and amplified using bacterial- or fungal-specific primers in PCR reactions to produce copies of 16S or 18S SSU-DNA fragments, respectively, for molecular analysis. Bacterial amplifications were carried out with universal eubacterial 16S primers substantially documented in the literature and routinely used for molecular studies of bacterial communities by many investigators. Fungal amplifications were initially attempted with some eukaryotic primer combinations found in the literature, but those conditions proved either too nonspecific or too limited in taxonomic range for environmental studies. Therefore, conditions were optimized using other primers and reaction conditions until an improved fungal protocol was demonstrated. Fluorescent fragment analysis was considered as a means for broad but indeterminate viewing of bacterial communities and was considered uninformative without prior identification of species. Quantitative Real-Time PCR was used successfully to determine the quantity of bacterial or fungal DNA extracted from a given mass of sediment; however, inconsistent physical and geochemical parameters such as particle size, surface area, and matrix consistency made site-to-site comparisons irrelevant. Ultimately, cloning and sequencing of bacterial DNA from sediments and fungal tissue from cave surfaces led to likely classifications for many bacteria, fungi, and protozoans.

Cave Conservation & Management Session

Management Successes at Nutty Putty Cave, Utah

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The recent number of cave rescues and the increased awareness of potential caving dangers have caused the Utah State Trust Lands Administration to consider various options regarding Nutty Putty Cave, including potential permanent closure to prevent a future fatality. Since its discovery, Nutty Putty Cave has required four full callout rescues; two of these rescues were over Labor Day Weekend 2004. The Trust Lands Administration had hoped to enter into a proposed lease arrangement in 2005 with several different organizations which had interest in managing the cave, but those efforts failed for various reasons. The drowning of four people in a Provo cave in 2005 likely affected those organizations' decision not to further consider a lease. The Trust Lands Administration has since signed a Memorandum of Understanding with the Timpanogos Grotto to gate the cave and implement a new management plan to improve training, safety, and resource protection.

The Timpanogos Grotto gated the cave on May 24, 2006, and is allowing access only to sufficiently prepared cavers. If this approach can eliminate the safety problems in Nutty Putty Cave, the threat of the cave's total closure will be avoided. With over 6000 visitors per year, the successes or failures at Nutty Putty Cave could largely affect how caves are managed throughout the state.

Bat Conservation in the Borderlands

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Bat protection enjoys many successes in the United States, but what happens to our migratory bats when they head south of the border? The situation in Mexico is very different, where subsistence-level living creates unique environmental pressures on wildlife and habitats. Bats, in particular, are greatly misunderstood and often feared; thus entire colonies of mixed species may be destroyed in the mistaken belief that they are all vampires. In addition, caves harboring some of the largest colonies in the world are often inadvertently damaged through inappropriate guano mining techniques. Bat Conservation International and its partners have instigated the documentation of bat caves in Mexico's northern states (Tamaulipas, Nuevo Léon, Coahuila, Chihuahua, and Sonora) in order to discover new colonies and assist in the conservation and management of these sites. To date, almost 90 caves have been visited. The data suggest that the top 19 sites may have held over 40 million bats, but have slightly over 18 million, a decline of 56%. In addition, BCI and its partners provide local outreach and assistance through meetings with local conservationists, landowners, and community leaders. By utilizing BCI-produced materials such as the book *Murciélagos Cavernícolas del Norte de México,* we are able to reach large numbers of local people with little previous bat education. Through this work we are setting more realistic conservation priorities, and are better able to assist with the successful management of our shared resources.

Geology and Geography

Karst Waterfalls – Features of Growing Interest

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Spectacular karst waterfalls — actually very large and complex tufa dams, occur in Croatia (Plitvice Lakes), China (Jiuzhaigou), and elsewhere. Scenic and spectacular, these waterfalls are actually growing taller as the tufa accumulates around the roots of trees and shrubs. Some reach heights of 30–50m, widths of 200–300m, and impound beautiful lakes behind them. Carbonate deposition is caused by a complex of physical and biological processes. The water issues from cold water springs and quickly becomes oversaturated in respect to carbonate. Partial pressure is lowered to atmospheric and the water warms. Plants extract large amounts of CO_2 from the water, playing a major, probably dominant, role in carbonate precipitation. In North America (Texas examples are Capote Falls and Gorman Falls), biological processes play little or no role in tufa deposition on waterfalls. Elsewhere are tufa deposits at waterfalls on major rivers such as Haungguoshu Waterfall and the Nine Dragon Waterfall Group in China that occur in much higher energy environments. Chinese examples are further complicated by the fact that the gorges below some waterfalls originated as cave passages that are now unroofed. Detailed study of Haungguoshu reveals that stream piracy occurred there. Although clearly the net result of long-term scarp retreat and erosion, including the pirating of river flow through a cave system and its subsequent unroofing to form a spectacular box gorge, the lip of the waterfall is mantled by 5–8 m of tufa that is actively being deposited today.

Cave Levels in Florida

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The concept of cave level is fundamental for understanding the geomorphic evolution of karst landscapes. In the Paleozoic limestones of Mammoth Cave, passage levels formed in response to base level changes of the Green River. Within the Cenozoic carbonates of Florida, sea level determines base level. Forty years ago, Florida hydrogeologists proposed, without data, that cavernous porosity in the Floridan Aquifer formed during sea-level still stands during the Quaternary. Our data affirm this hypothesis, and suggest a variety of paleo-watertable elevations. In air-filled caves, recent data from cave surveys and existing cave maps reveal levels at 5m, 12–15 m, 21 m, and 30 m above sea level over broad areas. The levels do not follow the large-scale structure of the Floridan aquifer. They do align with nearby, coastal marine terraces formed during times when sea level, and thus the water table, was higher than present. Data from well-cavities (e.g., bit drops) and existing maps of underwater Florida caves demonstrate passage levels at depths of 15 m, 40 m, 70 m, and 90–120 m below the modern water table. These below water table levels generally match the depth below sea level of distant submerged terraces and paleoshoreline features identified using multibeam bathymetric data in the Gulf of Mexico.

Geophysical Surveys Up-Flow of Gypsum Cave, Idaho

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Idaho's 4023-m long Gypsum Cave lava tube was created by a flow that came from an eruptive source over 15 km away. The entrance is at the distal end of a collapse sink. Reasoning that a continuation may be present up-flow from the entrance, a magnetometer survey was conducted in 1999. A well-shaped, negative, linear magnetic anomaly of as much as 5200 nano-teslas (nt) and 26-m wide crest-to-crest was present for over 25 m. Total field in this area is 54,000 nT. To better define the anomaly, a gradient-array resistivity survey was conducted. Prior experience dictated that the huge magnetic anomaly would yield an impressively high resistivity anomaly. Instead, values of less than 150 ohm-meters were found over the anomaly accompanied by 1500 ohm-meters at each side, the exact opposite of what was expected. One explanation is for the cavity to be filled to the ceiling with conductive salts. In 2004, the magnetometer survey was continued with an unambiguous negative anomaly traced for one kilometer. One part of the anomaly, surveyed for 110 m, measured over 7500 nt deep, and 35 m wide crest-to-crest. In 2005, gradient-array and dipole-dipole resistivity surveys conducted over a section ~0.5 km upflow from the entrance gave the same results as before - nearly a "short-circuit" over the magnetic anomaly. Surveys are continuing to find a suitable place to enter this prospect and to find an explanation for the anomalous resistivity results.

Geology of a Mystery Microbe: Reticulated Filaments in Speleothems

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Some carbonate speleothems commonly host fossil microbial filaments. We report herein on a new form of reticulated filament found in a variety of speleothems worldwide. Reticulated filaments are usually found inside speleothems by etching with weak (5-10%) hydrochloric acid before imaging in a scanning electron microscope (SEM). They often show a higher concentration of carbon, which apparently allows them to resist the acid etching. We currently have imaged 134 individual filaments from six different caves and one surface sample. Most come from pool precipitates in Carlsbad Cavern, Hidden, Cottonwood, and Endless Caves, Guadalupe Mountains, NM. Additional examples are found in cave pearls from Tabasco, Mexico, a lava tube in the Cape Verde Islands and one example in desert varnish from NM. Reticulate filaments are 1–75 µm in length. Two populations overlap in size, one averaging 0.5 µm and a second averaging 0.9 µm in diameter. The reticulated pattern resembles an open fish-net tube. Two varieties occur, one with diamond-shaped chambers that spiral, and a more common one with hexagonal-shaped chambers in a line. Some filaments are hollow, others are solid; a few samples are collapsed or even torn open. We hypothesize that reticulated filaments are the fossilized remains of an unknown microbe that is apparently common in damp cave environments. Efforts to identify living examples have so far failed, but cave microbes are notoriously difficult to culture. We are interested if finding out if anyone else has observed these filaments in living or fossil cave systems.

Ground Water Tracing in Rutherford County, Tennessee, with Emphasis on the BFI Landfill Area

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Rutherford County is located in the Central Basin and is underlain primarily by the cavernous Ridley Limestone of Ordovician age. The focus point of the investigation was around the BFI landfill in Walterhill, which is a large regional landfill seeking a permit for expansion. Dye tracing was also conducted from two sinkholes near the MTSU Coliseum and from a sinkhole near Dillton. Eight successful traces were conducted defining flow paths to six springs. Prior to this investigation, there was no information regarding the recharge area of five of these springs. The results have shown that significant areas around Walterhill cannot suffer from ground water contamination from the landfill if it were to leak pollutants to the subsurface. A trace near the Miller Coliseum shows that ground water from parts of this MTSU property moves to the stream in Black Fox Cave and then emerges at a large spring on the VA Hospital property. This spring is impounded to form a small lake containing a large trout population. Thus, a spill or leak at the Coliseum could endanger the fish. All of the springs at these two areas of investigation contribute water to surface water supply intakes for the City of Murfreesboro and the Consolidated Utility District. These intakes are located on impounded waters of the East Fork below the Walterhill Dam. Finally, one trace was successful in delineating a significant portion of Black Fox Spring, which is the headwaters of a TWRA protected wetlands.

Microbially enhanced carbonate dissolution in the Edwards Aquifer of Central Texas

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The eastern boundary of the Edwards Aquifer in Central Texas (USA) is marked by a transition to saline, anaerobic to disaerobic, H_2S-rich "bad-water" (BW). Down-hole video-logs from the Edwards Aquifer Authority (San Antonio) of uncased BW wells (depths from 100 - 400 m) reveal a complex network of fractures, solution pockets, and conduits, but also white colloids and filaments in the water column and thick biofilms coating the rocks. Despite some regional stratigraphic and structural variability, the BW is supersaturated with respect to calcite and undersaturated with respect to gypsum. *In situ* microcosms consisting of ~1 cm^3 calcite chips (totaling 10 g) were deployed in four BW wells for three months. Both sterile (excluding microbes from colonizing the chips) and non-sterile (allowing microcosms to colonize) microcosms were used to test if calcite dissolution was enhanced by microbes. Non-sterile chips lost ~3-5X as much weight as sterile chips in water supersaturated with respect to calcite; surfaces were also heavily weathered and had a variety of microbial cell morphologies on them. Gypsum occurred in some biofilms, despite the waters being undersaturated with respect to gypsum. These results indicate that surfaces were not in equilibrium with the surrounding waters and that microbes locally mediated both calcite dissolution and gypsum precipitation. Various microbial groups can generate acidity metabolically; genetic characterization identified *Epsilonproteobacteria*, sulfur-oxidizers that produce sulfuric acid. This study provides insight into the unique BW habitat and the potential role of microbes in deep subsurface carbonate weathering and karstification.

