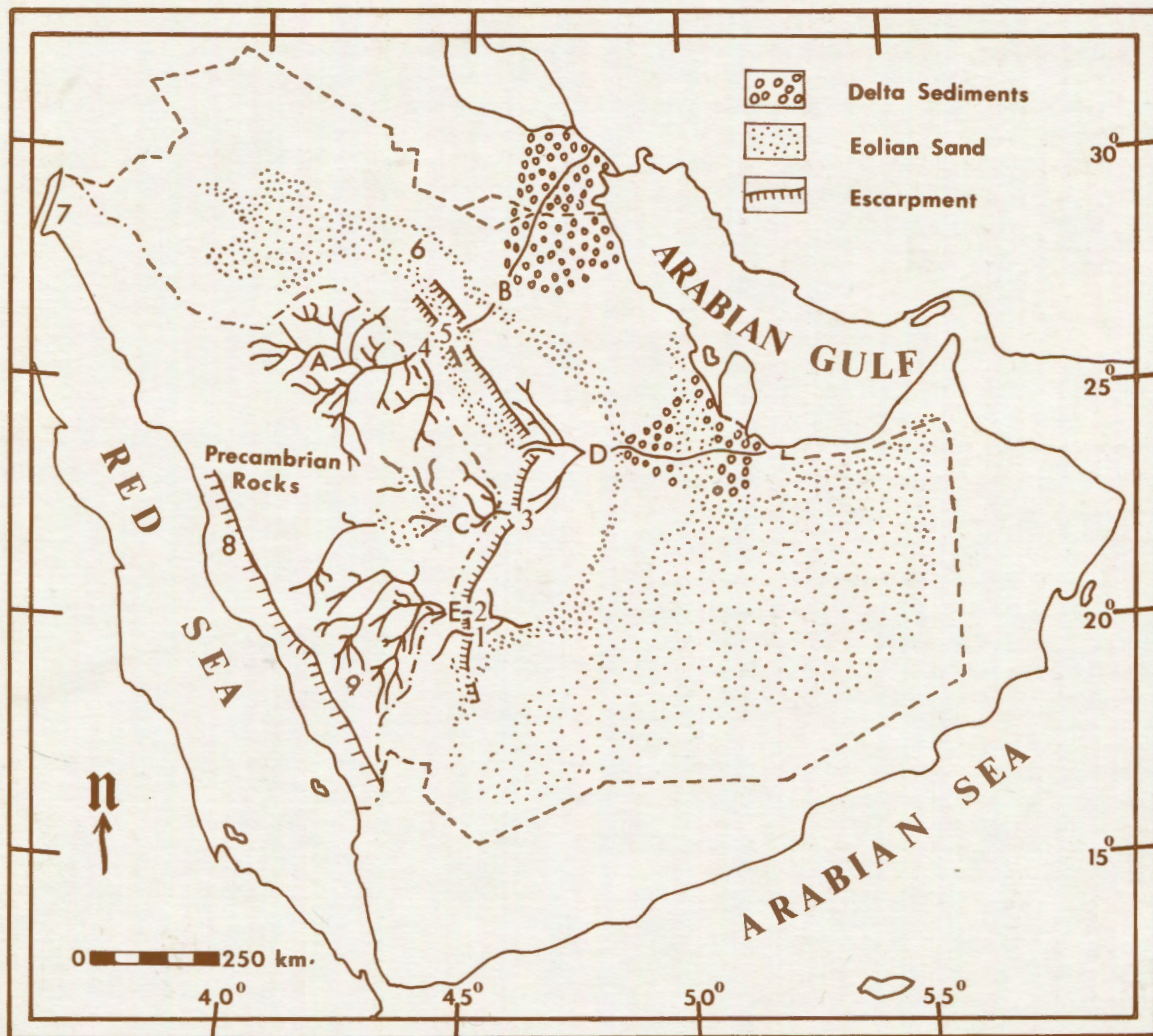


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# THIRTY YEARS OF MAPPING BY THE CAVE RESEARCH FOUNDATION

MICHAEL R. SUTTON

*The modern era of cave mapping at Mammoth Cave, Kentucky, originated with the exploration and mapping of Crystal Cave in the 1950's by William Austin. Austin recruited National Speleological Society cavers, who incorporated as the Cave Research Foundation with the purpose of mapping and studying the caves of the Mammoth Cave region. The project assumed enormous proportions as the major caves of Flint Ridge became integrated into the world's longest cave, and as Flint Ridge, Mammoth Cave, the River System, and Roppel Cave became integrated into one gigantic system. The world's longest cave requires the world's largest and most complex cave mapping project. As techniques, hardware, and mapping slowly evolved to cope with the extraordinary demands, CRF expanded its boundaries by incorporating with the Guadalupe Cave Survey and later with the Lilburn (California) Survey. The local expertise developed to meet the peculiar problems of mapping Carlsbad Cavern and Lilburn Cave in turn influenced styles and techniques at Mammoth Cave. The Ozarks of Arkansas were the scene of a CRF mapping project and this led indirectly to the present phase of highly detailed mapping at Mammoth Cave, initiated by Missouri mappers. The present status and likely future trends of CRF cave mapping are discussed.*

## ORIGINS

Cave mapping in the Mammoth Cave region has a long and altercaceous history. The earliest known map is the crude c.1811 "Eye-Draught" map of the big saltpetre cave on the Green River which was soon to become world famous as Mammoth Cave. Accurate maps of Mammoth Cave were highly sensitive and were usually suppressed—by showing where the cave lay beyond the Mammoth Cave property such maps might invite exploitation by competitors (Meloy, 1975). George Morrison's clandestine surveys and subsequent opening of the New Entrance in 1921 showed that fear to be well founded. The aura of secrecy persisted beyond the establishment of Mammoth Cave National Park in 1946.

One of the commercial caves left as an inholding within the park was Floyd Collins' Crystal Cave, a marginal business located in an out of the way corner on the far end of Flint Ridge. In the late 1940's the owners had an "accurate instrumental survey" of the tourist trails prepared. The map was shown in the promotional folder for the cave but the scale and orientation were deliberately omitted. By 1948, Bill Austin, grandson of the owner, was accompanying manager Jim Dyer and guide Luther Miller on trips to explore the extensive labyrinth below the tour trails. But Austin wasn't content to merely explore and he and Miller set to work with chain and compass. Austin's desire to map the lower levels of Crystal Cave started what was to become the greatest mapping project in the world of speleology, a project which continues to this day.

Austin's surveying expertise came from an academic background in civil engineering. He plotted his surveys by a "lati-

tude and departure" method, whereby the position of each survey station is calculated by trigonometry (R. Brucker, pers. comm.). The resulting line plots showed no walls or passage details but they indicated where the maze of passages lay with respect to each other and to the surface. Two years later, Austin and Dyer started recruiting outside cavers to assist with the work. Some, including Jack Lehrberger, were already active in the Flint Ridge caves; others, such as Roger Brucker, Phil Smith and Roger McClure, were new to Kentucky caving. Brucker, Smith, and McClure were members of the National Speleological Society (NSS). Austin proposed that the NSS launch an expedition to explore and map in Crystal Cave (Lawrence and Brucker, 1955).

There was another factor motivating the Crystal Cave expedition. By 1953, Austin, now manager of the cave, and his uncle E. Robert Pohl, who with his aunt owned the cave, realized that the day the property would be purchased by the National Park Service (NPS) was not far off. They were well aware of the publicity value of the expedition. If Crystal Cave could be shown, with much fanfare, to be large and significant, its market value might increase. The Collins' Crystal Cave (C-3) expedition took place in February 1954. The explorers didn't find or map very much new passage but the cavers who would form the nucleus of the Cave Research Foundation were now gathered.

While Austin wanted to show that his cave had a lot of significant passage, he was not anxious to publish a detailed map. The Crystal Cave management had an adversarial relationship with the NPS. Austin didn't want it widely known that his cave extended under NPS property or that some passages approached

very close to Salts Cave, a large Flint Ridge cave within the park. A few expedition members glimpsed Austin's line plots but he didn't make them available to the expedition. Some of the NSS cavers weren't content with this state of affairs and became enmeshed in the longstanding Kentucky tradition of clandestine cave surveys. Brucker, Earl Thierry, and Roy Charlton took the tour trail map, paced off some passages to scale it roughly, and took test sightings to orient it. Then Brucker secretly resurveyed a tie to Floyd's Lost Passage. This allowed him to extend a line from the expedition survey to the bottom of Bottomless Pit, where the tourist map ended (Lawrence and Brucker, 1975 reprint). The result was a rough composite map, showing passage outlines and surface topography. From it was drafted an isometric view used to illustrate Lawrence and Brucker's story of the expedition, *The Caves Beyond*. Austin forgave the indiscretion and co-opted the NSS cavers into his secret survey of the miles of uncharted passage that he, Lehrberger, and others had discovered in Unknown Cave on NPS property. These discoveries led, in September 1955, to the connection of Crystal and Unknown Caves (Brucker and Watson, 1976).

The NSS cavers already had some survey experience; McClure and Smith had mapped a few small caves for the Ohio Geological Survey (McClure, pers. comm.). But they learned a great deal from Austin, who had by now mapped much of Crystal and Salts Caves. Austin generally mapped with a two man crew. The NSS cavers switched at an early stage to a standardized three or four person crew. Two surveyors stretched out the "chain" (a steel tape) between successive survey stations while another took a compass bearing from one station to the next using a hand-held Brunton compass. The fourth member noted the readings and occasionally added a rough sketch of the passage. Vertical angles were measured only when they were estimated to exceed five degrees (Watson, R., 1981)—a hand-held Brunton clinometer is inaccurate and the inherent error might exceed smaller passage gradients. The system has remained fundamentally unchanged to the present, although refinements were slowly introduced.

Austin's maps were aimed at finding out where the cave went: How closely and at what points did Crystal Cave approach Salts Cave? Where, precisely, was the end of Pohl Avenue? The nature of the passages was a secondary consideration. The clandestine survey of Unknown Cave that Austin showed to the NSS cavers was a very crude line plot, linking only one survey station in five. The survey to find the site for the Austin Entrance to Unknown Cave was painstakingly repeated to ensure an accurate line but no attempt was made to portray the passage (Brucker and Watson, 1976). From the beginning, Brucker started to incorporate more detail and the focus shifted from the immediately practical—"Where does this passage go?"—to the descriptive—"What is the cave like?" Then, as now, there was a conflict between the desire to find out as quickly as possible where the cave lay and the desire to portray

it in detail. In *The Longest Cave*, Brucker's and Richard Watson's story of the Flint Ridge-Mammoth Cave connection, Brucker tells of having trouble keeping up with sketching Turner Avenue in Unknown Cave because of Austin's high-speed surveying. In part, the story of CRF mapping has been one of steady progression towards ever higher standards of detail and accuracy. It has also been a story of the struggle to come to grips with mapping a cave that expanded beyond the wildest imaginings to become, by far, the longest in the world.

#### THE EARLIEST CRF MAPS

In 1957, three years after the C-3 expedition, the group that had grown up around the exploration of the Flint Ridge caves incorporated as the Cave Research Foundation (CRF). Brucker became the chief cartographer of the new organization. In 1959, CRF signed an agreement with the NPS allowing them to undertake research and exploration in Mammoth Cave National Park. In November 1960, Crystal Cave was incorporated into the park, and at about the same time, Austin ceased to be actively involved with the exploration and survey.

The forerunner of CRF map making was a set of Crystal Cave maps plotted at a scale of 12 m/cm (100 ft./in) in 8-1/2 inch x 11 inch sections. The small size allowed the maps to be taken along by exploring parties. Brucker drafted the maps but abandoned the effort when the number reached 22—"The cave keeps going off the sections." A more systematic series was begun. The Mammoth Cave USGS topographic map was divided into quadrangles showing 30 seconds of latitude and longitude (roughly 800 m x 950 m). The map sections were enlarged by hand to a scale of 12 m/cm (100 ft./in.). A grid was laid out on the map and the intersection of the grid lines with contours were transferred, proportionately larger, to a sheet of drafting film. The enlarged contours were drawn freehand by connecting the dots, and the base maps were ready for cave passages to be added. (R. Brucker, pers. comm.).

The earliest CRF surveys, following Austin's style, were line plots (Watson, R., 1981). Occasionally the mappers recorded the nature of the passage, usually by drawing cross-sections. Brucker and Mickey (Louise) Storts plotted up surveys in the Flint Ridge "Spelee Hut" as soon as the survey crews brought them in. The first maps were drawn on vellum but the mappers soon switched to drafting film, which doesn't change dimensions with changing humidity. Austin's laborious method of calculating coordinates was abandoned in favor of using a less accurate but quicker drafting machine (basically, a ruler and protractor) Each survey was drawn on a separate sheet of paper, then traced onto one of the master maps. For several years the readings were recorded in a master survey book. By 1959, this had been abandoned and the original field survey books were stored instead. Most surveys now included a rough plan view of the passage. As the emphasis started to change towards more detailed documentation, the mappers found it necessary to resurvey certain passages for increased detail. The

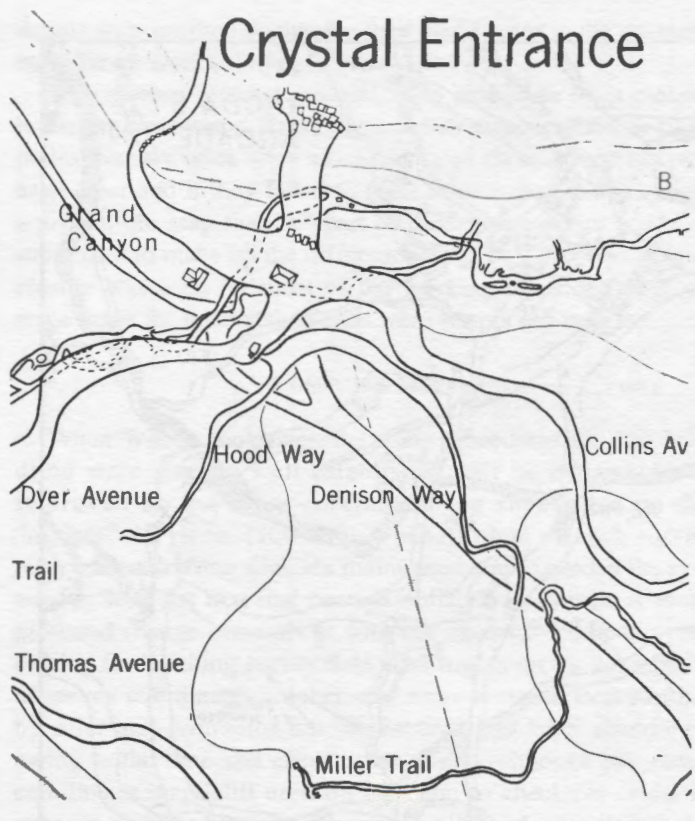
lack of good vertical data was already becoming a problem at this early stage, a problem that wasn't solved until much later.

In late 1959, the CRF surveyors started mapping Colossal Cave, southeast of the Crystal/Unknown system on Flint Ridge. This quickly led to the second connection, between Colossal and Salts Caves. A year later, explorers found a link between the Lower Crouchway in the Crystal/Unknown complex and Indian Avenue in Salts/Colossal (Brucker and Watson, 1976). Suddenly the cavers were dealing with one enormous Flint Ridge cave. When the link was plotted, the closure error was 45 m (150 ft.), or 0.6% of the traverse length, a very fair closure for the techniques used. The entrances, however, were not accurately located so the closure figure was not reliable. Nor was there any attempt to close the survey vertically (Watson, R., 1981; R. Brucker, pers. comm.). The mappers relied on the old line plot surveys of Salts Cave until 1962, when they systematically remapped its major passages.

About 1960, the CRF board of directors decided to publish the 30-second maps as a Flint Ridge Folio. There followed a flurry of drafting activity led by Brucker. Cincinnati cavers under the leadership of Ralph Ewers did much of the work of enlarging the topographic map and tracing the results onto illustration board. Jill Houston of Yellow Springs, Ohio, was hired to transfer the cave maps to the boards (R. Brucker, pers. comm.). But after the integration of the Flint Ridge caves, the fast influx of data became hard to cope with. In the CRF Annual Report for 1960, Brucker noted a delay in translating field notes to maps and called for mapping to follow exploration more closely. Also, the organization had expanded and the newcomers had no ready access to maps. One of the frustrated new generation was Denver Burns. He prevailed upon Brucker to try to get the data organized and the drafting up to date, but good intentions weren't enough. In 1965, with the assistance of Joe Davidson, Burns liberated from Brucker's house two small cardboard boxes containing all 128 survey books (Burns, 1987).

#### THE BOUNDARIES EXPAND

By the end of Burns' first year as chief cartographer the survey book collection had expanded to 200 and it was obvious that procedures had to be formalized. Burns set up a "map factory" in his house in Columbus, Ohio, where eight or nine people would show up for weekly sessions of drafting maps and filing data. Regulars at the map factory included Davidson, Fred Dickey, John Bridge, Gary Eller, Sarah and Bill Bishop, and Jack Freeman. (Burns, pers. comm.). Burns initiated two new procedures. First, each survey was drawn up more or less at once on drafting film for a permanent record. Second, the interconnections between the surveys were formally recorded in a master log book and on a series of "wiring diagrams" showing the connections between the surveys—this was necessary because many different surveys had the same letter designation. Now anyone who wished could find a particular survey and

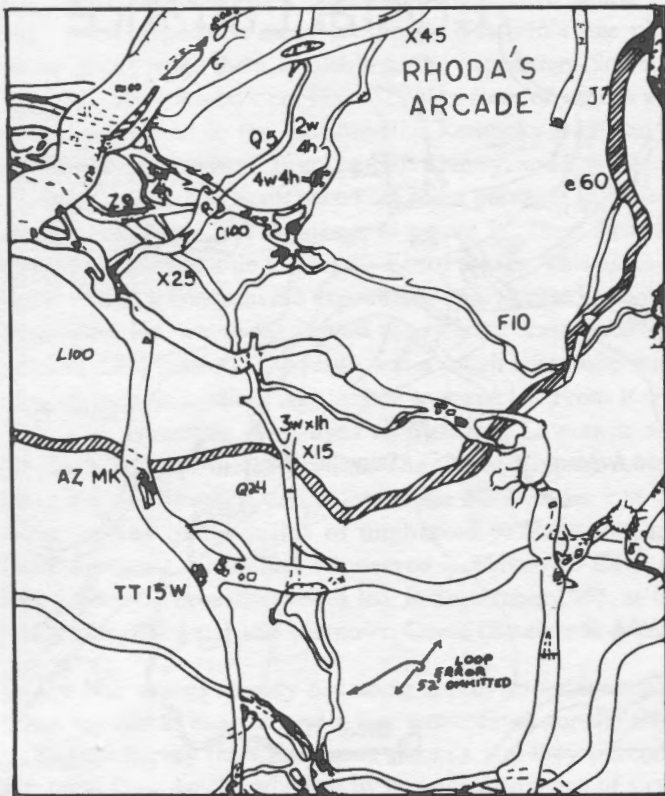


**Figure 1.** The Flint Ridge Folio, produced in 1965 was CRF's first published map. Thirty 11 inch x 14 inch sheets show the 70 km (44 miles) of the Flint Ridge system surveyed through 1962. The fine lines are 20 ft. surface contours; the feature that appears to underly the cave passages is a road. The scale is approximately 30 m/cm.

would know how it related to the total network (Burns, pers. comm.).

The innovations were put to good use in bringing the Flint Ridge Folio to completion. Burns picked up the project where Brucker had left off. Storts made labels for the passage names. Burns, with Davidson and Smith, devised a title format and had the type set. By late 1965 the folio was ready to print. Nobody had seen such a cave map before, professionally prepared and divided into handy sections. Early in 1966, the CRF hosted a dinner at the Mammoth Cave hotel and invited the senior staff of Mammoth Cave National Park for the official unveiling (R. Brucker, pers. comm.).

This cartographic epic consisted of 30 sheets, 11 inches x 14 inches, covering the whole of Flint Ridge. The 12 m/cm (100 ft./in.) working maps were reduced to a scale of roughly 30 m/cm. Twenty four sheets covered the 70 km (44 miles) of cave surveyed through 1962 (the other six sheets were "blanks," showing only surface features). An index map and two pages of explanatory text, written by Brucker and Burns, completed the



**Figure 2.** Detail from the draft map of the Cleaveland Avenue area of Mammoth Cave, drawn in 1975. TT15W is a Walker survey benchmark in Ole Bull's Concert Hall. The large passage at upper left is Blue Spring Branch. Note the method for closing loops. The scale is approximately 18 m/cm; scale of the original is 12 m/cm (100 ft./in.).

package. The Folio gave the first detailed look at the incredible Flint Ridge maze. The major passage interconnections and many of the minor ones were made clear and a fair amount of passage detail was included, at least for the larger passages. Surface topography and features such as roads were shown (Fig. 1). By the time the Folio was published, the Flint Ridge Cave System was 84 km (52 miles) long and had overtaken Switzerland's Hölloch as the longest known cave. The Folio was already out of date. Further editions were planned but were never produced.

Burns retained the post of chief cartographer for five more years, as the pace of discovery and mapping continued to increase. New survey was supplemented by a substantial amount of resurvey to bring inaccurate or undetailed older work up to current standards. In 1969, the geographic boundaries expanded drastically as the CRF mappers started surveying in Joppa Ridge and in Mammoth Cave itself (Watson, R., 1984.1).

Mapping in Mammoth Cave dates from the c.1811 "Eye-Draught" map and continues into the tourist era. Two maps are particularly useful. The first is Max Kaemper's cartographic

masterpiece of 1908, showing 58 km (36 miles) with great precision. It made a solid base around which to build the CRF exploration and mapping program. The second is the 1956 map by Ray Nelson, an NPS naturalist. His map shows 52 km (32 miles), 17 km (11 miles) of which had been surveyed since 1908. The map relies heavily on a 1936 transit survey by H.D. Walker, who mapped 34 km (21 miles) of trunk passage and placed permanent brass caps at major intersections (Fig. 2). Robert Hosley later reworked the Walker survey to form a very rigid framework—the longest loop miscloses by less than one foot (Hosley, 1973). The "benchmarks" presented the CRF mappers with 40 or so well-defined reference points.

An aerial survey helped tighten up the survey net under Flint Ridge, which had no system of "benchmarks" to compare with those of Mammoth Cave Ridge. The survey was run in 1970-1971 by arrangement with the Geodetic Science Department at Ohio State University (OSU), who were developing a means to locate and scale accurately photographs of the lunar surface. Their main difficulty was that computer programs couldn't simultaneously adjust points on more than nine photographs at once. OSU used the Flint Ridge aerial survey as a testing ground to develop research ideas for overcoming the problem. The aerial targets were assembled in Burns' basement, and several weekends were spent locating Geodetic markers and surveying from points inside entrances to the targets. OSU had to fly a second time due to bad weather on the first attempt. Later, Dennis Drum and others converted the photographic work to accurate entrance locations (Burns, pers. comm.).

#### CONNECTIONS

When Burns moved from Ohio in 1971, John Wilcox, a relatively new recruit to the mapping team, took over the map factory. To avoid having to move the factory he simply moved into Burns' old apartment (Burns, 1987). Dickey and Scooter (Charles) Hildebolt initially did the lion's share of survey plotting; later, Will and Pat Crowther, Bill Mann, and Richard Zopf joined the map makers. If the pace had seemed fast before, it now became dizzying. The year 1971 saw a record 31 km (19 miles) mapped. In 1972, 34 km (21 miles) were added as the survey net became integrated, under Wilcox's direction, into one Flint-Mammoth Cave System, 232 km (144 miles) long. In 1973, Mammoth Cave passed the legendary 150 mile mark, turning advertising hyperbole into fact, and breaking the survey record again with an astonishing 43 km (27 miles). (There are only 30 caves in the world with more than 43 km mapped—Courbon et al., 1989) Somewhere in the midst of this explosion of activity, the goal of publishing an updated map folio receded from sight. Wilcox and his colleagues were coping with more information coming in at a faster rate than any cave mapper had ever had to deal with.

The decade that followed was a time of experimentation with different formats and of realizing the broad-scale geography of a cave that now sprawled under four major ridges and

their intervening valleys. It's no surprise that many of the maps published during this period were broad in scope, encompassing the whole fantastic network and its relationship to the surface. A map card at a scale of 48 m/cm (400 ft./in.), based in part on CRF surveys, was produced in 1968 (and revised in 1969) by NPS hydrologist James Quinlan. The 6-inch x 10-inch card shows line plots of the as yet unconnected caves of Flint, Mammoth Cave, and Joppa Ridges, with the surface topography superimposed. In 1973, the CRF mappers produced a new map card at a scale of 360 m/cm (3000 ft./in.), based on the Crowthers' computer data base showing the now connected cave system. Two years later, a revised map card was published, showing 275 km (170 miles), including two outliers, Proctor Cave (at that time still unconnected to Mammoth Cave), and Great Onyx Cave. All of the map cards still relied on the old Walker survey, and even on pieces of the Kaemper map, for parts of Historic Mammoth Cave (P. and J. Wilcox, pers. comm.).

Another notable product of the period was Pat Crowther's 1975 map of Lee Cave, a large Joppa Ridge cave unconnected to the Mammoth system. The map, skillfully drafted at a scale of 30 m/cm shows a fair amount of passage detail with a generous number of cross sections and an unobtrusive topographic overlay. It was intended to be a prototype, setting graphic standards for a new set of maps (R. Brucker, pers. comm.) but unfortunately no further maps of this type were produced.

In contrast to these general purpose works, many of the maps published during the late 1960's and early 1970's responded to specific needs. In 1969, a Salts Cave manuscript map was adapted to illustrate Patty Jo Watson's *The Prehistory of Salts Cave, Kentucky*; in 1973 updated maps of Salts Cave, together with fairly detailed maps of Ganter Avenue in Mammoth Cave, were drawn to illustrate Watson's *Archaeology of the Mammoth Cave Area*. Perhaps the most striking of these efforts was the map series produced in 1976 to illustrate *The Longest Cave*. The series of ten maps vividly shows the sequence of exploration from 1952 to 1972, as the known fragments of the Flint Ridge system expanded in leaps and bounds, and then crept towards Mammoth Cave.

A lot of effort went into experimenting with unpublished working maps at different scales and in different formats. Several systems of partitioning were tried, based on map geography or on more arbitrary schemes (Zopf, pers. comm.). The Crowthers produced a map of the Bedquilt area of Colossal Cave. This is an intricate maze of small channels, and earlier efforts had failed to make sense of it. At about the same time a variety of "field maps"—pencil drafts to be elaborated on later—came into being. These included the Crowthers' map of the Cleaveland Avenue area (Fig. 2), Wilcox's maps of the New Discovery and Little Hope sections, Brucker's map of Proctor Cave, and area maps of Mystic River, Eastern Mammoth, and Carlo's Way (Watson, R., 1984.2). Walter Lipton was another active cartographer—his most notable effort was a 30 m/cm draft showing passage levels in east central Mammoth Cave. Passage

details were omitted so that the user could color in the passages by different level (Lipton, 1974).

No rigorous attempt was made to distribute loop closure errors on these maps. Rather, key points were selected as fixed nodes. Survey lines were extended from these points towards each other and if they failed to meet or overshot, it was simply noted on the map that "x" feet of passage had been added or subtracted to make up the difference (Fig. 2). This style of loop closure was used for most of the working maps, although on some maps the mismatched ends were simply left hanging.