Aqueous Geochemical Study of Tufa Creek, Shannon County, Missouri

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Carbon dioxide off-gassing due to agitation as Tufa Creek gradually falls 25 m in elevation over a 583 m stream reach is the principal mechanism for calcite deposition along this fen-fed stream. Water chemistry results support this conclusion. The stream water warmed from 14^o to 19^o C. The pH increased from 7.02 to 7.96 standard units. Specific conductivity decreased from 0.570 to 0.488 millimhos/cm. Alkalinity decreased from 368 to 321 mg/L. Dissolved calcium decreased from 157 mg/L to 117 mg/L. Magnesium decreased only marginally from 156 to 148 mg/L. Total hardness (calcium and magnesium) decreased from 313 to 265 mg/L. Chloride remained statistically unchanged from 7.6 to 7.5 ppm. Sulfate decreased from 5.7 to 4.7 ppm. Calcite saturation increased from −0.03 to 0.85. PCO_2 equilibrated from −1.51 to −2.56, but did not achieve atmospheric (−3.5) before entering the river. Biological mediation perturbs water quality data at a sedge-muck section of the forested fen. Tufa formation correlates with elevation drop. Comparing Tufa Creek data to nearby Ebb and Flow Spring, and Thompson Creek reveals that sufficient stream mineralization and optimal stream geometry are needed for freshwater calcite deposition. Tufa deposition rates along Tufa Creek are less than those predicted by the Plummer-Wigley-Parkhurst rate law. We speculate this is due to inhibiting effects of dissolved Mg^{2+} or rate changes effected due to periodic gravel scour on the stream.

The Potential Extent of the Jewel Cave System

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Research at Jewel Cave has shown a direct relationship between airflow at the entrance and the prevailing atmospheric pressure. A previous study of this barometric airflow estimated a total minimum cave volume of 1.1×10^8 m^3 (4×10^9 ft^3), of which less than three percent has been discovered. This study estimates the extent of undiscovered cave passages for Jewel Cave, as well as that of nearby Wind Cave. The estimate is based on: 1) the thickness and distribution of the Madison Limestone; 2) the potentiometric surface of the Madison aquifer; 3) the location and extent of potential geological obstacles; 4) the three-dimensional distribution of the cave systems within the host rock; and 5) the "cave density" at Jewel Cave and Wind Cave. Based on the minimum cave volumes and an estimated 9.3×10^{10} m^3 (3.3×10^{12} ft^3) of available limestone, the overall cave-to-rock ratio is 0.18%. This is at the low end of the range of known "cave density" values for Jewel Cave and Wind Cave, 0.15–0.59%.

A more recent airflow study indicates a larger minimum cave volume of at least 2.0×10^8 m^3 (7×10^9 ft^3). With that value, the overall ratio of cave to rock volume would be nearly the same as the average "cave density" for the known portions of Jewel Cave and Wind Cave. Most of Jewel Cave's volume extends toward Wind Cave, and vice versa, and the data support the possibility that the two volumes could be part of one large cave system.

Cave Detection on Mars

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Exploration of the Martian subterranean environment offers a unique avenue for: (1) investigating promising localities to search for extinct and/or extant life; (2) identifying areas likely to contain subterranean water-ice; (3) evaluating the suitability of caves for the establishment of human habitation areas; and, (4) investigating subsurface geologic materials. On Mars, use of remote sensing will be the most efficient means of cave detection. Due to the long and widespread volcanic history of Mars, the low gravity, possible low seismicity, and low rates of processes that could collapse or fill in caves, lava tubes are expected to be common and widespread. Their detection on Mars involves: (a) development and interpretation of thermal dynamic models of caves to identify the thermal sensor requirements for detection; (b) evaluation of available imagery of both Earth and Mars for their utility in cave detection; and, (c) collection, analysis and interpretation of ground-based measurements of thermal dynamics of terrestrial caves (and then relating these data to detection of Martian caves). Our models suggest detectability will be influenced by time of day and geologic substrate. Certain bands in THEMIS IR satellite data are best for cave detection and we have examined cave size in relation to thermal detectability. Thermal data from terrestrial caves support model results indicating imagery capture at the appropriate time of day is critical to detection. These data also reveal numerous interesting thermal characteristics of caves, which will improve our understanding of thermal properties of caves on both Earth and Mars.

Speleothems in Non-Spelean Environments

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In 2005, members of the Southern California Grotto discovered features typical of California speleothems in an abandoned mine near Los Angeles. Because they are in a mine rather than a cave, they do not fit the long-standing definition of *speleothem*. In the 50+ years since its definition in the *NSS News*, this definition has become increasingly awkward. We propose that the term be redefined in a refereed journal, clarifying that 1) speleothems are characteristic of caves but not limited to them; and 2) morphology, not mineralogy, determines whether a feature is or is not a speleothem.

Atmospheric Conditions at two Entrances of a Gypsum Cave

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This study was conducted to determine the relative difference in the atmospheric conditions (temperature and humidity) at the surface, at two entrances, and in a passage 15 m from each entrance of a gypsum cave near

Carlsbad, New Mexico. The higher entrance and passage is walking size, the lower entrance and passage is stooping size. The hypothesis was that there exists a relative difference in atmospheric conditions. At the entrance the temperature and the humidity would be higher than the passage, which would be cooler and less humid. The size of the passage would affect the temperature and humidity. The bigger the passage, the hotter and more humid it will be. Data were collected using wet-bulb/dry-bulb on the surface, at the entrances and 15 m down passage from each entrance. There was no pattern to changes in temperature and humidity between each entrance and associated passage. Nor was there any correlation in changes between upper and lower entrances and associated passage temperatures and humidity. Possible factors than might have influenced the atmospheric conditions include: additional entrances, cave configuration (it is a maze cave), impact of human presence, and faulty data collection techniques.

Spelean History

History of the Cascade Grotto: The First Thirty-Five Years

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The Cascade Grotto's application to become an Internal Organization was signed May 21, 1951 by ten National Speleological Society members, mostly living in the Seattle area. In those days of two-lane highways, no limestone cave was known in western Washington. Oregon Cave was a fourteen-hour drive from Seattle. The lava tube caves of Mount St. Helens and Mount Adams were believed to be few and hidden deep in wilderness forests. And the closest cave in Canada was believed to be Nakimu Cave in Glacier National Park. Diligent searches by the new group began to unearth limestone caves south of Mount Baker and high above Snoqualmie Pass, but the obstacles were too great and the grotto became inactive around 1955 after publishing just six issues of *Cascade Cave Report*. Almost at once, however, new cavers and new access produced a spectacular rejuvenation with a strong international orientation. A new publication, *The Cascade Caver,* appeared in 1961. The grotto subsequently emphasized international vulcanospeleology. It also pioneered American glaciospeleology, but its studies of the summit geothermal caves of Mount Baker were cut short by the 1980 eruptions of Mount St. Helens. There the Cascade Grotto undertook twenty follow-up trips to study the caves and pseudokarsts in the "Red Zone".

Schroeder's Pants Cave

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In the fall of 1947, brothers George and Lyndon Lyon, along with Herb Schroeder, discovered a beautifully decorated cave in New York that they would explore and lead school groups into for the next 18 years. On one of those explorations, Herb Schroeder wound up pants-less due to his size and the tightness of some of the squeezes. The cave would become known the world over as Schroeder's Pants Cave. It was featured in numerous NSS News articles in the late 1940s and early 1950s, and talked about throughout the Northeastern Grottos. Twenty-three year old James Gentry Mitchell of Waterville, Ohio, who was living and working in the Boston area, came to Dolgeville, New York on 13 February 1965, with two inexperienced cavers from the Boston Grotto. The three men began exploring the cave to the point where James was lowered into a seventy foot (21.33 m) bell-shaped room. Freezing water was pouring on him at this point and eventually led to his death. The National Capital Rescue Team was called to the scene but ultimately, and not without controversy, determined that it was not possible to get the body out. The cave was dynamited shut. In June of 2006, a group of experts, along with James Gentry Mitchell's brother, made a return trip to the cave to finally retrieve the remains of James for burial at Mitchell Lake, Ohio.

Two 1851 Accounts of Grotta del Cane

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Located in the Phlegrean Fields volcanic area near Naples, Italy, Grotta del Cane contains a concentration of CO_2 sufficient to anesthetize dogs (hence the name Cave of Dogs). As such it long was touted as a tourist curiosity. Recently the authors encountered two 1851 English-language observations which occurred a few days apart. Information gleaned from these accounts, including both relevant published information, and the important unpublished data of Rosario Varriato, suggest that the cave is artificial. It was probably excavated in a Greek colony during pre-Roman times, in pyroclastic material, as a "sudatorium" (excavated sauna). An illustration in A. Kircher's 18th Century "Mundus Subterraneus" showing the cave as an unroofed space in a travertine basin reflects imagination by the illustrator. Later, probably in Roman times, the cave was invaded by anesthetizing levels of CO2. This was demonstrated with dogs until about 1930. The cave was closed from 1970 to 1998 as a safety measure. In 2001 it was reopened and cleaned. Currently, the cave is T-shaped. The entrance is 1.9 m high and 0.9 m wide. Its passage slopes downward at 20° to the middle of a rectangular space about 3 m high and 9 m long. A hole in this room extends to the ceiling but is choked. The midpoint temperature is about 45° C, and the cave is hotter farther inside. Current CO_2 concentration data are not available.

Human and Medical Sciences

Caving-Related Fears Part 2: Behavioral Causes and Potential Solutions

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Anxieties and/or fears are common in caving, from brief situational heartrate acceleration (due to, for example, significant exposure, hairy climbs, or long tight squeezes) to actual panic attacks (from challenging one's claustrophobia, acrophobia [fear of heights], or potamophobia [fear of rivers or running water]). Some people are reticent to even try caving because of the fear of becoming anxious. The development of most anxiety and its related fears can be appreciated with behavioral or learning theory (the advanced version of the commonly understood reward system). By understanding the basic principles by which anxiety and fears form, it is much easier to intervene in the system that is creating, maintaining, and/or worsening these fears, and provide relief for the affected caver. When a caver wishes to better manage anxiety or overcome a significantly interfering caving situation that intrudes on the caver's ability to enjoy the sport (*e.g.*, tight crawls, hairy climb up or climb downs), there are strategies to address these anxieties, and allow cavers to participate more fully and enjoyably in their sport.