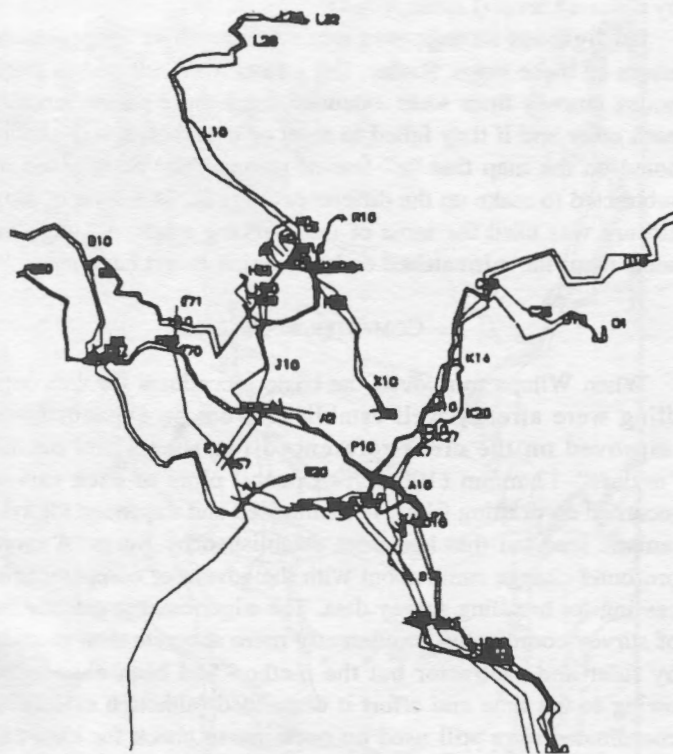
#### COMPUTER MAPS

When Wilcox took over, the basic procedures for data handling were already well established, but he expanded and improved on the cross-referenced log sheets and on the "mylars"—12 m/cm (100 ft./in.) pencil plots of each survey recorded on drafting film. He maintained and expanded the systematic lead list that had been established by Burns. A more profound change came about with the advent of computer processing for handling survey data. The trigonometric calculation of survey coordinates is inherently more accurate than plotting by ruler and protractor but the method had been abandoned owing to the time and effort it demanded (although calculated coordinates were still used on occasion to check for errors in surveys already plotted). The availability of computer technology changed all that.

Computer plotting of surveys had been tried since 1969, but the Crowthers began to exploit the new techniques to the full. Will Crowther wrote data reduction programs for a PDP 1 computer, which converted bearings and distances into survey station coordinates. A Calcomp drum plotter then turned the coordinates into line plots, which could be drawn at various scales. Several useful maps were made this way, including a small-scale map of the newly expanded Proctor Cave, at that time still unconnected to Mammoth Cave. Soon, all surveys were sent to the Crowthers, who typed them into the Bolt Beranak and Newman system from a Teletype terminal at their home in Arlington, Massachusetts. Eventually, the entire survey database was stored on computer tapes (J. and P. Wilcox, pers. comm.).

The line plots evolved by 1976 into large computer-drawn maps showing Walker and CRF surveys at a scale of 30 m/cm (Fig. 3). The maps crudely showed passage widths by including wall measurements at each station with straight lines drawn between them. No one, in all likelihood, would claim cartographic elegance for these maps; the superimposed lines of overlapping passages, the dense areas where station is piled upon station and the resurveys running parallel to the lines of earlier surveys, all serve to make the maps difficult to read. This was, however, a very advanced use for computer technology in cave mapping and the maps are still useful to an extent today.

Refinements in the tape and compass surveys helped to improve the accuracy and detail of the maps. The Crowthers intro-



**Figure 3.** Detail from map of Flint Ridge drawn by a Cal-comp plotter. The area depicted is centered on the Bögli Shafts. Passage widths are indicated by drawing straight lines between the wall measurements at each station. Swinerton Avenue (lower left) is shown as a single line, since the earliest survey did not include wall measurements. No attempt is made to differentiate overlapping levels. The scale is 30 m/cm (250 ft./in.).

duced the practice of two-way compass bearings (backsighting) to avoid errors and to solve the eccentricity problem (where the foresight and backsight of a given compass may not match). By 1977, backsighting had become routine (R. Brucker, pers. comm.). Likewise, vertical control was improved with the introduction of the easy-to-use Suunto clinometer, allowing vertical angles to be measured on all shots. The quality of in-cave sketching improved and muddy, illegible survey books became less prevalent.

Following earlier work by Alan Hill, Frank Reid experimented with finding the locations of selected points underground by "cave radio"—a magnetic induction device. While a team of cavers carried a transmitter and coil to suitable locations deep in Flint Ridge, a surface crew with a receiver recorded the corresponding point on the surface. In 1973, five accurate locations were obtained. Then a surface transit survey was run to tie these points to the survey net (Watson, R. 1984.1).

By 1975, the period of frantic activity had started to wane. Will Crowther ceased to be involved, and John and Pat (Crowther) Wilcox slackened off their activities, although they continued to contribute for many years. The computer applications had hinged on Will Crowther's access to an ancient PDP I computer and the effort came to a temporary halt. Mann and John Robinson took over for a time and rewrote the programs in Fortran for a PDP 10 computer, adding a capability for calculating loop closures (J. and P. Wilcox, pers. comm.). But by 1980, the mainframe computer system was in disarray and occasional attempts to revive it were not very successful (Palmer, M., 1980). Meanwhile, the pace of surveying continued to outstrip the capacity of the cartographers to deal with it. The CRF Annual Report for 1977 estimates a drafting backlog of 18 months—probably an optimistic assessment (Watson, R. 1984.2).

#### NEW MAP FORMATS

Wilcox last logged a survey book in May 1977. Tom Cottrell and Tomislav Gracanin had taken over some of the routine chores and Hildebolt offered his basement for map production. Brucker continued to be involved and Lynn Weller joined the team. But gradually the pieces of the mapping program accrued to Zopf and by late 1978 he had assumed complete responsibility (Zopf, pers. comm.). In the intervening period, work on the field maps continued and the field map concept was extended to the whole of Flint Ridge. The pencilled maps, at a scale of 12 m/cm (100 ft./in.), include passage cross-sections and topographic overlays. The Ralph's River Trail area of Unknown Cave was thoroughly reworked under the direction of Jim Borden. The priceless collection of survey books, now 1300 in number, were safeguarded by photographing them for a microfiche file, under the direction of Cottrell (R. Brucker, pers. comm.).

In 1979, with 345 km (214 miles) mapped in the Mammoth Cave System, map production was still slow, and in 1980 the mapping program was "not meeting the needs of the exploration program" (Palmer, M., 1980). By 1984, data processing was still behind and the CRF board of directors paid for some of Zopf's time so that he could catch up with the backlog. Despite the bottleneck, work continued steadily. Brucker compiled a Proctor Cave map in 1978; Gracanin updated Wilcox's New Discovery map; Weller worked on Wilcox's Little Hope map (R. Brucker, pers. comm.). Maps produced during the early 1980's included Gerry Estes' partial map of Salts Cave and Beth Estes' comprehensive map of the Brucker Breakdown area in Flint Ridge. Working drafts were still being produced—Scott Smithson drew up a map of the Ferguson Entrance area; Gerry Estes mapped a very complicated area centered on Lower Robertson Avenue (Palmer, M., 1982; Lavoie, 1983).

In 1981, two notable maps were published in time for the International Union of Speleology meeting at Mammoth Cave (Lindsley, K., 1981). One was a poster map at a scale of 120



m/cm (1000 ft./in.). The map shows Mammoth Cave in four colors on a striking black background, each color representing a range of passage levels. Many people, including Zopf, Lipton, Weller, Roger Brucker, and Tom Brucker, helped with its production. The poster was well received and won a prestigious design award from the Society of Typographic Artists. The other map was a colorful reproduction of Kaemper's 1908 survey of Mammoth Cave. Faithfully following the original, the map is handlettered and has no scale or north arrow (a second Kaemper map, keyed to the first, gave this vital information). Diana Daunt, who became active about 1974, redrew this interesting, popular, and useful map. Amazingly, it remains the only comprehensive map available for most of historic Mammoth Cave.

Zopf made several organizational refinements to help cope with the continuing influx of data. The density of passages in some areas of the 30 m/cm computer plots prompted him to sort out the mess with survey schematics—expanded versions of the “wiring diagrams” of Burns and Wilcox (Zopf, pers. comm.). The schematics developed into a comprehensive tool showing the survey net of the cave, indexed to the survey book collection. Although the schematics distorted the geography, they portrayed the interconnections accurately and they became indispensable tools for mapping and even for in-cave navigation in areas where detailed working maps didn't exist.

Survey techniques continued to show steady improvement. One important refinement was the establishment of a permanent compass calibration course at the Flint Ridge field station. Pat and John Wilcox had earlier set up a temporary course intended mainly to determine compass eccentricity errors, but it was occasionally mowed over and frost heaving caused further disruption. Zopf established the new course with deeply set posts positioned by compass and tape, and Gracanic surveyed it with a one-second theodolite (Palmer, M., 1980). All survey crews now calibrated their compasses shortly before entering the cave. In addition, long-term drift of the local magnetic declination could be monitored. The computer system enjoyed a partial revival and in 1981 CRF purchased an S-100 computer and Calcomp plotter dedicated to the mapping program. Roger Miller was one of the key people attempting to develop a more practical data reduction program; Mann and Bill Hawes were also involved with the computing activities (Zopf, pers. comm.). The computer produced line plots, but the line plots of individual surveys were fitted to the master maps and adjusted by hand—there was no coordinate system that could be applied uniformly to the whole cave.

During Zopf's tenure, the mapping program gradually became less centralized. The availability of microfiche survey books allowed subsidiary map factories to be set up. In 1981, Daunt set up such a factory in Louisville, Kentucky, where the Kaemper reproduction was drawn.

Meanwhile, the known limits of the cave continued to expand. In 1979, Joppa Ridge entered the system when Proctor and Morrison Caves were linked to Mammoth Cave via the

extensive River System (Borden and Crecelius, 1984). Don Coons, working for NPS hydrologist Quinlan, used CRF data to draft a working map of the River area. Then in 1983, Roppel Cave, a 78 km (49 mile) long system mapped and explored by the Central Kentucky Karst Coalition (CKKC) was linked to the River by a joint CRF/CKKC crew (Borden and Crecelius, 1984; Brucker, 1984). The cave now approached a staggering 500 km in length. The link with Roppel meant that the CRF mappers no longer controlled the mapping of the whole of Mammoth Cave, and an era of cooperation with an outside group began. The most visible product of this cooperation was a revised map card published in 1985, using both CRF and CKKC surveys to show the entire 500 km (300 miles). McClure, Smithson, Roger Brucker, and others worked on the project.

#### GEOLOGIC MAPS

Several geologists provided an impetus towards higher levels of detail and accuracy. The application of cave maps to Mammoth Cave geology dates back at least to 1955, when Pohl showed that vertical shafts in Mammoth, Colossal, and Proctor Caves occurred almost exclusively around the sandstone edge of the plateau (Pohl 1955). This required only that the shafts' positions be known to a fair approximation. Likewise, Roger Brucker's study showing that disjointed parts of trunk passages could be found on either side of an intervening valley required only rough positions and elevations (Brucker, 1966). But by the early 1960's, the geologists needed more detailed maps than the mapping program was providing. George Deike had learned cave mapping in Missouri, where detailed cave maps had become standard at an early date. He and Will White relied largely on Missouri maps for their study of the sinuosity of cave passages and the relation of passage orientation to jointing (Deike and White, 1967). Deike, then a graduate student, extended this study to Flint Ridge and Mammoth Cave, where he made detailed surveys.

In the late 1960's, geologists Art and Peggy Palmer started looking at the concordance between passage levels and geological structure. They needed precise elevations, a feature notably lacking from the mapping effort until then. They began leveling the major passages of the system, using hand levels and water tubes. In 1969, they started a detailed survey of the Crystal Cave section of Mammoth, the aim of which was to level and record the stratigraphy of every passage in this complex network. They chose Crystal Cave because of its large vertical range and its proximity to the Green River—any base level control of passage development would likely show up in the elevation data. The Palmers worked alone to minimize distractions. They measured elevation changes with a telescoping Locke hand level, using a datum-line method, whereby a continuous horizontal line is projected through each passage. Distances to features of interest (floor, ceiling, particular beds) were measured from the datum line. The survey was tied to the compass and tape horizontal survey. To obtain a closed loop, they

extended the levelling through Crystal Cave to the Austin Entrance and back overland, obtaining a remarkable misclosure of only 6 cm (0.2 ft.). This was no doubt fortuitous, but the largest error in any of their survey loops was less than 30 cm (1 ft.).

One of the first results of the levelling project was a stratigraphic column for Crystal Cave that includes 65 lithological units. Several major passage levels were distinguished and these were correlated with surface terraces, simultaneously mapped by Franz-Dieter Miotke (Miotke and Palmer, 1972). The Palmers fell short of their goal of levelling every passage, since many unsurveyed passages were encountered—they mapped all of these but levelled only the larger ones. Most of the work was complete by 1973 and the project was put on hold in favor of extending the stratigraphic work to other parts of the cave. Over the next ten years, the geology and levels of all major passages in the system were determined. The Crystal Cave lithological units were traced throughout Mammoth Cave, despite lateral changes in thickness and character (Palmer, A., 1981). On many of the tourist routes, elevations were measured with a tripod-mounted engineer's level, which provides one or two orders of magnitude higher precision than a hand level. This project continues today at a reduced pace. Work on Crystal Cave resumed and the Overlook area was added to the map.

The highly detailed geologic map is nearing completion; it will be produced at several scales, with enlargements of the most complicated sections (A. Palmer, pers. comm.).

WESTWARD EXPANSION—THE GUADALUPES

In 1972, CRF map making took a giant leap westward, as the Guadalupe Cave Survey (GCS), in its eighth year of operation, incorporated with the CRF. The GCS was organized in 1965 by Pete Lindsley, drawing heavily on members of the Sandia and Dallas-Fort Worth Grottos of the NSS. The group grew, with cavers from Arizona, New Mexico, and Texas working on government agency lands in the Guadalupe—mainly in Carlsbad Caverns National Park. Lindsley acted as the first cartographer for maps of new areas in Carlsbad Cavern and other caves in the Guadalupe, such as Cottonwood Cave (P. Lindsley, pers. comm.). By the time the GCS incorporated with the CRF, Jim Hardy, John Corcoran, and Robert Babb were primarily responsible for the mapping program. Later Bob Buecher, then Joe Repa took over; in 1981, Buecher again became chief cartographer, to be succeeded in 1985 by Alan Williams, and in 1988 by Dave Dell.

Mapping the Guadalupe caves, particularly Carlsbad Cavern with its large irregular rooms, ill-defined passages, and

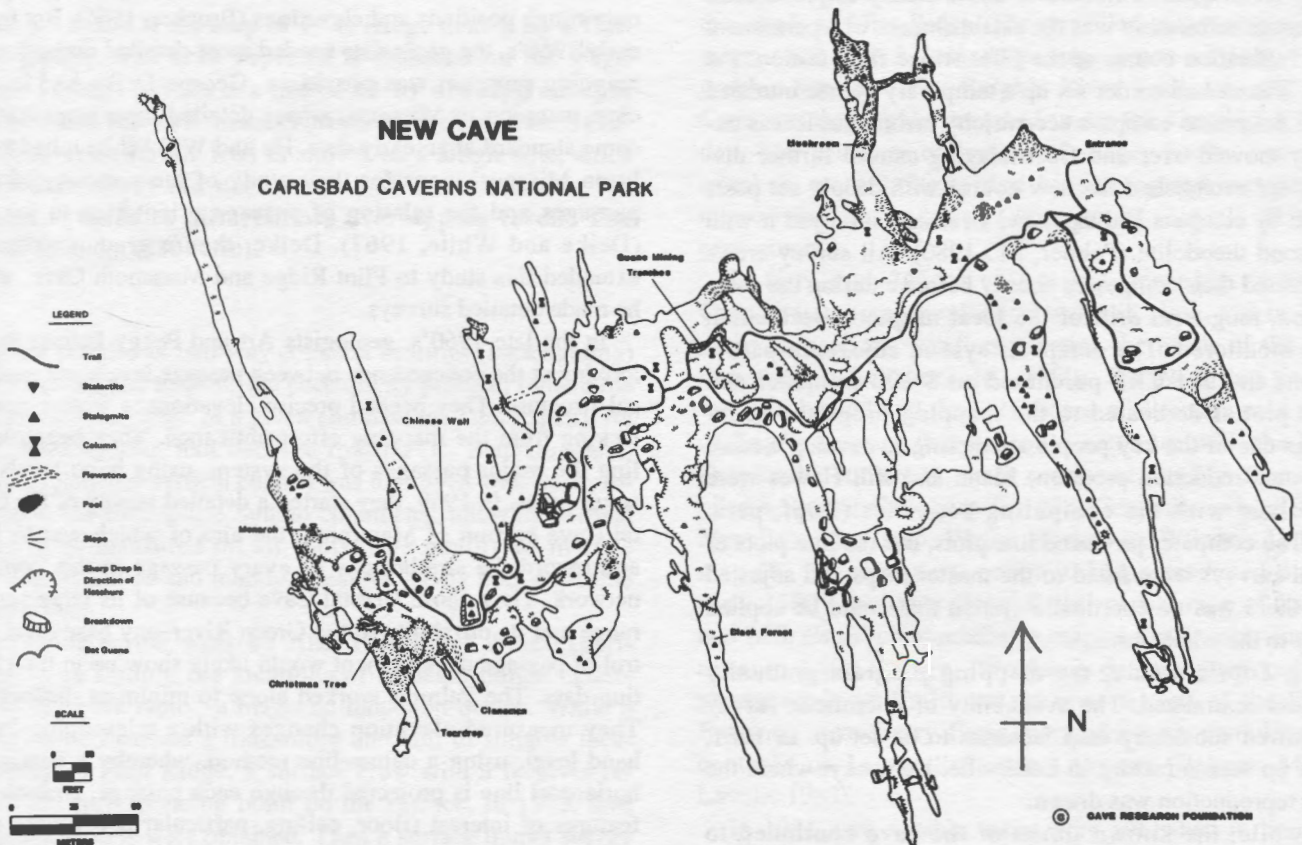


Figure 4. New Cave map card, published in 1979. Original is at a scale of 12 m/cm (100 ft./in.).

boneyard mazes, demanded different techniques from those developed in Mammoth Cave's network of linear tunnels. The vertical components of these caves had to be taken into account from the beginning and the irregular passages demanded close attention to changing passage widths and configurations in a way that didn't become standard at Mammoth Cave until much later. From the start, the emphasis was on high precision and detail. In the mid 1960's, Tom Rohrer set a baseline survey in Carlsbad Cavern, tied to USGS benchmarks, using precision levelling techniques and a theodolite. Rohrer's baseline was continued throughout Carlsbad Cavern using tripod-mounted Brunton compasses (implementing Lindsley's recently developed shadow technique—Lindsley, P., 1964) and the Brunton survey loops were adjusted for closure. Hardy and Elbert Bassham, both professional surveyors, supervised the development of a network of precision baselines that improved the accuracy of Rohrer's points. They connected the net to John McLean's gravity survey grid over the cave and ran surface baselines to connect to other cave surveys, including Spider Cave and Ogle Cave. In 1977, Bassham led a program to accurately map the Big Room by taking a series of radial shots with a laser range-finder set on Rohrer's well-defined stations.

Large-scale base maps were an early goal at Carlsbad Cavern. The cave was divided into a series of twelve 6 m/cm (50 ft./in.) quadrangles. In 1979, Buecher combined numerous working maps of separate areas to produce the first set of quadrangles. Intermediate drafts were used to construct smaller scale maps, notably the 24 m/cm (200 ft./in.) Carlsbad Caverns [sic.] map card, also published in 1979 under the leadership of McLean and Repa. As the quadrangles moved nearer to completion, Bill Wilson began to produce detailed profiles of the major passages using clinometers, water tubes, and laser range-finders for measuring inaccessible ceiling heights (Lavoie, 1983). New Cave, another major project of the Guadalupe mappers, was treated in much the same way. It was divided into nine 6 m/cm (50 ft./in.) quadrangles, and maps were produced at this scale and at 60 m/cm (500 ft./in.)—the latter was used as the basis for a New Cave map card, published in 1976 (Fig. 4).

The Guadalupe cavers have also surveyed over fifty smaller and not-so-small caves on public lands in the Guadalupe and throughout the southwest. Albuquerque area cavers worked on Edgewood Caverns, a large maze complex east of Albuquerque, and Fort Stanton Cave, where numerous quadrangles were completed under the leadership of Corcoran. The connection of Rainbow and Ogle Caves in Carlsbad Caverns National Park led to geologic investigations by David Jagnow, and an associated CRF survey of the system. The survey of Dry Cave, a multi-level maze on McKittrick Hill west of Carlsbad, has a history dating back to pre-CRF days; the mapping continues today under Hardy's direction. A systematic inventory of the gypsum karst southeast of Carlsbad Cavern began in 1976. In Spring 1988 a memorandum of agreement was signed between the CRF and Guadalupe Mountains National Park (GMNP), at the southern end of the Guadalupe range, to survey and in-

ventory the twenty or so known caves and to search for others. Jerry Atkinson is coordinating the GMNP survey.

As at Mammoth Cave, Guadalupe area geologists were both users and generators of maps. In 1975 Jagnow published *Cavern Development in the Guadalupe*, which emphasized the role of joints in Guadalupe speleogenesis and base level control of major levels. Jagnow also proposed that sulfuric acid solution was a major factor in development of the caves. The first two aspects in particular relied heavily on maps. CRF maps of Carlsbad Cavern, Cottonwood Cave, the Rainbow—Ogle system and many others were put to practical use in constructing joint-set rose diagrams. To augment his data, Jagnow field-checked and revised the map of Carlsbad Cavern's Left Hand Tunnel during 1972 and mapped several smaller caves, including Lechuguilla (only the entrance portion was then open, of course) and Queen of the Guadalupe. Carol Hill's landmark 1987 study, *The Geology of Carlsbad Cavern and other caves in the Guadalupe Mountains*, relied extensively on CRF mapping efforts, especially in Carlsbad Cavern, to develop her detailed thesis of sulfuric acid mediated speleogenesis.

Hardy, Corcoran, and Babb started the first computerized survey program for the Guadalupe operations. This happened in part because Hardy was a computer scientist as well as a professional surveyor. They developed a Fortran program to perform multiple loop closures (Hardy, 1987), a procedure which still has not been applied to the very long and complex loop network of Mammoth Cave. After Hardy became less active, Buecher continued the computerized reduction of Carlsbad Cavern data using a relational database on an Apple II computer. However, some of the early databases became scattered and disorganized. In 1979, McLean and Diana Northup took on the chore of retrieving and copying the widely dispersed survey books and created a survey book library with a duplicate stored in a separate location (Buecher, pers. comm.).

As at Mammoth Cave, Guadalupe area mapping has had its active and less active phases. Map production fell behind exploration and survey in the early 1980's but over the last few years the program has been brought back on track. A more detailed version of the Carlsbad Cavern quadrangles (including a new lower-level quadrangle) is now nearing completion, with only minor details and refinements needed. The goal is to include all available plan view surveys, with floor detail. The project is directed by Ron Lipinski; the other mappers involved are Dell, Atkinson, Dick Venters, Laura Reeves and Ron Bridgemon. A preliminary pencil draft version was published in 1988. This is available either at full scale—6 m/cm (50 ft./in.) or as a folio of reduced scale 12 m/cm (100 ft./in.) maps (Fig 5). The next phase of production will be loop closure using computer programs to distribute errors in the survey points. The preliminary version has been closed only in selected local areas—to expand to larger areas will require putting the entire Carlsbad Cavern data base on computer. About 8,000 cards of data and programs were laboriously punched by Corcoran and Fritz and Jim Hardy 20 years ago. The best card files were re-

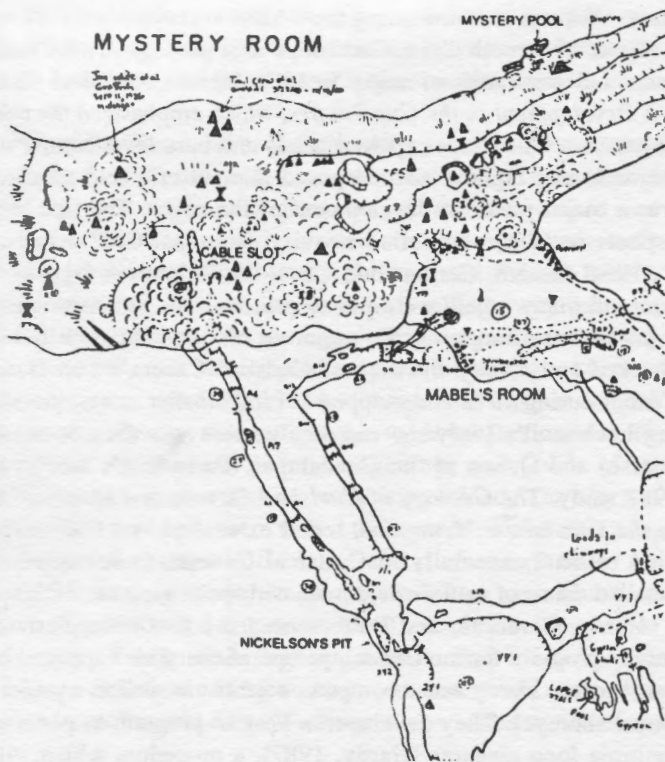


Figure 5. Detail from the 12 m/cm (100 ft./in.) Carlsbad Cavern map folio, preliminary pencil draft published in 1988. Thirteen sheets at an original scale of 6 m/cm (50 ft./in.) cover the entire cave.

cently salvaged and the data transferred to disks. Including more recent data, about 75% of the survey net is now on disks (Lipinski, pers. comm.).

The survey refinement will use the SMAPS program and a Fortran program written by Hardy. In addition, Gary Petrie of the Lechuguilla Cave Project has offered his program to assist in data manipulation. Following loop closure, the maps will be inked. This will be a major milestone for the CRF Guadalupe Escarpment area. Other benefits from having all the data on computer will include the ability to produce statistical information and to generate projections of the cave from various points of view (Lipinski, pers. comm.). Increasingly, there are demands for even more detailed maps; some of the current biological and geological research requires 2.5 m/cm detail.

Many CRF mappers are involved in the ongoing survey by the independent Lechuguilla Cave Project (LCP) of Lechuguilla Cave, which quickly became the longest and deepest cave in the Guadalupe. In July 1989, Hardy and Babb established the Lechuguilla Cave Precision Survey Project, a joint undertaking between the CRF and the LCP. The goal is to set a precision theodolite survey, using state of the art equipment, into all the major rooms of Lechuguilla Cave. This will provide an accurate

grid on which to base the present LCP surveys, and will provide essential support for the scientific program at Lechuguilla.

#### ARIZONA

Two short-term projects in Arizona in the mid 1970's added variety to the tasks of the Guadalupe area mappers. In 1975-1976, Bridgemon led a study of the earth cracks at Wupatki National Monument in northern Arizona (Bridgemon, et al., 1976). The cracks are low-displacement faults which penetrate the Kaibab Limestone and Coconino Sandstone. Several of them are enterable and the deepest, Sipapu Cavern, is 150 m (500 ft.) deep. Seven earth cracks were mapped, for a total of 1030 m (3,400 ft.). Buecher directed a theodolite surface survey in the areas of highest crack density.

In 1977-1978, Buecher led a comprehensive study, including mapping, of the caves of Horseshoe Mesa, Grand Canyon National Park. The mesa contains the densest concentration of caves within the park (Watson, R., 1984.2). The caves, all of them small, are developed in the Redwall Limestone along the mesa's edge. Plans and profiles of ten caves were produced, totalling 790 m (2,580 ft.) in length.