The Caving Experience

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New and experienced cavers in Arkansas and New York were interviewed and observed concerning what attracts them to their pursuit and how they go about caving and preparing to cave. The research approach, methods, and preliminary findings concerning the discovery, access, social relations, adventure, risk, and sensory appeal of caving are presented here before the final study is complete in an effort to share preliminary results as soon as possible. Theories in leisure and recreational user research and theories of place connectedness, introduced here, are important additions to the environmental social study of caves. Findings from this project are intended to contribute to the literature concerning the experience of a recreational user of the natural environment, particularly cavers. Furthermore, documenting and analyzing cavers' actions and beliefs can add to the development of conservation policies that impact the recreational use of natural environments.

Why We Love and Hate Caves

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Caves harbored nearly all symbols for at least 80% of our existence. Language may have begun in caves, as our two earliest concepts may have been light/dark and above/below, simple dualities made most vivid and memorable in caves via many states of consciousness. Caves soon exemplified ecologic reciprocity with spirits by mediating female/male, life/death, old/new, being/becoming, mortal/immortal, horizontal/vertical, community/ individual, physical/mental, dreaming/awakeness, and cyclic timelessness/linear change. Based on archeology, whatever prompted cave importance via symbolic systems or otherwise remained intact from at least 78,000 to 14,000 years ago. The value of caves declined in the Middle East when social stratification and writing 6,000 years ago reduced reciprocity with nature and tolerance of consciousness diversity. When the concept of absolute good and evil spread in late Roman times, the negative view of caves dominated as they were most distant from sky gods, of low material value, and didn't serve leaders. Except for some caves blessed by saints, there was little cave use for a thousand years in the West or in Islamic areas. By the Renaissance, an unintended result of the desanctification of worlds below the sky was to promote capitalism, science, and democracy rather than fear-based theocracies. The Romantic sublime united cave fear and beauty. By the mid-1800s, these world views helped make caves as interesting to visit as they had been during the birth of our subspecies.

Risks to Cavers and Cave Workers from Exposures to Low-Level Ionizing a Radiation from ^{222}Rn Decay in Caves

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Human health risks posed by exposure to elevated levels of ^{222}Rn in caves are not well documented. Various studies throughout the world have detailed the often very high ^{222}Rn gas concentrations in caves and exposures to cavers and commercial tour guides and other employees, but without a consequent assessment of the overall impact on human health. Although ^{222}Rn concentrations in caves are considered high relative to most above ground dwellings, the levels identified are also considered to be low for ionizing α radiation. Low-level ionizing radiation impacts on human health are deduced by application of the linear no-threshold theory (LNT) of radiation carcinogenesis. Comprehensive reviews of the published literature and an understanding of exposure time suggests that commercial cave workers (*e.g.*, tour guides) and commercial ^{238}U-mine workers are both exposed for the same number of hours per month (~170 h), but cave workers are exposed to much lower ^{222}Rn concentrations than are mine workers. Cavers will generally be exposed for a smaller number of hours per month. Risk estimates suggest that cavers will likely be subject to insignificant risks, but that cave workers may be subject to low-level risks of developing lung cancers from elevated levels of ^{222}Rn gas concentrations in caves.

The Petzl S61 NEST Rescue Stretcher

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While rarely seen in North America, the Petzl S61 NEST rescue stretcher is the dominant caving stretcher in Europe. It was developed in cooperation with Speleo Secours Français, the French cave rescue group. It is highly adapted for rescue from the narrow vertical caves predominant in alpine regions. An integral harness and PVC flaps contain the patient. The stretcher design assists in spinal stabilization. His position is maintained by adjustable leg stirrups with integral support blocks for the feet. A flexible plastic skid plate protects caver and stretcher during evacuation through low ceiling passages. Multiple carry handles and lifting straps permit horizontal or vertical evacuation. It weighs 11.5 kg and measures 1.9 m long by 0.5 m wide, and can be further reduced in volume by removing rigid support slats and a shoulder-level metal stay. Thus configured the stretcher may be rolled for transport. It may also be folded along its long axis. With a price of nearly US$2000 (as of early 2006) the S61 NEST is a highly specialized device best suited to specialist cave rescue teams rather than general caving and wilderness rescue.

International Exploration

Houping 2006 - Exploration In South-western China

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A multi-national team of six returned to the Houping karst area situated in the mountainous Chongqing Provincial Municipality in southwest China, where previous expeditions had partially explored segments of an extensive karst system. Despite multiple illnesses, the team surveyed more than 10 km of new passage in Er Wang Dong and San Wang Dong, taking advantage of the dry season to push multiple shaft series down to the flood-prone active stream levels of the caves. A complex network of large draughting streamways was explored and left continuing at the end of the expedition, in some cases heading off our maps. The combined flow of the currently documented streams accounts for only a small fraction of the six cumecs of water that flows from the area's primary resurgence. The cultural (and gastro-intestinal) adventures of rural Chinese village life, made our subterranean discoveries all the more memorable, and the hospitality of the people of Er Wang Dong Village and the government of Wulong County was amazing. Attempts to connect Er Wang Dong and San Wang Dong were unsuccessful in 2006, however newly discovered passages in both caves present exiting possibilities for a connection during a future expedition. Such a connection would result in a system more than 40 km in length, and one of the great caves of the world.

South China - Xilian'05 and Nandan '06

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The China-based, Hong Meigui Cave Exploration Society and international cavers conducted an expedition to Xilian in 2005 and Nandan in 2006. Xilian is located on the north edge of Hunan Province. The potential of this area was seen as so good, a planned trip to the Zhangjiajie area was canceled and the team rode five additional hours north where 7.4 km of nice cave was mapped in 6 days. Nandan is a small city in northwest Guangxi Province. Just east of the city, the Nandan River disappears into the edge of a cone karst plateau, creating great river passages and giant paleo borehole. Undocumented caves are so numerous in the area that one hardly knows where to start. On Hong Meigui's 4th Nandan expedition, 9.8 kilometers of cave were surveyed bringing the area total to just shy of 40 km. With each of these trips, our fascination with China has grown. The caves delight in both quality and quantity amid a culture of endless surprises. The Chinese view of karst in very practical terms makes any research into better understanding the hydrology a welcome enterprise. From a pure caving perspective, we're exploring and documenting world-class cave development.

Xibalba Mapping and Exploration Team: Belize, 2006

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Over 30 cavers from 12 states worked in Belize for a month during February-March of 2006. This is the 6th consecutive year we have worked there under the auspices of the Institute of Archaeology of Belize (Dr. Jaime Aiwe, Director). Efforts were concentrated this year in 4 caves: Painted, Chapat, Yaxteel (Yaxteel Ahau) and Blue Hole #3 (Jaguar) Cave. Mapping was completed in Painted and Blue Hole #3 and the main passages of Chapat were delineated. Above-water survey in lower Yaxteel was completed. There was significant archaeological support work done by our team in Painted and Upper Yaxteel. A dye trace and underwater survey were started in Lower Yaxteel. Several days were spent laying groundwork for the 2007 trip, and one member spent significant time cataloging the Institute's library and a large photo collection compiled from past expedition members' pictures. Work in the Chiquibul System, one of our initial objectives, was deferred to another year due to concerns about safety and security. These are nearly all large river caves, voluminous, and well decorated in places, and the dry passages frequently contain quantities of Mayan artifacts.

Sensitive Ecological Areas And Species Inventory Of Actun Chapat Cave, Vaca Plateau, Belize

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This project is the first effort to synthesize information on both invertebrate and vertebrate observations from a Belize cave. Based on limited field research and a review of literature, we identified two ecologically sensitive areas, and developed a species inventory list containing 41 vertebrate and invertebrate morphospecies in Actun Chapat, Vaca Plateau, west-central Belize. Actun Chapat contains two ecologically sensitive areas: (1) a large multiple species bat roost, and (2) a subterranean pool containing troglobites and stygobites. The inventory list is a product of sporadic research conducted between

1973 and 2001. Ecological research in this cave system remains incomplete. An intensive systematic ecological survey of Actun Chapat, with data collection over multiple seasons using a suite of survey techniques, will provide a more complete inventory list. To minimize human disturbance to the ecologically sensitive areas, associated with ecotourism, we recommend limited to no access in the areas identified as "sensitive."

2004 Expedition of the Sangkulirang Peninsula in Eastern Kalimantan

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In the August 2004 Cyndie Walck and Shane Fryer assisted a Nature Conservancy expedition to Eastern Kalimantan to assess future protective status for four karst areas that included orangutan habitat on the Sangkulirang peninsula. The multidisciplinary expedition involved geographers, entomologist, arborist, biologist, archeologist and geologist just to name a few. A large effort was placed on understanding cave development, cave biological communities and hydrologic systems of the areas.

Ecotourist caving in guangxi province, china

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China is home to half the world's karst, and Guangxi province is renowned for its spectacular fengcong and fenglin tower karst. Several organizations are now offering ecotourist-type cave trips to this region, and three of us from the USA spent two weeks in October with one of them, visiting a dozen caves in Leye and Fengshan provinces, several of them unsurveyed, and conferring with the Karst Institute of Guilin about a program of American expeditions. Our guides were local cavers, including the Flycats club in Leye. Until recently, harvesting formations for sale was rampant in some of these caves until the government outlawed it. Ecotourism in the caves provides an alternative means of income for the local people and may offer the best protection for them yet. Cave-for-pay in undeveloped caves is a mixed bag, and we made numerous suggestions for better conservation (especially flagging routes through areas of delicate floors). But most of the caves are large and spectacular and very easy to explore, and could result in less overall impact when led by those with a stake in the cave's resources. China also has many spectacular show caves ranging from small operations controlled by local villages, to large tourist meccas with carved marble walkways and interestingly translated signs.

Entering the Jaguar's Realm: Discovery of Pictographs and Glyphs in a Belizean Cave

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The recent discovery of Painted Cave is significant, as it represents only the ninth cave known to contain painted Maya writing and the first to be found in Belize. The Painted Cave corpus is unique as the glyphs are large and executed entirely in red. A rare depiction of a jaguar, a symbol of Maya royalty and common occupant of cave entrances, accompanies the text.

National Karst Database Initiatives

Subterranean Biodiversity Databases: Data Acquisition and Quality Control

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There are several problems associated with data acquisition, including (1) intellectual property rights, (2) issues of security and accessibility, and (3) data compatability. Each data entry is typically the result of considerable effort both in the field and in the laboratory, and there are typically hundreds if not thousands of entries from dozens of scientists and collectors. A great deal of concern has been raised about accessibility of data, but little advantage has been taken of the possibilities of making location information less precise than would be needed to find the cave. Different researchers have proposed often elaborate database structures whose complexity is often in inverse proportion to the amount of data collected. A minimum database was proposed at a workshop on mapping subterranean biodiversity sponsored by the Karst Waters Institute and the Laboratoire Souterrain. A major problem with most lists of location information is the relatively high rate of errors resulting from transcription errors from maps and failure to indicate which datum (*e.g.*, 1927 North American Datum) is being used. Another problem is how to treat undescribed species or specimens that could not be identified to species with certainty. Finally, the problem of taxonomic synonymies is an especially vexing one.