#### CALIFORNIA

In 1976, CRF map making moved farther west as the Lilburn Cave mappers, led by Stan Ulfeldt, joined the organization. Lilburn is a large, pristine cave, the second longest in California, located in a roadless area of Kings Canyon National Park. It provides a superb opportunity for basic research in a complex cave which has suffered almost no human alteration. The survey had been going through the doldrums. Despite years of survey, no detailed map had been produced, a fact that the NPS found increasingly unacceptable. Ulfeldt believed that incorporating with the CRF would solve some of the problems by providing a fresh input of people and expertise—a hope that proved well founded (Ulfeldt, 1987). Ellis Hedlund was the first chief cartographer; he was succeeded by Lee Blackburn, Dave DesMarais, and since 1983 by Peter Bosted (Bosted, 1987).

The development of Lilburn mapping since the merger parallels on a smaller scale that at Mammoth Cave, with a relatively crude early survey giving way to a much more comprehensive, systematic and detailed approach. Hedlund's survey began in 1966. Much of the cave had been mapped by 1973, but trips continued into 1979. A line plot of the entire survey was made but only about one third of the 11 km (7 miles) of passages were drawn onto a working map. The survey was basically accurate but lacked detail. In 1980 a systematic upgrading began and by the following year was in full swing. Working conditions had changed since Hedlund's day, as the road leading to the cave was closed and access now involved an eight km (5 mile) backpack trip, sometimes on skis or snowshoes.

Work in the first few years concentrated on resurveying the major known passages, using 2-4 person crews. New stainless

steel survey markers were set and very detailed sketches drawn. Surveys were made from the South Seas (the main stream sump at the south end of the cave) to the Myer Entrance at the north end. Details were filled in for many of the areas in between, such as the East and West Streams, Pandora's Complex, and the Schreiber Complex. Very little new survey was done at this stage. By the end of 1983, about 6 km had been remapped, using 1,260 survey stations. The average of five meters (17 ft.) per shot decreased in following years as work shifted to the smaller passages. Since 1983, most of the known secondary network has been resurveyed or resketched, and unmapped or unexplored passages have been systematically added. Currently, about 14.5 km (9 miles) are recorded, with at least 1.5 km (one mile) of known passage still to be mapped.

The Lilburn mappers match their counterparts in the Guadalupe in their use of advanced computer techniques. Bosted wrote a program that calculates coordinates and simultaneously closes up to 300 survey loops using a least squares method. The program also helps to pinpoint survey errors. Line plots are sent to the survey sketchers, who fill in the details from their in-cave sketches. The results are added to a 2.4 m/cm (20 ft./in.) master map. The map is on two sections of drafting film, each about one meter wide and three meters long. Cross-sections and station labels are not included, because of the mazy nature of the cave. Several areas had to be portrayed with two or more levels shown separately because of their great complexity. A 12 m/cm (100 ft./in.) color map showing different levels has been produced, as have color 3-D slides of portions of the cave, using computer graphics. Ideas for future maps include versions showing the entire cave but emphasizing different features (passage shapes, sediments, air flow, water flow, etc.), as well as detailed maps of specific areas. The latter will be on 11 inch x 17 inch quadrangles, showing the various levels on separate sheets and including cross-sections (Bosted, pers. comm.). Most recently, nearby Cedar Cave has been added to the mapping program.

#### ARKANSAS

In 1978, under the direction of Cal Welbourne, CRF cavers began a project to map and inventory caves of the Buffalo National Scenic Riverways in the Arkansas Ozarks. Two years later, the project expanded to encompass caves of the adjoining National Forest Sylamore District. CRF entered into a contract with the Forest Service to map 23 selected caves; these were finished later the same year by mappers Bridgemon, Bob Buecher, and Debbie Buecher. A second contract to map the other dozen or so known caves in the Sylamore District was extended until 1984. Tom Brucker took an active role in completion of the field work of the Sylamore caves, as did Missouri mappers Doug Baker, Scott House, and Mick Sutton.

The Fitton Cave Survey was started in the fall of 1984 under the leadership of Pete Lindsley, Gary Schaecher, Paul Blore, and Dave Hoffman. The goal was a highly detailed map of Fit-

ton Cave, the best known and longest cave in the Buffalo River country. Surveyors are drawn from Arkansas, Missouri, Oklahoma, and Texas. With the emphasis on high precision, the survey has moved slowly and in 1988 field work came to a complete halt while a backlog of survey was drawn up. But in late 1988, six preliminary 6 m/cm (50 ft./in.) pencilled quadrangle maps were drawn by Schaecher, Hoffman, Bob Taylor, Jack Regal, and John Brooks. Surveying in Fitton Cave is scheduled to resume in 1989.

#### NEW DIRECTIONS AT MAMMOTH CAVE

Missouri mappers House and Baker were introduced to CRF cavers when they took part in the Sylamore District project, where Tom Brucker recruited them for Mammoth Cave. House and Baker in turn introduced other Missouri mappers to Mammoth Cave. Until then, almost all Mammoth Cave cartographers had started from scratch and learned on the job. The new recruits, in contrast, had a background of cave mapping with the Missouri Speleological Survey (MSS). The MSS is a state-wide confederation of cavers which serves to pool mapping expertise. The result has been a long tradition of detailed cave maps with more or less uniform standards. House was in charge of an ambitious MSS project to map all the caves on government agency land in Missouri: the Ozark National Scenic Riverways, the Mark Twain National Forest, and the State Park and Forest systems. Hence, he had a lot of experience in producing detailed cave maps and in working with government agencies.

When the Missouri cavers started coming to Mammoth Cave it was not with the idea of setting up a detailed mapping program; rather, caving at Mammoth was seen as an exciting break from weekends in the Ozarks. It didn't take long, though, to notice that the available maps lacked detail and were generally not up to date and to wonder what a section of Mammoth Cave would look like given the Missouri treatment. In the summer of 1984, House started remapping Mather and Turner Avenues in Flint Ridge and drew up the results as a 6 m/cm (50 ft./in.) pencil draft. The choice of area was somewhat arbitrary but it had several desirable features—Mather and Turner Avenues formed a self-contained loop, they were large trunk passages with plenty of detail, and existing surveys were very old and therefore very crude (House, pers. comm.).

The first problem House ran into was the lack of a coordinate system, a feature that would be essential for the handling of survey data and for the rigorous closing of survey loops. He set up a temporary system based on an arbitrary point in Al-bright Junction. The map would be self consistent but couldn't be precisely related to the rest of the world. The Mather and Turner survey turned out well enough but when the 6-8 km (4-5 miles) of other passages which fell within the boundaries of the map were considered, the concept of an isolated map quickly broke down. The problem comes when a passage loops off the map and rejoins it by a different route. To portray the parts that

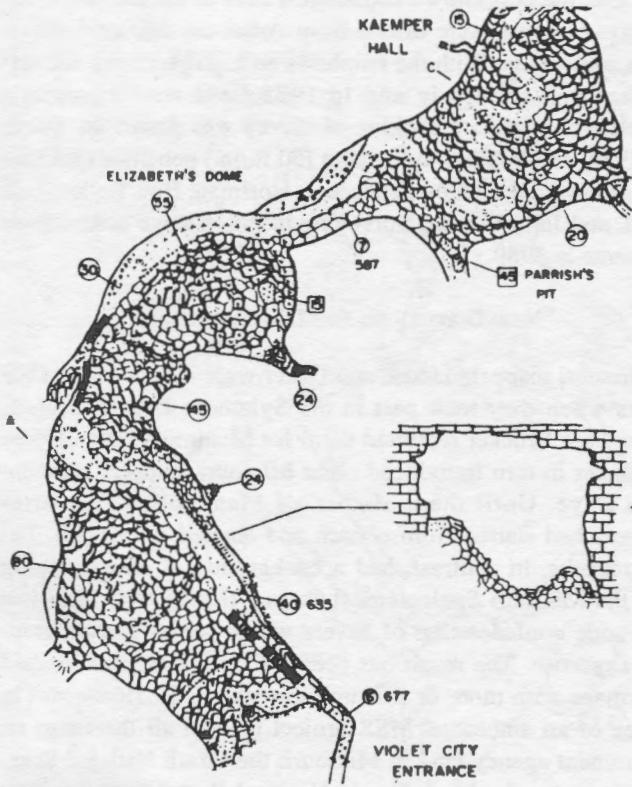


Figure 6. Detail from the reduced scale 12 m/cm; 100 ft./in.) Cleaveland Avenue tour trail map, 1987. Main Cave at Violet City is depicted—this is the exit for the lantern tour.

fall on the map, one must collect good data for the entire loop and, having collected that data, it's hard to justify not using it. So the Mather/Turner map soon spawned a Gravel Avenue map and the Gravel Avenue map spawned a Northwest Passage map. While Sutton attended to those, House continued north on Turner Avenue to Brucker Breakdown. Paul Hauck picked up the survey from the Breakdown and proceeded down Pohl Avenue to the Austin Entrance. There is an inevitable built in progression and soon the project was spread over the entire western half of Flint Ridge. The large scale of the maps allowed the most detailed look yet at Flint Ridge. Passage shapes and general contents could be discerned, complex junctions were made clearer, relative passage elevations were shown, ambiguities and errors from the older maps were cleared up, and a large backlog of older survey data was finally plotted.

Given time, the inevitable progression would have taken the map series under Eaton Valley into Mammoth Cave Ridge, but as it happened the large-scale map program entered Mammoth Cave by the front door. The NPS asked CRF to produce a series of detailed maps of the tour trails but they didn't define "detailed," thus setting the stage for a clash of values between the "traditional" approach, with its standard scale of 12 m/cm (100 ft./in.), and the new high resolution map program. Diana

Miller and Gerry Estes opted to produce maps at a scale of 12 m/cm (100 ft./in.) for the historic tour and part of the half-day tour. The maps were viewed as special purpose products, distinct from the overall mapping effort. House and Baker chose to produce maps of Frozen Niagara and Cleaveland Avenue at a scale of 6 m/cm (50 ft./in.) (Fig. 6). While these were seen as valuable in their own right, House and Baker also viewed them in a broader context. While they collected data for the tour trails, they worked towards putting all the other passages in the area onto expanded versions of the maps (House, pers. comm.). Miller finished her Historic area map but Estes left owing to job requirements before his map could be completed. Later, it was split into two 6 m/cm (50 ft./in.) sections, with House, Eric Compas, and Jerry Wagner taking charge of one, and Sutton the other. The Walker survey "benchmarks" in Mammoth Cave made the job of setting up a basic survey framework easy. Baker took the published positions and converted them to coordinates based on a surface benchmark at the Carmichael Entrance (Baker, pers. comm.).

While the Mammoth Cave maps were progressing, the Flint Ridge operation came to a temporary halt. Hauck, an engineering surveyor, had been working with the surface transit surveys done in the 1970's by Wilcox, Zopf and others. He discovered that Flint Ridge could almost, but not quite, be tied to the Mam-

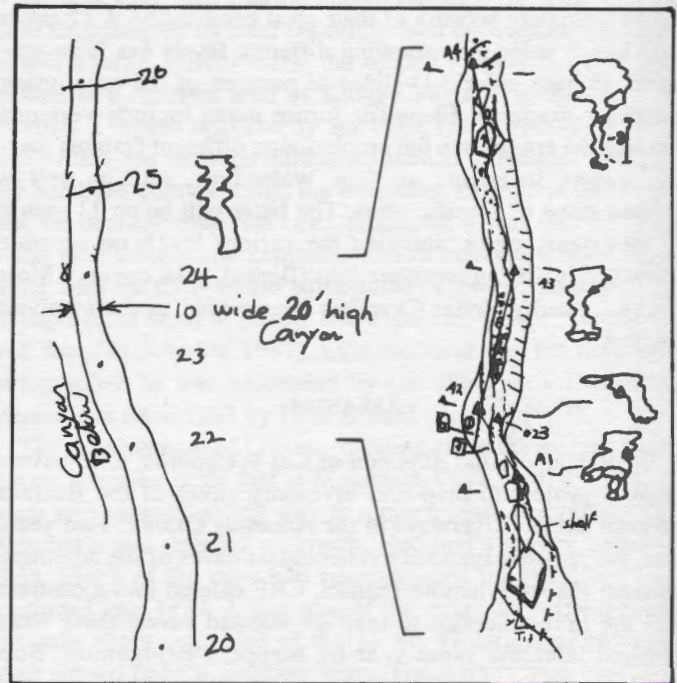
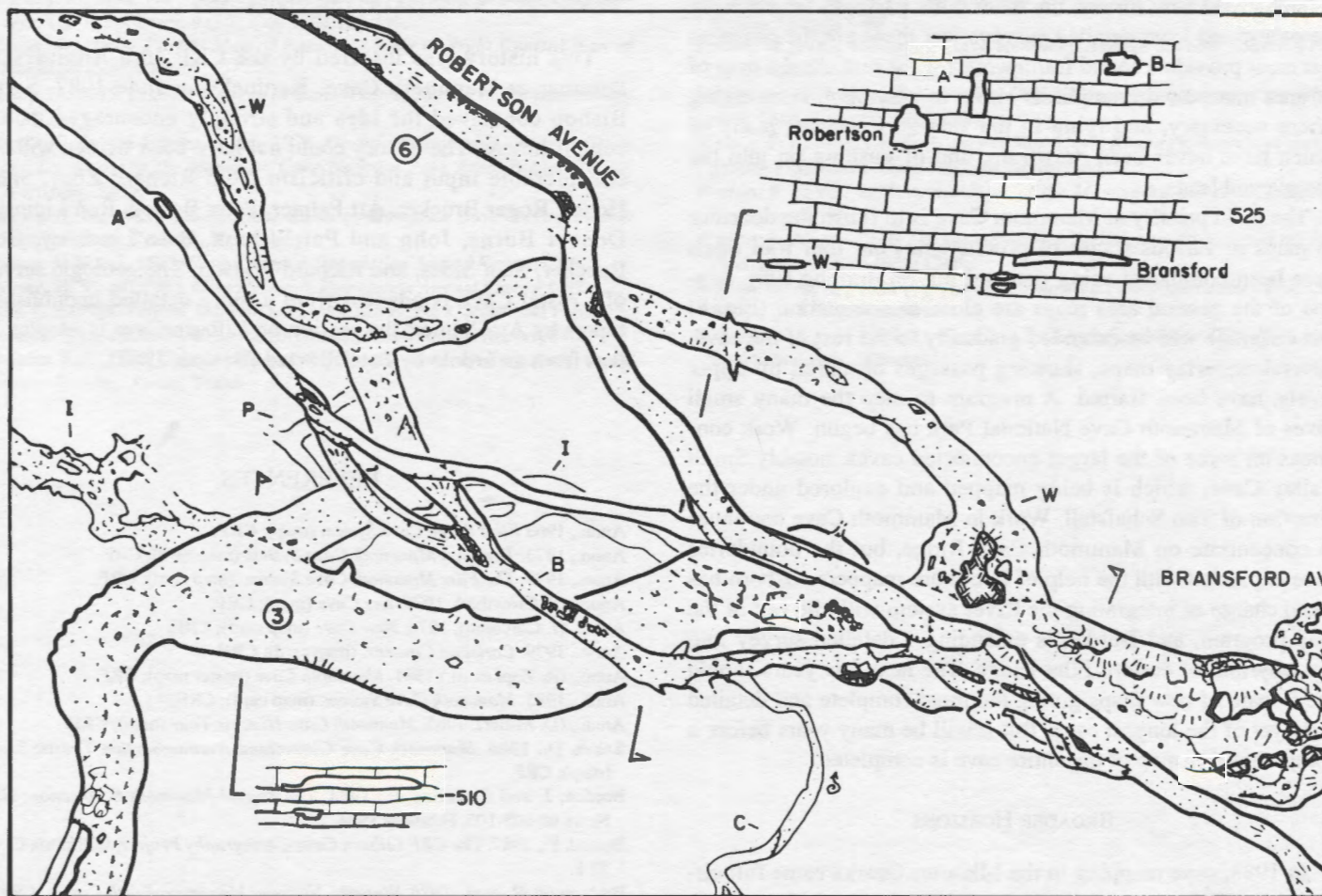


Figure 7. The Mammoth Cave 6 m/cm map series depends on detailed survey sketches. Left—a page from a Gravel Avenue survey book, 1959. Right—a resurvey of the same passage, 1985. Both survey books are reduced 50%. The earlier sketch shows about 3.5 times as much passage as the later sketch.



**Figure 8.** Detail centered on Robertson Avenue from the unpublished 6 m/cm (50 ft./in.) Kentucky Avenue. Mammoth Cave sheet. The numbers on the cross sections are elevations in feet. This map is nearing completion. Passages obscured by upper levels will be clarified on a separate Bransford Avenue underlay sheet.

moth Cave coordinate grid. There was no longer any point in continuing to draw up Flint Ridge on House's arbitrary system, since the map boundaries would have to be adjusted to fit the uniform grid. The surface traverses required to tie in both Flint Ridge and the River System to the Mammoth Cave grid are being run under the direction of Zopf, Robert Osburn, and Gail Wagner, and are almost complete.

In 1986 the CRF board of directors agreed that the large-scale map program would encompass the whole cave, excluding the Roppel Section (CKKC mappers, led by Borden, were already drafting Roppel at a large scale). House became chief cartographer, responsible for map production, while Zopf took on the newly created position of chief surveyor, responsible for maintaining and recording the survey net. House set a standard width of 40 inches for the maps. The lengths of the sheets and their orientation north/south or east/west—vary depending on cave geography.

Advances in techniques accompanying the detailed map program have been relatively minor. The biggest change is the greater demand placed on the survey team sketcher (Fig. 7), a problem which is being addressed by ongoing training. The other big change has occurred in the realm of data processing. After years of struggling to make the central computer facilities sufficiently flexible, mappers now routinely process survey data with small, versatile personal computers. A program for data reduction and loop closure was written, and continues to be refined, by Compas. Other refinements in survey technique continue to be made. In recent years, fiberglass tapes have supplanted steel, and Suunto compasses have replaced the harder to read hand-held Brunton for the majority of surveys. Tripod-mounted Bruntons continue to be used for trunk passage surveys. The introduction of waterproof surveyor's paper has improved the general quality of the survey sketch.

The detailed map program has performed emphasized re-

mapping over new survey; the main trunk passages tend to have the oldest and least detailed surveys, yet these are the passages that must provide a sound framework for the rest. As the map of an area matures, the emphasis shifts to assessing, resurveying where necessary, and tying in the smaller passages, many of which have never been drawn up, and of pushing on into the unsurveyed leads.

The main priority at Mammoth Cave is to finish the dozen or so maps in various stages of production. Four tour trail maps have been completed using pen and ink on drafting film. Several of the general area maps are close to completion (Fig. 8) and coverage will be extended gradually to the rest of the cave. Several underlay maps, showing passages obscured by upper levels, have been started. A program to map the many small caves of Mammoth Cave National Park has begun. Work continues on some of the larger unconnected caves, notably Smith Valley Cave, which is being mapped and explored under the direction of Tim Schafstall. Work in Mammoth Cave continues to concentrate on Mammoth Cave Ridge, but the boundaries have expanded with the help of two more mappers. Osborn has taken charge of integrating the River system with the rest of the map program, and Borden is extending a detailed survey into the labyrinth of eastern Flint Ridge. The next few years should see a spate of new maps giving the most complete and detailed view yet of the longest cave. But it will be many years before a comprehensive map of the entire cave is completed.

#### BROADER HORIZONS

In 1988, cave mapping in the Missouri Ozarks came full circle when CRF entered into a partnership with the MSS, assuming joint responsibility for the Government Agencies project under the direction of House. Most of Mammoth Cave's cartographers—House, Baker, Sutton, Osborn, Compas, Hauck—are active in this long-term project. In the fall of 1988, CRF operations expanded to a new area in Northern California, where Janet Sowers is leading a survey and inventory of the many lava tubes in Lava Beds National Monument.

Perhaps the most exciting new development of 1988, though, is the international impetus given to CRF mapping by the March, 1988 expedition to the karst of southern China. This was not CRF's first international venture—in 1973, Zopf led a month long, nine person expedition to investigate the caves of the Barra Honda region for the Costa Rica National Park Service. But the China expedition, led by Bridgemon, was on a more ambitious scale. The 12 expedition members mapped six kilometers of previously uncharted passage in Guangdong and Hunan provinces. The Buechers are drawing up the maps. It is exciting and appropriate that CRF cave mapping standards, which are perhaps among the most exacting in the world, should be applied to the world's largest area of karst.

#### ACKNOWLEDGEMENTS

This history was inspired by the CRF 30th Anniversary Seminar at Mammoth Cave, Kentucky in June 1987. Sarah Bishop conceived the idea and strongly encouraged its accomplishment. The history could not have been written without considerable input and criticism from Richard Zopf, Scott House, Roger Brucker, Art Palmer, Peter Bosted, Ron Lipinski, Denver Burns, John and Pat Wilcox, Pete Lindsley, Bob Buecher, Stan Sides, and Richard Watson. The geologic survey of Crystal Cave is adapted from a more detailed unpublished report by Art Palmer; the section on Lilburn Cave is adapted in part from an article by Peter Bosted (Bosted, 1987).

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# THE CAVES OF CROWN POINT TOBAGO, WEST INDIES

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FRED GRADY<sup>2</sup>

*Four caves on the island of Tobago, three previously unrecorded, were explored, mapped, and prospected for vertebrate paleontological resources. The caves and surface features, such as dry valleys and sink holes, suggest they were part of a single large cave system which we have designated the Crown Point Cave System. The largest, deepest, and most interesting cave is Amblypygid Cave. Archaeological resources of Effigy Cave and paleontological resource of Robinson Crusoe and Remnant Caves indicate all of these caves are valuable resources to the island of Tobago and should be protected.*

## INTRODUCTION

The island of Tobago is located in the West Indies, just off shore from Venezuela on the southern border of the Caribbean Sea and is the seaward-most island of Trinidad and Tobago, a former British colony. Tobago is about 32 km long and 11 km wide at its widest point. Much of the interior is densely forested.

During July of 1979 Ralph Eshelman, Fred Grady, Gary Morgan, Dave Hardy, and Ralph Bartlett attempted to locate Robinson Crusoe Cave at Crown Point on the southwest end of the island. Robinson Crusoe Cave and three others were discovered at this time. As the caves showed potential for further study, especially paleontological, Eshelman, Grady, and Morgan returned in April of 1981 for more detailed study. It was during this second visit that surveying of the caves was undertaken. This report is a summary of that survey. A preliminary report was published by Grady (1982).

The caves are located on the southwestern tip of Tobago in St. Patrick Parish (latitude 11° 9' 15" N, longitude 60° 51' 30" W) just south of the Crown Point Airport and east of Crown Point itself (Tobago, sheet 1E, scale 1:10,000, published by Directorate of Overseas Surveys, 1961). The caves are formed in an unnamed coralline limestone of Quaternary age which covers the southwestern end of the island and reaches up to 30 m in thickness where it is above sea level (Rowley, 1979). The unconsolidated marls of the Rockley Bay Formation, middle Pliocene in age, underlie the limestone in the area of the caves (Saunders and Muller-Merz, 1979; B. Carr-Brown in Rowley,

1979) and limits the lower formation of the caves. Except for the southwestern end of Tobago, the remainder of the island consists of metamorphic and igneous rocks (Maxwell, 1948). However, sea caves, blow holes, and at least one submerged arch were encountered on the northeast end of the island at Man of War Bay. These features, however, are not true karst features, but the result of wave action on fractures and other structural weakness in non-carbonated rocks.

All of the solution caves were discovered within 0.5 km of one another. However, fissures in the coralline limestone were common along the shore where limestone sea cliffs are present, such as at Crown Point and especially near Fort James at Buccoo Point, where cliffs up to 30 m high were encountered. The size of these fissures can be gauged from Crazy Woman Fissure, named after an apparently demented woman who threatened us with a stick. Located near Fort James, it measured 30 m long, 3.6 m deep, and up to 1.2 m in width. These fissures are presumed to be the result of erosion by waves along the cliffs, undercutting the cliffs and causing subsequent slumping. Most of the fissures are parallel to the cliff, which supports this hypothesis.

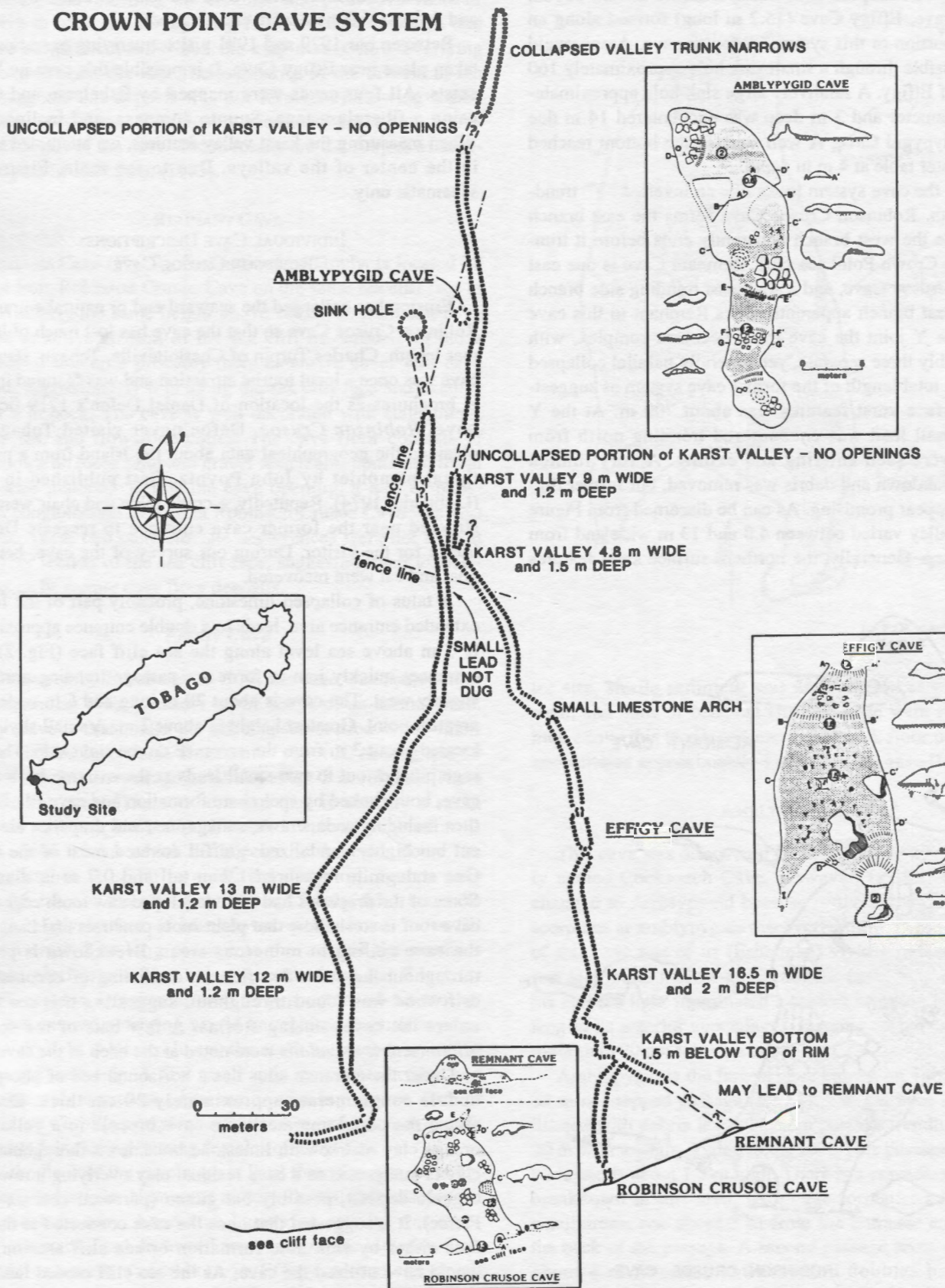
## OVERALL DESCRIPTION: THE CROWN POINT CAVE SYSTEM

Mapping of the caves and surficial solution features, such as dry valleys and sink holes, suggests that all the features are part of a single large cave system which we have designated the Crown Point Cave System (Fig. 1). Oral tradition holds that when the Crown Point Airport was constructed, caves were discovered and filled in. One story states that a cave once led from Robinson Crusoe Cave under what is today the airport and surfaced again at Store Bay, approximately 1,200 m to the north northeast. Robinson Crusoe Cave and Remnant Cave are exposed in an actively eroding sea cliff 10 m high. A karst val-

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# CROWN POINT CAVE SYSTEM



ley (dry valley or collapsed cave trunk) leads northward 107 m, with a third cave, Effigy Cave (15.2 m long) formed along an uncollapsed portion of this system. A fourth cave, Amblypygid Cave, is accessible through a small sink hole approximately 160 m northeast of Effigy. A relatively large sink hole approximately 12 m in diameter and 3 m deep was encountered 14 m due west of Amblypygid Cave. A well sunk in the bottom reached the ground water table at 4 m in depth.