The National Karst Map and its Relationship to Karst Feature Databases

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The U.S. Geological Survey KARST Project is producing a new national karst map of the United States. This map is being compiled in a GIS at a resolution of 1:1 million. The new data are being generated in several phases. A first approximation of karst areas is provided by isolation of soluble bedrock units derived primarily from state geologic maps. The potential karst areas are then subdivided into karst types reflecting regional styles of karstification. Criteria being considered include: geologic setting, physiography, and the distribution and density of caves, sinkholes, and other karst features. Other variables such as ecoregions and the known geographic distribution of cave organisms may also be considered. The compilation and classification process is complicated by: 1) unevenness in spatial precision and classification of lithologic units between the various geologic maps; 2) lack of easily obtainable statewide and region-wide karst data, especially cave locations; and, 3) recognition of key, nonlithologic factors affecting the development and expression of karst features. Because of differences in scale and scope, the National Karst Map dataset will have a top-down relationship to other karst databases. This relationship can be thought of as somewhat analogous to the relationship of metadata to data. The new Karst Information Portal (KIP) offers a potential framework for integration of data sets of all resolutions from national to local scales.

Cooperative Databases

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Missouri Department of Conservation

My experience includes creating and managing cave and cave life databases for the Texas Speleological Survey, Texas Parks & Wildlife Department, Balcones Habitat Conservation Plan (Texas), and the Missouri Department of Conservation. I also contribute to and borrow data from the Missouri Speleological Survey. My discussion is derived from the perspectives of cavers, cave surveys, conservationists, researchers, and bureaucrats. In my opinion, a national cave or karst database will be unpopular unless state cave surveys are invited to participate. There are two key questions: 1) Will cave names and precise cave locations be available to the public or only to qualified researchers? 2) Who owns the data, or who controls it? The Missouri Cave Life Database (CLD) is a cooperative project of 12 partners that I developed. It contains no permanent tables of cave coordinates, but it has cave name, county, and MSS accession number. This avoids political/legal problems. When needed for GIS work and analysis, a special table of "biocaves" from the MSS can be related.

About 17% of the 6,100 caves in Missouri are "biocaves." The end products are maps with cave symbols generalized to diameters of 3-10 mi. (5-15 km). Decimal degree coordinates provide several advantages over other systems. A national cave life database is achievable. The CLD is adaptable to other states and countries. It draws on published literature and observations by multiple partners. It allows fauna lists to be produced for a cave or an area, and it provides for biodiversity analysis.

The Functions and Frustrations of State and Regional Speleological Surveys

George Veni
President, Texas Speleological Survey

The Texas Speleological Survey (TSS) "is organized for scientific, educational, and conservation purposes, with the specific objectives to collect, organize, and maintain information on Texas caves and karst, and to generally make that information available to responsible persons and organizations. [It] reserves the right not to distribute certain information if it could result in the exploitation or degradation of cave or karst resources [and] will work with caving organizations to make science an important part of all cave-related activities." Speleological surveys around the world are created with the same general goals as the TSS. They share the often conflicting challenges of collecting, archiving, and disseminating cave data, while protecting the data and ultimately the caves from misuse and harm. Methods vary from having membership to non-membership organizations, free to fee-based data access, and access based on personal acquaintance to contractual agreements. The methods appropriate to one region may not be completely effective elsewhere. Most data collection and data-basing methods have arisen independently. International standardization methods have yet to become popular due to language barriers, cultural differences, rapid changes in software, cumbersome communication methods, and different needs and types of information gathered. Many of these obstacles are breaking down and more cave surveys are also beginning to archive information on karst features. Growing pains will occur, but multi-regional and international speleological surveys will inevitably develop as communication between regional surveys increases.

Development of a Karst Information Portal (KIP): The Importance of Karst Databases

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The University of New Mexico, the National Cave and Karst Research Institute, Los Alamos National Laboratory, and the University of South Florida are partnering to develop the Karst Information Portal (KIP) to promote open access to karst, cave, and aquifer information and linkages among karst scientists. Our purpose is to advance karst knowledge by: (1) facilitating access to and preservation of karst information both published and unpublished, (2) developing linkages and communication amongst the karst community, (3) promoting knowledge-discovery to help develop solutions to problems in karst, (4) developing interactive databases of information of ongoing karst research in different disciplines, (5) enriching fundamental multidisciplinary and interdisciplinary science, and (6) facilitating collection of new data about karst. The KIP project is currently (1) transforming *A Guide to Speleological Literature of the English Language 1794-1996* into the portal's first searchable on-line database and (2) creating an institutional repository of scanning electron micrographs from research in caves that includes social software to promote linkages among karst scientists. In addition to these initial databasing efforts, KIP organizers hope to stimulate the development of new karst-related databases and the inclusion of existing ones.

Conservation & Restoration

Robber Baron Cave, Texas: Surface Restoration and Management for Subsurface Species

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Known since the 1910s, Robber Baron Cave is a former show cave that developed a rich history as San Antonio, Texas, grew around it. Vandalism resulting from the cave's urban location resulted in the construction of a series of four gates beginning in 1980, each more secure than the last, until the placement of an impenetrable five-ton concrete bunker. However, this bunker restricted airflow and nutrients into the Robber Baron Cave, which contains six endemic invertebrate species of which two are federally listed as endangered. The Texas Cave Management Association (TCMA) has since acquired the cave and also a grant from the U.S. Fish and Wildlife Service to improve the species' habitat. Originally, TCMA planned to modify the bunker, but structural instabilities were discovered that required its complete removal. This allowed restoration of the entrance to its near-original state, with a secure but ecological sound gate that allows the natural passage of air, water, nutrients, and organisms. Restoration work currently in progress includes new fencing, trails, and sinkhole stabilization. Additionally, exotic vegetation has been removed and native vegetation will be planted to support some non-listed yet ecologically key cave species that exit at night to forage. The use of native plants will obviate the need for watering and chemical treatment, while supporting the cave's endangered species. When restoration is complete, signage and a kiosk will be installed so the landscape over the cave can serve as an educational resource for the community.

Got Cave? No Bats? We Can Help with That: Bat Conservation International's Search for Restoration Sites

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The traditional approach to cave conservation for bats has been to identify caves with populations and then to limit access during the critical season, either by voluntary closure or by gating if necessary. However, recent discoveries have shown that many of these protected caves are only marginally suitable. In 2005, based on the research of Dr. Merlin D. Tuttle, Bat Conservation International initiated a project to locate and survey caves that may contain evidence of previous habitation. In 2005–2006, a team of cavers led by Cat Kennedy visited 39 caves in Indiana and Kentucky during six weeks of field work. Assistance was also provided by caving organizations, state authorities, cavers and local landowners. As a result, BCI has identified 10 key sites that combined would have housed millions of bats. Our next step is to further evaluate each site for restoration to its former, more suitable conditions. One example is Saltpetre Pit in Kentucky, which currently serves as a home for the third largest known colony of Rafinesque's Big Eared Bats in the world. The 22- meter pit entrance to this cave was more than half filled with household trash and debris. The American Cave Conservation Association and BCI conducted a sinkhole cleanup in July 2006, to remove the entrance flight zone obstructions. BCI continues to lead field work to document these sites and make management recommendations in order to restore bat populations, especially for the endangered Indiana bat.

Creative Funding of Gray Bat Protection in Southwestern Virginia

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Virginia Speleological Survey Director Jim West observed clustering bats in Bacon Cave, Lee County, Virginia, in 2002 while surveying. The Virginia Department of Conservation and Recreation (DCR) and Department of Game and Inland Fisheries documented a resident bachelor colony of up to

4000 federally listed endangered Gray bats (*Myotis grisescens*). The cave's entrances are in a cliff face along the Powell River, a tributary of the Upper Tennessee River. Trash, fire pits, and excavations made by pothunters and partiers indicated the need for a cave gate. Grigsby Cave in Scott County hosts a transient population of Gray bats from April through June, ranging from a handful of individuals to several thousand bats. Over the last decade, cavers documented increased guano accumulation rates and new roosting sites in the cave, suggesting possible maternity use. Evidence of ongoing disturbance by spelunkers made clear the need for a gate. Interagency coordination between DCR, Department of Game and Inland Fisheries, and the Department of Mines Minerals and Energy arranged for Paramount Coal Company to fund gating of Bacon Cave by the American Cave Conservation Association (ACCA) as compensatory mitigation for closure of an unstable mine portal in Wise County used by a small population of *Myotis liebii*. ACCA worked with the US Fish and Wildlife Service to gate Grigsby Cave, using the $14,000 Paramount settlement as matching funds. Other conservation partners included Bat Conservation International, The Nature Conservancy, and NSS cavers. Bacon was gated in August 2005, and Grigsby in June 2006.

Caving and the Boy Scouts – Oh the Horror! Reaching out to the Future of a Karst Community via a Speleo Venture Crew Program

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The NSS has worked hard to develop guidelines for youth group caving activities. Initial reaction to forming a caving-based Venture Crew, a youth group associated with the Boy Scouts, was negative. Supporting the organization of such a group was needed for the following conservation reasons: the community was located in a karst region, dependent on karst based industries (oil, gas, and cave tourism), and those kids who stayed in the region as adults would be faced with karst land-use decisions. Support for future cave and karst stewardship is dependent on the kids we take caving today. The Carlsbad Speleo Venture Crew teens learn how to cave responsibly and are exposed to various aspects of speleology and cave conservation. We anticipate that participation will increase their understanding of cave environments and ecosystems, as well as karst systems in general, so they can become responsible cavers now, and be responsible cave neighbors and managers in the future.

Cave Biota—An Evolving "Webumentary"

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Media can be a successful partner in cave conservation. Newspaper, film, and the Internet can help inform the public on land use practices that affect cave life and that are general indicators of environmental conditions such as water quality. There is a direct correlation between the number of informed public and the quality of cave stewardship. The Hoosier National Forest, Indiana Karst Conservancy, and National Speleological Society are sponsoring a cave biology video produced by Ravenswood Media of Chicago, Illinois. Various clips are currently available on northern cavefish, cave salamanders, bats, pseudoscorpions, and macroinvertebrates, and more are in the works. The clips will be edited into a thirty-minute video for distribution and use by individuals and organizations. Educational components that relate to general academic standards and integrate with cave education programs such as Project Underground, Project Wet, and Project Wild have been developed. The project is being considered for television production. For more information, see: www.cavebiota.com.

Containing Human-Introduced Debris along the Public Tour Route in Oregon Caves

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More than 53,000 visitors touring Oregon Caves each year bring in debris such as dirt, lint, hair, and shoe material. Many show caves contain and/or remove such material because of its ecologic and visual impact. The effectiveness debris mitigation depends on the environment and tour route design. Oregon Caves has a higher ratio of natural versus introduced organics than many dry caves. This reduces ecologic impacts, but dripping water increases organic decay and reduces the effectiveness of traditional lint removal. Water also spreads organic material to areas beyond the trail areas. Clear, vinyl tarps were ordered to size with grommets and installed in Oregon Caves below stairs and grated walkways. On tarps below stairs, debris and water flow into basins fitted with filters that retain debris and release water. Fittings mounted in tarps below horizontal bridges and walkways allow drainage into buckets with filters. The tarps are periodically rinsed with cave water to flush collected debris into the filters, and the filters on the buckets and basins are cleaned regularly. The tarps likely mitigate much of the impacts of human-introduced debris on cave biota.