In general, the cave system looks like an inverted "Y" trending north-south. Robinson Crusoe Cave forms the east branch of the Y while the west branch apparently ends before it truncates with the Crown Point sea cliff. Remnant Cave is due east of Robinson Crusoe Cave, and a southeast trending side branch of the main east branch apparently links Remnant to this cave system. At the Y joint the cave trunk becomes complex, with two and possibly three separate, yet generally parallel collapsed passages. The total length of the former cave system as suggested by the surface karst features was about 700 m. At the Y juncture a small lead was encountered trending north from which bats were seen entering and exiting. A very limited amount of breakdown and debris was removed, but further digging did not appear promising. As can be discerned from Figure 1, the karst valley varied between 4.8 and 13 m wide and from 2 to 1.2 m deep. Generally, the northern surface karst features

were shallower and were where the deepest and longest cave and deepest sink hole were encountered.

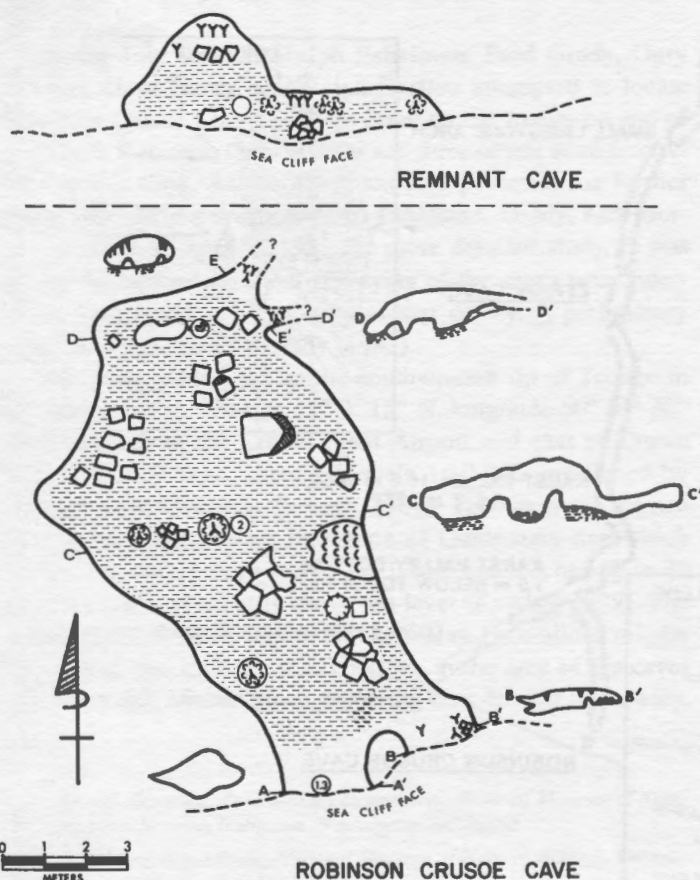
Between our 1979 and 1981 visits, quarrying operations had taken place near Effigy Cave. It is possible this cave no longer exists. All four caves were mapped by Eshelman and Grady using a fiberglass tape, Suunto compass, and inclinometer. When measuring the karst valley features, we attempted to stay in the center of the valleys. Due to the scale, Figure 1 is schematic only.

#### INDIVIDUAL CAVE DESCRIPTIONS: ROBINSON CRUSOE CAVE

Erosion has collapsed the seaward end or natural entrance of Robinson Crusoe Cave so that the cave has lost much of its former length. Charles Turpin of Charlotteville, Tobago, stated the cave was once a local tourist attraction and was featured in travel brochures as the location of Daniel Defoe's 1719 fictional novel *Robinson Crusoe*. Defoe never visited Tobago but obtained the geographical data about the island from a promotional pamphlet by John Poyntz, first published in 1685 (Lichtveld, 1974). Reputedly, a crude table and chair were constructed near the former cave entrance to recreate Defoe's image for the visitor. During our survey of the cave, bones of goat and cat were recovered.

A talus of collapsed limestone, probably part of the former extended entrance area, leads to a double entrance approximately 3 m above sea level along the sea cliff face (Fig. 2). The entrances quickly join to form one passage trending north and slightly west. The cave is about 20 m long and 6 m wide at its greatest point. Greatest height is about 2 m. A small skylight is located about 3 m from the entrance on the right side. The passage pinches out to two small leads at the extreme back of the cave, both choked by spelothem formation and cave fill. Stalactites including soda straws, stalagmites, and draperies are present but highly vandalized: graffiti covered most of the walls. One stalagmite measured 1.2 m tall and 0.7 m in diameter. Some of the draperies had well developed saw tooth edges. The cave roof is so shallow that plant roots penetrate and hang from the cave ceiling in numerous areas. Breakdown is present throughout the cave. Sea flotsam consisting of coconuts and driftwood was found throughout, suggesting that sea water enters the caves during storms. A few bats of the species *Micronycteris megalotis* were noted at the back of the cave.

Under the entrance talus lies a horizontal bed of phosphatic nodule conglomerate approximately 20 cm thick. Directly above the conglomerate lies a cave breccia in a yellowish-orange clay matrix with limestone breakdown throughout. The clay is interpreted as a cave residual clay overlying a reworked organic deposit, possibly bat guano (personal comm., J. W. Pierce). It is suggested that once the cave connected to the surface either by sink hole formation or sea cliff erosion, bats would have utilized the cave. As the sea cliff eroded landward in conjunction with Holocene sea level rise the cave became



shortened, thus lessening the darkness and protective value of the cave to bats. Eventually, clay from limestone solution and surface contamination formed the clay matrix now overlying the conglomerate deposit. The angularity of the breccia in the clay suggests this deposit was not formed by flowing water. Important vertebrate fossils were recovered from both stratigraphic levels of the cave. These fossils are the subject of separate papers by Eshelman (1985).

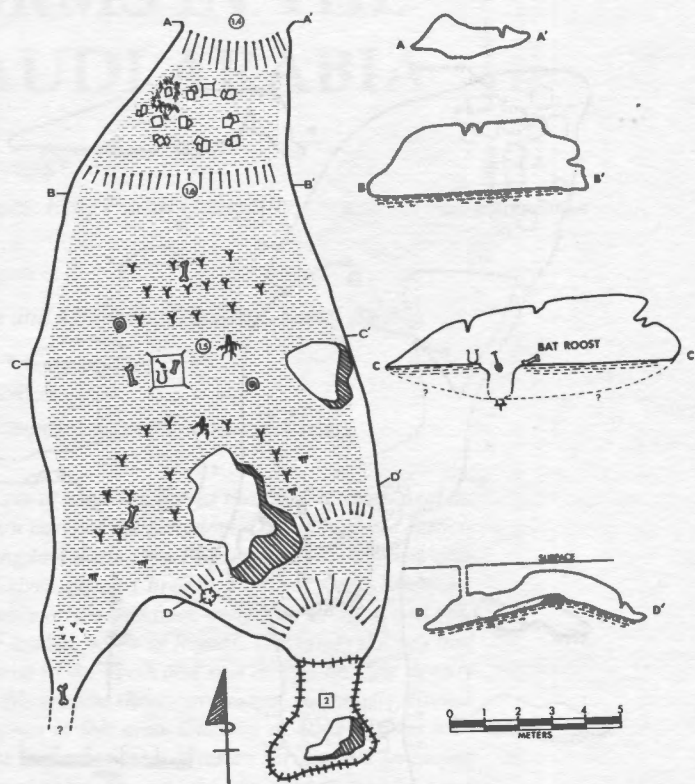
#### REMNANT CAVE

Remnant Cave (Fig. 2), first noticed by Grady, is located 38 m east from Robinson Crusoe Cave on the same sea cliff face at approximately the same height above sea level. Remnant is so named as active erosion of the sea cliff has eroded all but a remnant of this once probably more extensive cave. This cave extends approximately 8 m along the sea cliff face and extends about 3 m back. The cave is well decorated with stalagmites, stalactites, and flowstone cones. The cave floor consists of breakdown on loose sand and gravel which also contained fossil vertebrate material. Below the cave opening, a lens of phosphatic conglomerate as seen at Robinson Crusoe Cave was also present. These two conglomerate occurrences were not seen at any other section of the sea cliff face, suggesting their association as early, former cave floor deposits.

#### EFFIGY CAVE

Discovered by Eshelman in 1979, the cave was named after an Amerindian pottery handle in the shape of an animal head. Effigy Cave is essentially the uncollapsed section of an otherwise collapsed cave trunk. It measures about 20 m long and 10 m wide and has an average height of about 2 m (Fig. 3). There are two entrances. The southern entrance is actually a small passable collapse, choked with breakdown and vegetation. It opens above a talus which leads down to the cave floor. The north entrance is easier to enter. By stooping, one can pass down the talus to the cave floor. Except for the talus areas the cave is relatively free of breakdown with a level, loose-fill floor. A small 3 m long passage to the west of the southern entrance pinches out. This area was named the Bat Roost for obvious reasons. Digging allowed us to penetrate about another 2 m, but extensive digging would be required to push any farther. A skylight is located just at the south entrance talus terminus on the west side. A few small soda straws, stalactites, and draperies with saw tooth edges are present in the cave. Bats of the species *Carollia perspicollata* and *Glossophaga longirostris* were noted, including nursing females of *Carollia*.

On the floor of the cave were at least three fire pits, possibly of aboriginal origin. Numerous pottery shards were discovered throughout the cave. Land crab burrowing activity was especially noticeable, and destroyed any stratigraphic integrity. Two excavations were undertaken in Effigy, one at the north entrance talus and a second in the center of the cave. At the lat-



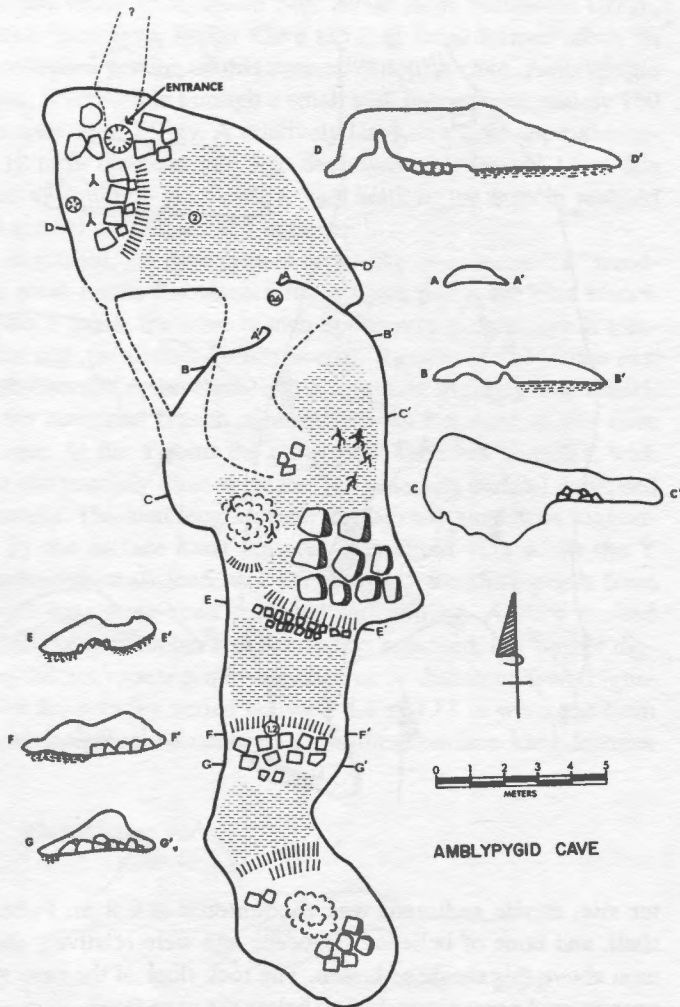
EFFIGY CAVE - TOBAGO

ter site, sterile sediment was encountered at 0.8 m. Pottery, shell, and bone of believed Holocene age were relatively common above this sterile sediment. The rock floor of the cave was encountered approximately 1 m below the cave floor.

#### AMBLYPYGID CAVE

This cave was discovered by Eshelman in 1979 and originally named Cockroach Cave. However, in 1981 the name was changed to Amblypygid because of the numerous tailless whip scorpions or amblypygids discovered there. During the mapping of this cave one of us (Eshelman) vividly remembers taking a rest in a rather narrow portion of the cave, turning on his back, his carbide light illuminated a tailless scorpion holding a small frog in its anterior appendages, hanging on the cave ceiling not more than 20 cm from his head.

Amblypygid is the largest cave known on Tobago with some 35 m of mapped passage (Fig. 4). The entrance is a small sink littered with debris leading into a passage trending south about 20 m with a slight dogleg to the east. This passage averages 3 m wide and is about 1.5 m high. There is a considerable amount of breakdown in this area, with cave formations limited to two small areas, one about 5 m from the entrance and the other at the back of the passage. A second passage starts as a low crawl about 4 m from the entrance and doubles back under the entrance trending north about 15 m before leading into a room



about 7 m wide and 2 m high. At the extreme north end of the room is a large breakdown pile with a low passage continuing north. The breakdown was unstable, and determined too dangerous to pursue. A few stalagmites were found in this room, and a large flowstone formation just before the breakdown pile.