Paleontology

A Pleistocene Tapir from a Virginia Cave

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Remains of a Pleistocene tapir have been found in a newly discovered cave in Bath County, Virginia about five hundred meters from the dug open entrance to the cave. The tapir remains include a nearly complete but dorsoventrally crushed skull, three cervical vertebrae, rib parts, a partial scapula, a humerus and a partial ulna. A metatarsal was found about 3 meters from the main cluster of bones. The skull has deciduous premolars and freshly erupted first molars indicting a juvenile. Based on available measurements, the tapir is identified as *Tapirus veroensis* and is probably late Pleistocene in age. Other vertebrates found near to the tapir include bats, a deer mouse, and a snapping turtle skull.

Mississippian and Pleistocene vertebrates from Haynes Cave, West Virginia

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Haynes Cave in Monroe County, West Virginia has produced vertebrate fossils from the Mississippian limestone and the Pleistocene sediments in the cave. The Mississippian fossils are represented by the small teeth of two kinds of shark, a xenacanth and a pavement toothed type. The Pleistocene vertebrates include fish, amphibians, reptiles, birds and mammals. The mammals include two large extinct species: a ground sloth, *Megalonyx jeffersonii*, and a peccary, *Mylohyus fossilis.* There are nearly 30 species of small mammals. The fauna includes two rodents, the Cumberland deer mouse and the Trout Cave vole, both extinct species that probably date to the late Irvingtonian land mammal age, about 600,000 years before present. Most of the other species are late Pleistocene in age and include the yellow-cheeked vole, a species that now inhabits northern Canada and Alaska. A partial scapula of the sloth has been radiocarbon dated at nearly 36,000 years before present. Unfortunately Haynes cave was heavily mined for saltpeter, thus making interpretation of the stratigraphy of the sediments difficult.

Let Those Bones Be: Lessons in Paleontological Context at Unthanks Cave, Virginia

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In the fall of 1996, a caver called saying he'd passed the notorious Easter Pig Sump in Unthanks Cave. He'd found a borehole passage with a large bone protruding from a mud bank. Concerned that the sump would re-close for another decade or that the bone might wash away before a recovery trip could be made, he packaged and transported the bone beyond the sump in this gated cave. The authors obtained written owner permission, which satisfied our existent blanket paleontological permit, and recovered the limb-bone during the 1996 DOM. The well-packaged tibia was missing its proximal end (knee-end of the lower leg-bone) at a fresh break, and the distal end was too abraded to make a determination. After a discussion on the importance of context and the missing terminus with the caver, he made a return visit and determined that addition bone was present and scheduled a joint visit. In September 1997, a very modest excavation yielded the missing proximal end and the fragmental fibula of *Arctodus simus*, the greater short-faced bear. The proximal end of the tibia was in contact with bedrock and buried in a sandy gravel deposit underlying an over-bank deposit of clayey silt in a paleo-streambed. The same periodic high-stage flooding events that sent flood waters coursing through the pirated cave stream passage and transported the bones to their location, deposited gravel and a clayey silt layer over the bones, eventually eroded those sediments to partially expose the tibia, and replenished the paleo-stream passage sump. The discovery of the 12,000 year-old short-faced bear of Unthanks Cave provides an important illustrative lesson on context. As initially recovered, the fragmental tibia was unidentifiable, but examination of the bone site allowed full recovery of the specimen, subsequent identification and rationale for radiocarbon dating, and a partial interpretation of how these remains came to rest in Unthanks Cave.

Survey & Cartography

Survey Shot Linking Order as an Indicator of Accuracy

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Development of the CMAP survey data reduction program to handle forward references led to having versions that produced three different survey shot linking orders. If the survey network is sufficiently well connected, the different versions produce three relatively independent survey paths to any part of the survey. This small sample provides an indication of the consistency and accuracy of our surveys. For a good survey with blunders having been resurveyed, the different locations of a station fit inside a box whose diagonal is on the order of 3 to 4 percent of the straight-line distance from the entrance. This tends to support the old rule of thumb that the accuracy of a survey is about 2 percent. Of course the linking order does not affect the location of stations after closure adjustment, but the adjustment method does. Locations produced by least-squares and sequential adjustments differ by 0.5 to 1.0 percent. Different weighting factors in the least-squares adjustment affect the locations by less than 0.5 percent. This type of analysis is less effective for non-maze caves.

Baseline Information for Understanding, Managing and Protecting Caves and Karst

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In order to effectively manage, protect and conserver caves and karst, it is important to have basic knowledge about their physical extent, nature and attributes. Geographic data, resource inventories, and photodocumentation provide the baseline of information necessary to understand cave and karst resources. Synthesis of this information into maps, databases and geographic information systems provides the framework from which to make sound and intelligent resource management decisions. Such baseline data and information is also a starting point for scientific research. Ultimately it is research that will further knowledge and understanding about caves and karst.

Human Factors and Controls – Mitigation and Detection of Common Sources of Problems that Influence the Accuracy of Cave Surveys

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In-cave surveys create a perfect storm for errors and blunders. Poor conditions, substandard equipment, and inexperienced and fatigued personnel all contribute to poor-quality surveys. Thirty years of surveying in Mammoth Cave have taught us much about survey techniques and the sources of errors and blunders. Besides the often discussed, albeit general, topic of survey accuracy, we have become aware of common situation occurrences (the human factor) that have the greatest likelihood of creating the bane of surveyors — the blunder. A good understanding of these common causes of errors, and of the in-cave survey-scenarios that can contribute to this problem, offers opportunities to not only prevent survey problems, but also to detect them during post-survey analysis. There are common, blunder-prone survey-scenarios; approaches that have proven to be effective in addressing them; and techniques for analysis to assist in blunder detection.

US Exploration

Black Chasm Cavern: Jewel of the Mother Lode

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Black Chasm is a vertical cave developed in Permian-age, recrystallized limestones of the Calaveras group near the gold rush town of Volcano, in Amador County, California. Its passages likely began forming some two million years ago. The earliest written record of the cave dates to 1854, when it was explored by gold miners during the gold rush era, including a perilous rope descent of over 30 meters to the bottom of its main chamber. In the 1950s, local grottos began exploring it, and a group of Sierra Club climbers traversed the main pit and found a room festooned with crystal-clear helictites. Tom Rohrer made a very basic map of the cave in the 1960s, published in *Caves of California*, and one of the cave's deep lakes was dove to 24 meters with scuba gear. The cave was designated a National Natural Landmark in 1976 for its helictites. In 1996 the cave was purchased by Sierra Nevada Recreation for development, and construction of an elevated trail was completed in 2001. In 2003 we began a project to thoroughly survey and photo-document this unusual cave. We located at least one new area and rediscovered a few others. A detailed map produced by Hazel Barton shows 956 meters of passage and 45 meters of depth. Besides the helictites, the cave is notable for its large boxwork and many outstanding examples of pool spar, some of it hexagonal in form.

Recent Exploration at Jewel Cave

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Since July 2006, over 4.2 km of passages were discovered and mapped. All but 365 meters were discovered in the southeastern section of the cave on four four-day trips. Several unsuccessful attempts were made to push beyond a linear geologic obstruction that had stopped several passages in the area. Other new mapped passages stopped against a second linear obstruction, but barometric airflow indicates there is much more cave beyond. New discoveries include passages up to 20 m wide and 15 m high, and upper-level passages with tilted bedding. In January, a 1,524 meter loop was closed with only 3 m of closure error. In February, explorers finished mapping the Encore, a room 45 m wide, 75 m long, and 9 meters high, that had been discovered in early 2005. The total surveyed length of Jewel Cave reached 218.2 km and surpassed that of Optymistychna Cave, making Jewel Cave the second-longest cave in the world.

Caves of the 1919 Lava Flow in Kilauea Caldera, Hawaii: a preliminary report on a 12 year study of 200+ caves

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A 12-year application of speleological techniques documented that the 1919 Postal Rift lava flow in Hawaii's Kilauea Caldera contains more than 200 caves. For this, 167 field trips were conducted in 22 field seasons. Only two caves had been identified here prior to this study. Most of this flow's caves were found to be drainage structures rather than classical lava tube conduits: hollow tumuli, drained flow lobes, tongues, breakouts, etc. Several melt holes were found to have integrated once-individual caves into compound caves. Many of these caves are hyperthermal, with 100% relative humidity. Some are notable for thermostratification and/or changing underground wind currents. These meteorological conditions required development of new exploration techniques. Noxious gas (probably HCl) was encountered only in one tiny cave on the edge of Halemaumau Crater. Two types of CO_2 monitors required for the last five field trips were found to be useless in hyperthermal caves. Hundreds of pages of raw data and individual field trip reports have been submitted to the National Park Service. Processing these data is expected to require many months. Systematic speleological studies are urged for other Kilauea lava flows, especially another 1919 flow in Hawaii Volcanoes National Park. Also, mineralogical studies of these caves begun by Bobby Camara in cooperation with the USGS Hawaiian Volcano Observatory should be completed.

Wind Cave Survey Project Update, 2006

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The first ever Wind Cave Quadrangle book has recently been completed. This Atlas contains 192.45 kilometers of drafted survey drawn on 37 individual Mylar sheets at a scale of 6 m/cm (50 ft/inch). These "quadrangle" maps cover an area of 457 × 305 m (1,500 × 1,000 ft). The atlas contains survey statistics for the entire Wind Cave survey project, including a list of everyone that has gone on more than five survey trips (205 people). During the previous seven years, the Wind Cave survey has grown at an average rate of 7.2 km a year, and this trend is expected to continue into the foreseeable future. Since July 2005, a total of 82 trips resulted in 6.79 km of survey and inventory. The official length of Wind Cave increased from 187.76 to 194.65 km. The most significant discoveries during this time period were the Gas Chamber, Ghost Town, Stalactites Galore, EX survey, Big Fish Canyon, Cow Hoof Lake, & End of the Road areas. On February 13, 2006, the Wind Cave survey passed Hoelloch Cave of Switzerland to become the fourth longest cave in the world. In recognition for 16 years of volunteer service at Wind Cave National Park, The Colorado Grotto was chosen by the Midwest Region of the National Park Service as their nomination for the 2005 George B. Hertzog Volunteer Group Service Award.

Snowy River Discovery in Fort Stanton Cave

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Fort Stanton Cave, New Mexico, has 17.7 km of surveyed passage, with large trunk passages and long crawls. Significant portions of the cave have been found through digs. Beginning in 1970 a team of cavers began digging through collapsed breccia, with solid wall on one side and loose breakdown on the other. After five years of difficult work chasing air, they suspended operations at Menacing Dome. This portion of the northern branch of the cave required traversing through deep mud and flooded passage during the 1980s and early 1990s. When the water receded, work resumed in a dig called Priority 7. In 2001, the 140-meter-long dig opened into a stunning trunk that paralleled previously known cave, and was paved for ~2.9 km with a white calcite coating from wall to wall. Methods were developed to minimize impact while studying and surveying the new passage, called Snowy River. In 2003, nearly five kilometers were surveyed in Snowy River and a large parallel paleo-trunk named the Metro. An unexplored stream heads off the map at the northern end of Snowy River. The south end was not pushed due to logistics. In 2005, cavers decided that the risk of sending teams through the challenging Priority 7 route was unacceptable, and a new bypass dig was planned and started. When the new dig is completed, stabilized, and an environmental gate installed, further exploration of Snowy River will continue.

Exploration in Lechuguilla Cave

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Lechuguilla Cave, New Mexico, was dug open 20 years ago. Rapid exploration of the cave occurred in the first 5 years, but progress has slowed as the frontier has become more remote. Survey expeditions continue to take place in the massive western branch, primarily in the Chandelier Graveyard, Widowmaker, Mirage Room, Hudson Bay, Zombie Zoo, Mother Lode, and Southern Climes. In the southern branch, a big dome above the Prickly Ice Cube Room known since 1988 was climbed 39 meters into an area named Flatlands. Another long, promising climb in Prickly Ice Cube room was started, but not completed. In the eastern branch, a second expedition to Coral Seas found additional passages between Boundary Waters and La Morada room. Teams continued exploration near La Morada and the Outback, finding additional passage at the -404 meter depth. Several teams continued exploration and mapping in day trips near the Rift, fixing loops and sketching errors and discovering some new passages. Since July 2005, cavers have mapped 7.3 km of passage, increasing the cave length to 189.4 km (117.7 mi).

The Discovery and Exploration of Russell's Reserve Cave---Bath County, Virginia

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Clues pointed to the existence of a large cave in a limestone ridge in southern Bath County, Virginia. The indicators included swallets in the stream bed that resurge many kilometers away, a sandstone capped limestone anticlinal ridge, and blowing fissures. In April of 2005, work began on a strongly blowing opening more than a meter above the surface stream level. The following October, after digging 26 m through the fissure filled with sandstone breakdown, cavers broke into Russell's Reserve Cave. The cave's passages were found to be on several levels, being generally large and having many classic phreatic features, including a large natural bridge. In some areas, numerous drill holes in the clay deposits exposed bones washed free from ancient sediments. Initial discoveries include a Pleistocene tapir and a remarkably intact black bear skull, also probably of Pleistocene age. Surveyors discovered a sizable stream in the furthest reach of the cave. The stream is flowing in an open passage and headed toward a surface river just 366 m away, but at an elevation nearly 12 meters lower. As of June 2006, 5.9 km have been surveyed.

Cave Hill: The beginning of the End?

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Major new discoveries have been made over the last two and half years during the Virginia Region's (VAR) survey project at Grand Caverns, the United State's longest continuously operating commercial cave, now a regional park. The cave celebrates its bicentennial this year, and the VAR was asked by the park to create a new map of the cave befitting this milestone. At the 2005 NSS Convention we reported the discovery of a previously-untouched tight crawlway which led to massive virgin cave. Since that time, even more major passage has been found in Grand Caverns. The survey was finally declared finished this year, expanding the cave from 1.1 km (3600 ft) to over 6.1 km (3.82 mi). On other parts of the hill, several more caves have been found, and will be mapped.

Lava Caves of Southern Washington

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The lava caves of southern Washington are mostly spread over four flows from two separate mountains. During the last decade, a concentrated effort to locate and map these caves has led to an understanding of the flow dimensions. The two sources are Mount Saint Helens and Lemei Rock. On Mt St Helens, the flow is over 8 km long with over 457 m of elevation change. Lemei Rock is in the Indian Heavens Volcanic Field and has three distinct flows from its center. On the west side is the Fall Creek flow, to the northeast is the Smokey Creek flow and to the southeast is the Trout Lake flow. Each of these flows can be traced over eight kilometers and probably represent many eruption events. Cavers have surveyed over 200 caves totaling nearly 80.5 km of passages. Approximately three quarters of these caves are located within the Gifford Pinchot National Forest. Cavers are working with the Forest Service to record locations, photograph, place monument markers, and incorporate cave survey data into their GIS for all of their significant caves.

Update on exploration in the Omega Cave System: 2000 to 2006

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Since 2000, the Omega Cave System has grown dramatically in length and complexity. Annual week-long camp trips deep in the system have discovered and mapped more than 16 km of new passage, with no end in sight. The discovery of several large stacked paleo levels above this main stream passage, as well as an extensive paleo infeeder complex from a small surface stream gap, has contributed much of the new passage. The main stream passage in the cave continues upstream and to date has a total length of 8.5 km. The upstream extension of the cave was discovered at the top of a climb bypassing a waterfall. This discovery promises to be just as complex and extensive as the rest of the system. A new cave entrance leading to a stream passage descended a series of wet and muddy shafts and connected to the main system in 2005, bringing the total number of entrances to three. The total length of the Omega System now stands at 36.76 km, with a depth of 385 m. Potential to add additional length and depth remains high. Other caves near Omega have been found, surveyed and explored. Including Omega, nearly 50 km of passage have been surveyed in the past 10 years. Hydrologic studies have been used to aid exploration efforts in the area and are revealing a highly complex system.

Exploring the Depths of Main Drain Cave, Utah

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In the summer of 2004, a breakthrough in entrance series of Main Drain Cave led to passages reaching a terminal sump at a depth of 358 m, making it Utah's deepest cave. In 2005, exploration continued through an overflow route to another terminal sump at a depth of 374 m. Main Drain Cave now stands as the ninth deepest cave in the United States. There is still potential to bypass this sump and push the cave deeper.

The Webster Cave Complex Survey Group (WCCSG)

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The WCCSG is dedicated to the exploration and survey of the Webster Cave Complex, Breckinridge County, Kentucky. The three known entrances to the system are nestled in Sinking Creek Valley, surrounded by the 243-meter-high ridges. More than a dozen caves make up the Webster Complex. The main passage of this cave is over 5 km long and frequently 12 m in diameter, making it one of the largest continuous trunks in the state. In places, continuous lakes extend for over 800 m with neck deep water from wall to wall. Recently, the WCCSG has started a systematic resurvey and exploration of the known caves of the area. This commenced in May, 2005 with the survey and continued exploration of Webster Cave. The main cave survey is more than 8 km long (including about 1,600 m of newly discovered passage) and has not been fully mapped. Numerous leads remain unexplored. The source and resurgence of this stream are not known, so the potential for additional cave discovery in the areas is high.

Caves of the Pohakuloa Training Area, U. S. Army, Big Island Hawaii

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The United States Army has sponsored the study of lava tubes on the Pahokuloa Training Area on the Big Island of Hawaii. Recent efforts to study these features have included the documentation of many kilometers of lava tubes. To date, three major lava flows have been studied. Each flow has distinct characteristics and has resulted in a variety of cave systems. The Delta Cave System is the longest to date, with just over 8 km of accumulated survey. Formation is believed to have happened quickly (days to weeks) within a flow of average volume (probably 1–3 m^3/s). The tube is best described as embryonic in nature. Bobcat Trail Cave resulted from a larger flow volume with longer flow duration and has resulted in a more mature type of cave development. Puu Koli (Red Cone) is radically different from either of the other two systems currently under study. The cave is layered or stacked and was the result of a long duration, small volume flow. Extensive downcutting and false floors between levels have built the cave into its current form. This cave is located at higher elevation than the others under study, which has resulted in smaller amounts of water percolation through the system, allowing extensive gypsum deposition within the cave.

The Great Crack — Big Island, Hawaii

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The majority of lava caves in Hawaii are formed by very fluid lava flowing down the sides of the mountain to form tubes at shallow depth beneath the surface. Recent exploration on the Big Island has revealed a much more interesting and challenging type of volcanic cave development. Each of the three active mountains is formed on the same basic plan. Three equilateral fault zones radiate outward from a central dominant caldera. In each case, two of the zones are dominant. The third is buried beneath the shoulder of the adjacent mountain. The Southwest Fault Zone of Kilauea Volcano is a nearly continuous single fault that often opens to the surface and can be traced for nearly 48 km along this line. Exploration into this fault system has documented caves more than 183 m deep and up to 800 m long. These primarily tectonic features have also been found to have carried lava flows for distances of up to thirty-two kilometers outward from the center of the volcano. In many cases, these secondary flow events have modified the original crack structure and added a roof to the open crack system. A new term, crubes, has been suggested to describe these combined crack-tube features.

Exploration and Mapping at Gap Cave and in the Pine Mountain Region of Kentucky, Virginia, and Tennessee

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The Cave Research Foundation (CRF) Cumberland Gap Project has been conducting a multidisciplinary study at Cumberland Gap National Historical Park in Kentucky, Virginia, and Tennessee. Since 2003, CRF has been mapping Gap Cave, and 50% of the known cave has been surveyed. The cave is currently more than 13 km (8 mi) long and 145.7 m (478 ft) deep. Since the start of the project, 3.7 km (2.3 mi) of virgin passage has been mapped. Cumberland Mountain is the southern edge of an uplifted fault sheet more than 85 km (53 mi) long. The limestone containing the cave is 171 m thick in this area. The northern exposed edge of the uplifted fault sheet, Pine Mountain, is the secondary focus of research. Mapping and exploration of this area has resulted in 56 caves, including Pit-Up Straight Creek. There is high potential for additional cave exploration and research in the area.

Further Exploration in Roppel Cave, Kentucky

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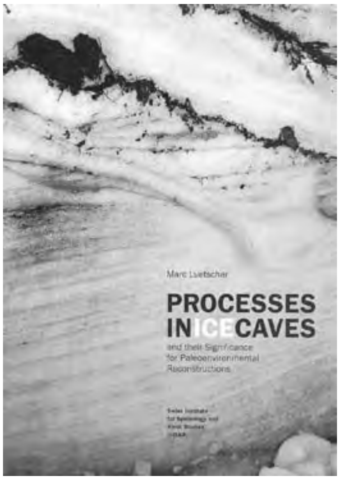
Roppel Cave, Kentucky, was discovered in 1976 and mapped to a length of 79 km before it was connected with Mammoth Cave in 1983, forming a system of 473 km. Since the connection, further work in Roppel has evolved from early, rapid exploration into a systematic, three-dimensional mapping and exploration project. While the areal extent of the cave has not changed a great deal in the ensuing 23 years, an additional 48 km of passage have been explored, including some large passages. New passage has been found in multiple additional levels within only a few meters of known passage. Technical climbing has been used extensively to reach unexplored upper levels. "Micro-camps" during trips longer than 36 hours, as well as camping for up to four days, have been used to explore remote areas. Exploration of other caves in the area has led to the connection of Hoover Cave into the system in 2005. This was the first new natural Mammoth entrance since the 1983 connection. There has been a strong emphasis on survey standards, and the project has been recognized as having the second highest data quality of any large cave project in the world.



Processes in Ice Caves and Their Significance for Paleoenvironmental Reconstructions

Marc Luetscher, 2005. Swiss Institute for Speleology and Karst Studies, La Chaux-de-Fonds, Switzerland, 154 p. ISBN 3-908495-19-9, softbound, 7.8 × 10.8 inches, $40 + $4.90 shipping. Order on-line at www.speleobooks.com.

This book, which concerns perennial ice in caves, is the published version of a doctoral dissertation at the University of Zurich, Switzerland. Although it contains some fairly technical sections, most of the book can be easily understood by non-specialists. It is written in clear English, with short summaries in French and German, and is well illustrated with maps, diagrams, and black-and-white photos.

The author's study encompasses the low-altitude caves in the Jura Mountains, with special attention given to the Monlési Ice Cave, near Neuchâtel, Switzerland. In quantifying the ice-forming process in the caves, he strikes a nice balance between theory and field observation. He measured such variables as the temperatures of air, rock, and ice, as well as changes in ice volume and water flow entering the cave. On the basis of these measurements he modeled the energy balance of the system and compared it with physical theory, an approach that has rarely been applied to the subject.

The book is divided into three parts: Part 1, which includes about half the book, concerns the ice-forming process in caves, and the significance of cave ice in paleoenvironmental studies. This section is fairly easy reading, with only a few brief excursions into heat transfer and the energy balance. It gives a thorough introduction to ice caves and their distribution, thermal characteristics of caves, types of cave ice, and processes of ice formation. Specific study sites are described with the aid of detailed cave maps. The heat flux is interpreted from the field data. The effect of climate is considered, and predictive models are devised. The modeling in Part I is mainly conceptual, rather than mathematical.

Part 2 consists of ten short papers on cave ice that have been published in scientific journals by Dr. Luetscher and his colleagues. All are in English except for two short papers in French and one in both French and German. Topics include classification of alpine ice caves based on ice-forming processes; effects of temperature and of air and water movement on cave ice; evidence for variations in winter climate in the study area; modeling heat transfer and energy flux; variations in ice volume with time; and ice dating procedures. Part 3 consists of a selected bibliography of the international literature on ice caves, which gives broad coverage to the subject and does not simply duplicate the more specific references cited in earlier sections.

The author calculates that about 79% of the heat transfer in the Monlési Ice Cave is caused by winter air circulation, and that nearly all of the remainder is caused by direct influx of snow. He concludes that circulating winter air can make the caves cold enough to support ice, even in climates where the mean-annual temperature is well above freezing. This makes them highly sensitive to changes in the surrounding climate. Ice in the Monlési Cave averages about 12 m thick, but measurements of ice strata and texture, in combination with isotopic evidence, show that the accessible ice in the cave averages only about 120 years old. Some caves elsewhere are known to contain ice more than 1000 years old. Ice caves in the mid- to low-altitude caves of the Jura Mountains lie near population centers and are very sensitive to airborne contaminants. They serve well as archives for changes in climate and air quality.

Although most of this book is focused on a single ice cave, it provides a broad background on cave ice. Anyone with an interest in the subject will find this to be one of the very few essential references.

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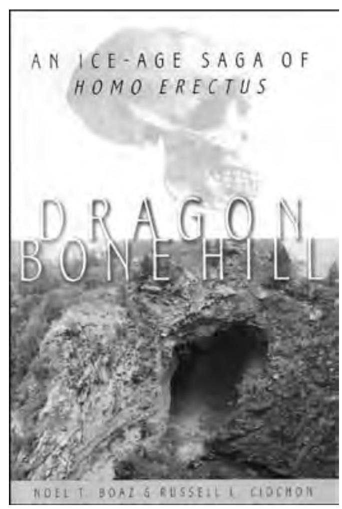

Dragon Bone Hill: An Ice-Age Saga of *Homo erectus*

Noel T. Boaz and Russell L. Ciochon, 2004. Oxford University Press, New York, 232 p. ISBN 0-19-515291-3, hardcover, 6¼ × 9½", $30.00.

For thousands of years, Chinese pharmacists have made use of ground-up fossil bones and teeth (so-called dragon bones and dragon teeth) as ingredients in medicinal elixirs. These were claimed to cure a wide array of illnesses and fueled the long-standing fossil-mining industry among Chinese peasants. Such finds, coming from the many fossil-rich caves of China, have long been sold to big-city apothecaries. The practice survives to this day. Fossil teeth and bones of long-extinct creatures can be found among the wares of a well-stocked Chinese pharmacy. The local drugstore has often been the starting point for many anthropological and paleontological expeditions in this part of the world.

In *Dragon Bone Hill*, Boaz and Ciochon recount the remarkable tale of Zhoukoudian Cave. Located 30 miles southwest of Beijing, this is the most famous of China's dragon bone collecting sites. The discovery of fossilized hominid teeth at Zhoukoudian caused great excitement among anthropologists. On the strength of these meager finds, the Rockefeller Foundation funded a major excavation of the cave. The early remains found at Zhoukoudian formed the basis of what was eventually regarded as a new genus and species of hominid. *Homo erectus*, or Peking Man as he became known to the world, pre-dated even the Neanderthals in human evolution.

This book describes (1) the impact of dragon bones on China's archaeology and anthropology, (2) the discovery of the Peking Man fossils, (3) loss of the Peking Man fossils, (4) the worldwide search for the fossils, (5) attempts to understand the habits and lifestyle of Peking Man, and (6) attempts to unravel the evolutionary significance of this hominid. The authors set their narrative against the political turmoil gripping China when Chiang Kai-shek and Mao Tse-tung were vying for power. Nevertheless, progress at the site was remarkable and, within a few years, the cave had achieved a worldwide reputation. By the late 1920s and early 1930s, fossil finds—including primitive stone tools, evidence of the use of fire, and, at long last, the elusive skull of Peking Man—were pouring in. The scientific validity of early tooth finds was confirmed. By the early 1930s, Zhoukoudian Cave had been transformed from simply a place where local peasants could dig up dragon bones to that of a world-renowned hominid fossil site.

Excavations at Zhoukoudian Cave continued until the beginning of the Sino-Japanese war in 1937. Franz Weidenreich from the University of Frankfurt was in charge of the dig, and worked tirelessly on the Zhoukoudian fossils until his research laboratory at the Medical College was shut down by the Japanese invasion of Beijing. Weidenreich was forced to flee to America, but managed to carry plaster casts of the entire Zhoukoudian fossil collection with him. For years, Weidenreich worked at the American Museum of Natural History in New York to get the original fossils shipped to the United States for safekeeping during the course of World War II. Finally, in 1941, they were carefully packed and crated for shipment. And then, these priceless relics of human history and a Chinese national treasure simply vanished and have not been seen since.

It is now known that the origin of *Homo erectus* was in Africa. This incredible species rode a wave of opportunity out of Africa and across Eurasia. Armed only with fire and sharp rocks, *Homo erectus* managed to survive for more than 1.5 million years. In China, he came to be known as Peking Man, which occupied the environs of Zhoukoudian Cave intermittently between 410,000 and 670,000 years ago.

Fossils from Zhoukoudian Cave have helped anthropologists develop a day-to-day picture of *Homo erectus*' struggle for survival. Life was far from idyllic. Evidence suggests that Zhoukoudian Cave was primarily used as a den by the giant cave hyena, which was the size of a modern African lion. The interaction between man and beast remains unknown. Indeed, many of the hominid remains found within the cave may represent individuals that fell prey to the animal predators.

Primarily scavengers rather than hunters, the largely speechless hominids used primitive stone tools to strip the flesh from the bones of animals killed by local predators. Boaz and Ciochon theorize that the hominids living near Dragon Bone Hill made periodic commando-style raids on the cave. Temporarily driving the big carnivores off with fire afforded Peking Man the opportunity to pilfer partially consumed kills, many of which were probably their own fallen comrades. Thus, the ability of Peking Man to tame fire must certainly have played a pivotal role in his survival. Moreover, the fossil evidence suggests that they were not averse to de-fleshing members of their own species for a good meal.

By 2000, scientists studying the sediments in Zhoukoudian Cave were able to correlate specific strata with climatic conditions of the time. It is now known that Peking Man lived in and around the cave during relatively warm spells, when food and rain were plentiful. However, during periods of glacial cold, Peking Man is believed to have sought refuge farther south, where glacial winds were blocked by the Qinling Mountains.

More hominid fossils have been retrieved from Zhoukoudian Cave than from almost any other site yet excavated. They include fully 1/3 of all known fossils of *Homo erectus*. In 1987, Dragon Bone Hill was designated a United Nations World Heritage site. The treasure trove, despite its loss, that the cave yielded has helped to revolutionize our understanding of human evolution. For non-scientists interested in the evolution of man and the study of caves and cave men, most of this book is highly readable, despite technical discussions of population genetics and terminology.

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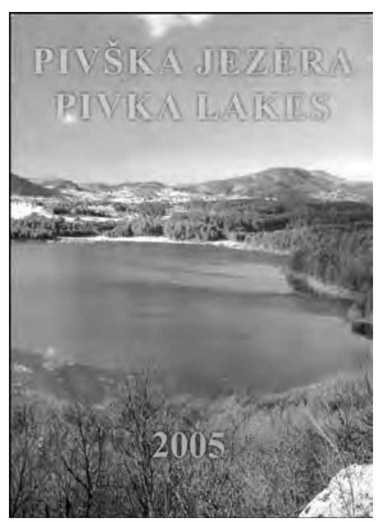

Pivka Lakes

Janez Mulec, editor, 2005. Acta Carsologica, Ljubljana, Slovenia, vol. 34, no. 3, 291 p. ISBN 0583-6050, softbound, 6.5 × 8.8 inches, 11.68 euros. Order on-line at www.zrc-sazu.si/zalozba.

This special issue of the karst journal *Acta Carsologica* provides an interdisciplinary description of the Pivka Lakes, which are located in the heart of the classical Karst area of Slovenia. *Pivka* is pronounced, roughly, "*pewka*." The Pivka River occupies a large closed karst basin south of Postojna, home of the Slovenian Karst Institute, and at least half of the contributing authors in the book are scientists at the Karst Institute. The book draws together all the scientific and cultural aspects of this important drainage basin. The text is in both Slovene and English, which occupy adjacent columns.

The Pivka River heads on insoluble rocks but drains onto limestone, where it eventually sinks into Postojnska jama, one of the world's most popular show caves. (Note: the Slovene *j* is pronounced *y*.) During high discharge, water in the low-relief middle parts of the basin fills fault-aligned depressions to form intermittent lakes. The river is connected to the lakes by underground conduits, although known caves in the lake area are small. These caves show the effects of severe flooding and act alternately as both springs and inlets as the water level varies. Between floods the fertile lake bottoms are farmed and also serve as the home of many cleverly adapted animals and plants. Environmental problems in the area include flooding during wet periods and a shortage of water during dry periods. People, plants, and animals all must adapt to the varied conditions.

The area is a natural corridor between central Europe and the Mediterranean. It was once inhabited by Stone Age humans. It also contains the remnants of a Roman road and medieval fortifications, and experienced much damage and hardship during the world wars. During the 20^{th} century the land changed hands from Austria to France and then to Italy. Persecution and economic crises led to mass emigration.

This book gives a well-rounded introduction to the area that goes well beyond mere geographic description. There are chapters on geology, hydrology, water-tracing studies, detailed observations during a flood, aquatic and terrestrial fauna, archaeology, the strategic position of the region during World War I, and suggestions for protecting the environmental heritage.

Illustrations are clear and well prepared. They may seem sparse because of the double-length text. Most photographs are in attractive color but are a bit low in contrast. Despite the formatting difficulties inherent in a dual-language book, and the fact that the area is not an obvious target for tourists, this is an attractive volume that invites browsing. Prospective visitors will appreciate the holistic approach to the subject. In addition, this book gives insight into strategies of land management that can be of benefit in similar karst areas.

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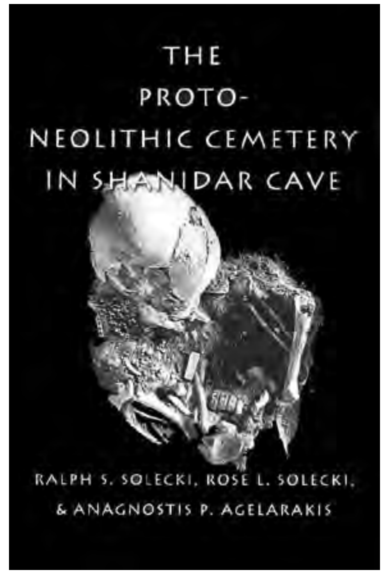

The Proto-Neolithic Cemetery in Shanidar Cave

Ralph S. Solecki, Rose L. Solecki, and Anagnostis Agelarakis, 2004. Texas A&M University Press, College Station, Texas, 234 p. ISBN 1-58544-272-0, hardcover, 6¼” × 9½”, $50.00.

Shanidar Cave is located about 250 miles north of Baghdad, in the Zagros Mountains of Iraq. Its known history of human habitation extends from the time of Neanderthal Man (about 100,000 years ago) up to the present. Even in recent times it has been a seasonally used refuge, sheltering local Kurdish tribesmen during the winter. Similarly, a community of Proto-Neolithic people living in the 9^{th} millennium BCE are also known to have spent their winters in the cave. During warmer months, they likely lived in open villages, such as the nearby Proto-Neolithic village of Zawi Chemi Shanidar. Between 1951 and 1960, Ralph Solecki and his team of archaeologists and anthropologists excavated in Shanidar Cave and at the Zawi Chemi Shanidar site. The deteriorating political climate in the country prevented further fieldwork.

During these excavations, four major cultural layers were uncovered in Shanidar Cave. From top to bottom these can be distinguished chronologically: 1) from present day until about 6,000 years ago, 2) about 10,000–13,000 years ago, 3) about 8,000–40,000 years ago, and 4) about 80,000–100,000 or more years ago. The 2^{nd} layer from the top, located at a depth of one meter below present ground surface in the cave, is referred to as the Proto-Neolithic layer. It contained the remains of anatomically modern humans (*i.e.*, people just like us). The significance of the Proto-Neolithic culture is that it represents transition between the older Paleolithic and the younger Neolithic cultures—a transitional period between an earlier hunting-and-gathering culture and a later one that primarily depended on the domestication of plants and animals. The 4^{th} (oldest) layer, referred to as the Middle Paleolithic or Mousterian layer, contained the remains of Neanderthals. Skeletons unearthed by Solecki from this layer are among the most important Neanderthal finds ever made. His interpretation of these finds revolutionized our appreciation of the Neanderthal culture and contributed greatly to our understanding of their innate humanity.*

During the initial years of excavation, the rear section of the cave had been blocked off by the presence of a corral and a stone wall. However, by the end of the 1960 field season, these impediments had been removed by local tribesmen, allowing the archaeologists access to portions of the cave that had previously been off-limits to them. At that time an ancient cemetery, attributed to a once-thriving Proto-Neolithic culture, was discovered near the back of the cave. Excavation of this cemetery uncovered the skeletal remains of 35 people, including 20 infants and children, five adolescents, and 10 adults. These were contained in 26 distinct graves and dated to approximately 11,000 years ago. In addition, various grave offerings, consisting mainly of bone tools and stone beads, were associated with many of the remains. Because of time constraints at the end of the 1960 field season, none of the cemetery was excavated.

Excavation revealed the cemetery to be surrounded by a series of stone pavements. These were fashioned from hundreds of carefully placed, fist-sized limestone fragments. The authors believe these pavements to have been components of mortuary hearths (*i.e.*, fire pits) used in ritual interment ceremonies. These pavements and an adjoining curved wall of stone separated the burial sites from the remaining (habitable) regions of the cave.

The most commonly found grave offerings were ornaments of personal adornment, primarily strings of beads. These were fashioned from perforated gastropod shells, crab-claw tips (both locally available), or colorful stones. Moreover, many of the stone beads were formed from materials not found in the vicinity of the cave. This suggests that the Proto-Neolithic people of Shanidar Cave had established extensive trading networks with more distant locales, although it is unknown if this involved trade in raw materials or in fully finished products.

The fact that these people buried their dead in a localized cemetery, accompanied by valuable goods, and perhaps associated with a ritualized interment ceremony, provides insight into their religious and spiritual lives. They may have believed in an afterlife. Because no obvious symbols of rank or status were found among the grave offerings, the authors suggest that these people lived in a socially classless society.

All of the skeletal remains and most of the grave goods excavated from Shanidar Cave were ultimately delivered to the Iraq Antiquities Museum in Baghdad. Over a 30-year period following the excavations of Shanidar's burial site, these artifacts have been studied and re-studied in attempts to further define the culture, technology, and even common medical afflictions of our distant human ancestors.

In *The Proto-Neolithic Cemetery in Shanidar Cave*, the authors provide a complete and carefully cataloged documentation of the 11,000-year-old human skeletal remains and grave goods found in Shanidar Cave. The book is well illustrated with black-and-white photographs and ink drawings and is very readable. It provides an exemplary account of the diversity and wealth of information that can be derived from the study of caves. Moreover, it is an excellent showcase for explaining what cave archaeology can tell us from a systematic study of prehistoric artifacts. The more we learn about our distant ancestors, the more we ultimately know about ourselves.

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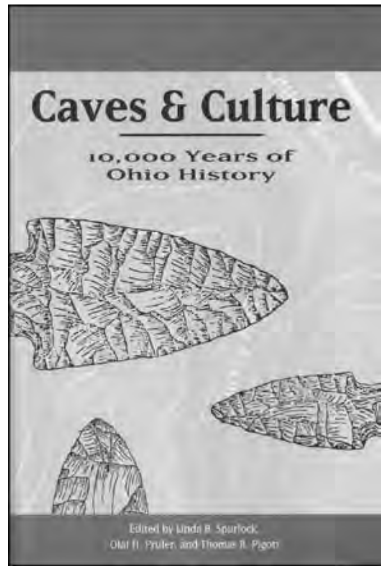
[*] Solecki, Ralph S. (1971). *Shanidar: The Humanity of Neanderthal Man*. Allen Lane/Penguin, London. Readers interested in Solecki's earlier excavations might also be interested to know that several of his finds at Shanidar served as the foundation for Neanderthal society in Jean Auel's best-selling novel, *The Clan of the Cave Bear*. The discovery of a very old and deformed Neanderthal male—who couldn't have possibly survived on his own—was the basis for the character of Kreb, the clan's holy man or Mogur. Although controversial, the finding of a Neanderthal grave filled with pollen was interpreted as a ritualized burial, similar to the one depicted in the book and movie.



Caves and Culture: 10,000 Years of Ohio History

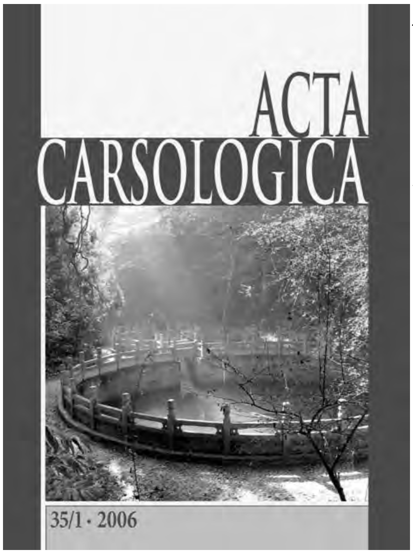
Linda B. Spurlock, Olaf H. Prufer, and Thomas R. Pigott (eds.), 2006, Kent State University Press, 463 p. ISBN 0-87338-865-8, hardcover, 6½" × 9½", $45.00.

Primarily intended for professional and serious avocational archaeologists, *Caves and Culture* presents an in-depth discussion of archaeological finds in the various caves and rock shelters that dot the state of Ohio. Continued surveys of these sites reveal their repeated use by humans and provide evidence for prehistoric habitation over three millennia in the region. While archaeological investigations of Ohio's caves and rock shelters have been ongoing for almost half a century, early discovery and interpretations of unearthed artifacts were hampered by many problems, including theft, poorly organized field notes and collecting techniques, accidental loss or deliberate disposal of valuable material, outright fraud, and disturbance of sites by modern human activity. These and other issues are considered in the detailed description of various sites.

Each chapter is devoted to a separate study site and typically includes a discussion of the physical setting of the cave or rock shelter; historical aspects of research at the site, including both local politics and personalities of those involved; and archaeological finds and interpretations. The book concludes with a brief discussion of the historic use of local caves over the past few hundred years.

Although largely free of complicated jargon, this work is not a popularized account of archaeology written for the lay reader. Serious students of archaeology or human prehistory will find much to interest them.

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



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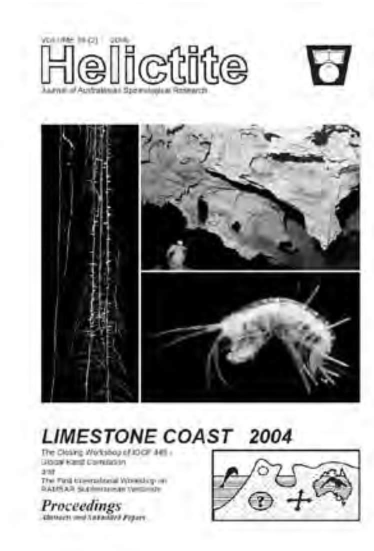

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www. speleogenesis.info

This is a special issue, a joint publication with *Cave & Karst Science* (vol.32, 2-3) and *Carsologica Sinica* (vol.25), dedicated to tiankengs (giant dolines) in South China and elsewhere. This is a prime outcome from the 2005 Tiankeng International Investigation Project, organized by Prof. Zhu Xuewen and his team.

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This index covers all articles and abstracts published in volume 68 parts 1, 2, and 3. Selected abstracts from the 2006 Society convention in Bellingham, Washington are included.

The index has three sections. The first is a **Keyword** index, containing general and specific terms from the title and body of an article. This includes cave names, geographic names, etc. Numerical keywords (such as 1814) are indexed according to alphabetic spelling (Eighteen fourteen). The second section is a **Biologic** names index. These terms are Latin names of organisms discussed in articles. For articles containing extensive lists of organisms, indexing was conducted at least to the level of Order. The third section is an alphabetical **Author** index. Articles with multiple authors are indexed for each author, and each author's name was cited as given.

Citations include only the name of the author, followed by the page numbers. Within an index listing, such as "Bats", the earliest article is cited first.

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