Amblypygid Cave was the wettest, deepest, and largest cave encountered. Only superficial bone was collected at Amblypygid and, as at Effigy, appeared to be relatively late Holocene in age.

#### SIGNIFICANCE

Tobago caves are small and not particularly attractive, especially in comparison to those on the sister island of Trinidad. However, the presence of tailless whip scorpions in Amblypygid Cave represents a zoological resource presently not documented anywhere else on the island of Tobago. The archaeological material discovered at Effigy Cave warrants further investigation. The fossil material from Robinson Crusoe and Remnant Caves represents the earliest terrestrial vertebrate remains thus far known from the island. Collectively, these ver-

tebrate fossils (Eshelman, 1985) indicate that nearly half of the living mammalian species are extirpated from the island today. The present depauperate fauna could have resulted from a combination of the following related occurrences: a change from a drier climate and grassland vegetation to a present, more mesic vegetation; the Holocene rise in sea level and consequent severing of Tobago from Trinidad and the mainland of South America; and the altering of the fauna and flora with the arrival of Indian and European cultures. Further work on these fossils and their environmental implications is being undertaken by Eshelman and Morgan.

The caves of Tobago are a limited unique natural and cultural resource. At least one cave, Effigy, is presently threatened, if not already destroyed by quarrying operations. These caves warrant protection by the government of Trinidad and Tobago.

#### ACKNOWLEDGEMENTS

The authors are indebted to Messrs. Delano Dillon, Gerald Crooks, and Audrey Tales for allowing us permission to explore their property for caves. Edward Hernandez, curator of the Museum of Tobago History, was most helpful in providing possible leads to caves and fossils on the island.

This research was supported by a grant (2252-80) from the National Geographic Society. J. David Hardy, Gary Morgan, Ralph Bartlett, and Susan Grady helped in the 1979 exploration for caves. Gary Morgan, Mimi Harrington and Lindon Gordon assisted with the 1981 survey. Patricia Cutts and Fran Younger did the illustrations. J. W. Pierce of the Paleobiology Department, National Museum of Natural History, Smithsonian Institution, assisted in the assessment of the cave sediments. Dr. Thomas Miller and an anonymous reviewer improved the paper by their editing and suggestions for which the authors are grateful.

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# KARST LANDFORMS IN THE KINGDOM OF SAUDI ARABIA

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*Between 1982 and 1987, the authors explored a wide variety of karst landforms throughout Saudi Arabia. These landforms are found primarily in the central and eastern parts of the Kingdom. Dry valleys are associated with the three major river systems which drained the Kingdom during the Pliocene and Pleistocene pluvial periods. Five deep gorges associated with these relict river systems breach a belt of steep limestone escarpments in central Arabia. Two large lakes, which probably originated from anhydrite solution and collapse of the overlying limestone units, are located in central Arabia, south of Riyadh. Countless dolines and a few cave systems pierce the limestone plateaus in a wide area to the north and east of Riyadh. The density of these dolines and caves is highest in the As Sulb region. We present three cave maps and briefly discuss the characteristics of eleven different types of caves and dolines in this area. Clusters of karst springs provide water for two large oases on the Arabian Gulf coast. The largest of these artesian springs has an output of 1700 liters per second. Vertical fissures, with a ground-level entry, are cut into low escarpments in some parts of eastern Saudi Arabia. One maze-like fissure system includes 745 meters of passage.*

## INTRODUCTION

The speleological community lacks general awareness of the existence and nature of the karst landforms in Saudi Arabia. For instance, neither Jennings (1971), Sweeting (1972), Waltham (1976) nor Blair (1986) mention Saudi Arabia in their discussions of karst and caves. While literature (Powers et. al. 1966, AlSayari and Zötl 1978, and others) and published maps (USGSARAMCO 1963, Arabian American Oil Co. [ARAMCO] F-series, Defense Mapping Agency 1501 series) depicting the Kingdom's karst do exist, these sources are not readily available. Recent articles by Davis (1983) and Pint and Peters (1985) provide sketchy, popular accounts about caving in Arabia. We take this opportunity to review what is currently known about this extensive, but little known karst region and to detail the findings of our cave explorations. A glossary of Arabic terms used in the text is found in Table 1.

## GENERAL DESCRIPTION OF SAUDI ARABIA

Saudi Arabia (Fig. 1), with a land mass of 2,300,000 square kilometers, occupies most of the Arabian Peninsula. The west-

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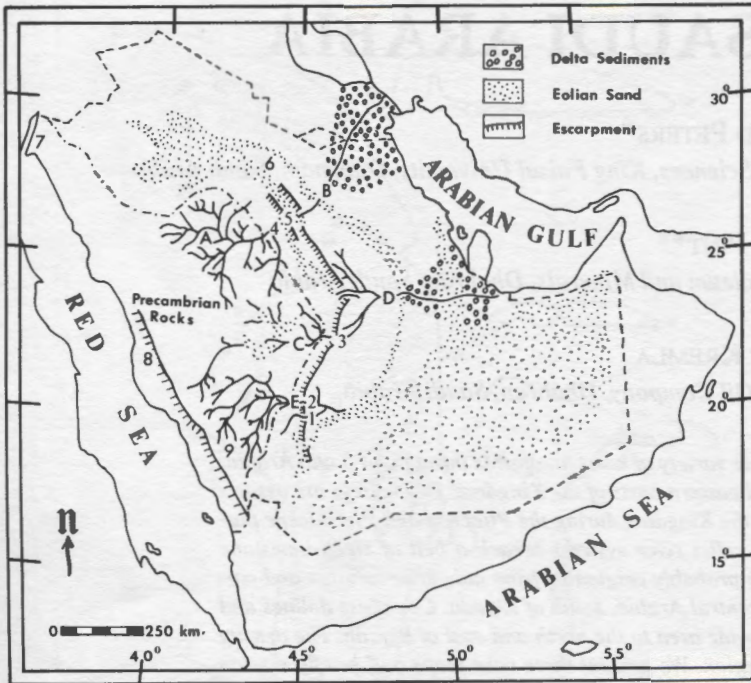
\*\*Current Address: Apartado Postal 103, Ciudad Granja, Jalisco, 44240, Mexico

ern third of the Kingdom consists primarily of Precambrian igneous and metamorphic rocks capped, in places, by extensive Tertiary lava flows. This Precambrian plateau slopes gently to the north, northeast and east where it is overlain by sedimentary deposits.

Sedimentary rocks make up the land surface of another third of the Kingdom. They extend in a broad arch from Jordan in the northwest, to the Arabian Gulf in the east and down to Yemen in the southwest. Rocks from Cambrian to Pliocene age outcrop sequentially eastward from the Precambrian plateau. Eolian sands of Quaternary age cover the remainder of the Kingdom. Arabia's largest sand desert, the Ar Rub' Al Khali, occupies the southeastern quarter of the Kingdom at the border with Yemen, Oman and the United Arab Emirates.

TABLE 1. ARABIC WORDS USED IN THE TEXT

Dahl	deep sink hole or solutional cavity
'Ayn	naturally occurring spring, well or lake
Wadi	dry valley of a water course
Ghar	vertical fissure with a ground-level entry which penetrates a sheer rock face
Jabal	escarpment, low mesa
Umm	mother of, used with place names
Abu	father of, used with place names



**Figure 1. The Kingdom of Saudi Arabia. Approximate political boundaries are indicated by dashed lines. Precambrian igneous and metamorphic rocks outcrop to the west of the dot and dashed line. To the east, the rocks are sedimentary. Major wadi systems are noted by letter: A. Ar Rimah, B. Al Batin, C. Al Birk, D. As Sah'ba, E. Ad Dawaser. Karst locations are noted by number: 1. Wadi Al Hinw gorge, 2. Wadi Ad Dawaser gorge, 3. Wadi Al Birk gorge, 4. Dry valley (see Fig. 3), 5. Wadi Ar Rimah gorge, 6. Dahl Jabana, 7. Dahl Hamdah, 8. Cave of Thaur, 9. Khamis Mushayt caves.**

This geological background is summarized from Powers et al. (1966) and Chapman (1978: 4-31). The characteristics of rock units with significant karst development are presented in Table 2.

During the Upper Jurassic and Lower Cretaceous, shallow seas covered much of eastern and central Saudi Arabia. Compact limestone units deposited from these seas now stand in sharp relief to form the extensive west-facing escarpments of central Arabia (Fig. 1). To the east, these erosion-resistant limestones are capped by anhydrites and limestones of the Arab (Fig. 2), Hith (Fig. 2 #13) and Sulaiy (Fig. 2 #14) Formations. Throughout this area, extensive slumping is observed due to anhydrite solution and collapse of the limestone units.

Late Lower and Middle Cretaceous clastics, which overlie the Sulaiy Limestone and outcrop to its east, are primarily of continental origin. These calcarenitic limestone and sandstone rock units show little karst development. They have weathered to form low-relief plains.

The Aruma (Fig. 2) Formation overlies the Middle Cretaceous clastics and is exposed in a wide belt across central Arabia. It is an erosion-resistant complex of shale, dolomite and limestone deposited by shallow seas during the Upper Cretaceous. The western edge of the Aruma forms a steep west-facing escarpment. To the east of the Aruma, a broad expanse of relatively lower-relief terrain extends to the Arabian Gulf.

The Umm Ar Radhuma (UAR) limestone and dolomite overlie Aruma shale (Fig. 2). The UAR was deposited by shallow seas during the Paleocene and Early Eocene. It is a thick, hydraulic unit with an established gradient ranging from water-table conditions on or near the outcrop to flowing artesian conditions in Al Hasa and Al Qatif (Fig. 2) along the Arabian Gulf. UAR outcrops form gently undulating plains with isolated low hills and benches. In the Ma'aqala region (Fig. 2), the UAR is penetrated by numerous dolines.

Overlying the UAR are the Rus and Dammam Formations of Lower to Middle Eocene age. Outcrops of these rocks are quite uncommon. Both function as hydraulic units along the Gulf coast. They are infused with water mainly from the UAR aquifer. Rus rocks are primarily dolomitic marl, limestone and

**TABLE 2. GEOLOGICAL FORMATIONS SHOWING KARST DEVELOPMENT IN NORTHEASTERN SAUDI ARABIA**

TIME UNIT	FORMATION	DESCRIPTION
Miocene/Pliocene	Tertiary Sandstone and Marl (TSM)	Lacustrine-deltaic conglomerate, sand, marl and clay; calcareous sandstone, some sandy limestone and shale; locally includes gypsum. Separated into HADRUKH, DAM and HOFUF Formations along the Arabian Gulf coast
Middle to Lower Eocene	Dammam	Dolomite and limestone interbedded with marl and shale
Lower Eocene	Rus	Marl, chalky limestone and gypsum; all dolomitic to some extent
Lower Eocene Paleocene	Umm Ar Radhuma (UAR)	Calcarenitic limestone, dolomitic limestone and dolomite
Upper Cretaceous	Aruma	Limestone, chalky limestone, dolomite, dolomitic and shaly marl, and shale
Lower Cretaceous	Sulaiy	Compact limestone with a few, thin calcarenite and coquina beds
Upper Jurassic	Hith	Massively bedded anhydrite
Upper Jurassic	Arab	Anhydrite and gypsum interbedded with limestone, dolomite and calcarenite

Reference: USGSARAMCO 1963 GEOLOGIC MAP



gypsum. Dammam rocks consist of dolomite, limestone, marl and shale.

Coastal Miocene and Pliocene clastics can be divided into three formations based on the presence of marine rocks. From bottom to top these are the Hadruk, Dam and Hofuf Formations.

About 100 to 120 kilometers west of the coast, the marine beds grade into continental rocks and the three formations can no longer be recognized. Where this happens, the above formations are treated as a single unit - the Tertiary Sandstone and Marl (TSM) formation.

Hadruk rocks make up much of the coastal land surface northwest of Al Qatif. Dam and Hofuf outcrops are widely scattered over the coastal region. Distribution of the TSM formation corresponds roughly to the extensive As Summan plateau (Fig. 2). In the north, the TSM beds form a wedge increasing in thickness from 0 meters in the west to about 100 meters where they grade into marine deposits near the coast. Miocene and Pliocene rocks are in discordant contact with underlying units. Near Ma'aqala, the TSM overlies UAR rocks. Near the coast, Hadruk rocks overlie Dammam units.

#### AGE OF KARST DEVELOPMENT

The development of karst landforms in Saudi Arabia is a product of tectonically-related tilting of the peninsula to the northeast and climatic history. During the Cretaceous and Eocene, Arabia was joined to the African continent. In this period a dome developed in the Precambrian rocks of the African-Arabian area and the crest of this dome cracked. Between the Eocene and Oligocene periods, faulting and rifting of this crack thrust the western part of Arabia upward producing a high, sheer escarpment (Fig. 1), and tilting the peninsula to the northeast (Chapman 1978:17). During this period, the Umm Ar Radhuma (Fig. 2), Rus and basal Dammam Formations were subjected to intense weathering and erosion which resulted in their karstification and development as aquifers (Schyfsma 1978:163-166).

During the Miocene and Pliocene periods, a break occurred in the Precambrian basement crust along the Red Sea rift. Arabia started drifting away from Africa and into present-day Iran causing further tilting of the peninsula (Chapman 1978:17). The previously karstified Paleocene and Eocene rocks were overlain with clastics deposited by pluvial and eolian erosion of upland surfaces (Hadruk, Hofuf) and by a marine transgression (Dam). The As Summan plateau (TSM) and the eastern coastal region are a product of these events (Fig. 2). A second marine transgression in the middle to late Pliocene cut an east-facing escarpment in the Hofuf rocks near Al Hasa (Holm 1960). The initial development of ghar caves in Al Hasa's escarpment was due to the enlargement of the vertical joints in the Hofuf rocks by marine erosion at this time. These marine transgressions were probably caused by tectonics related to the folding of the Zagros Mountains along Iran's Gulf Coast (Hötzl et al. 1978:59-62).

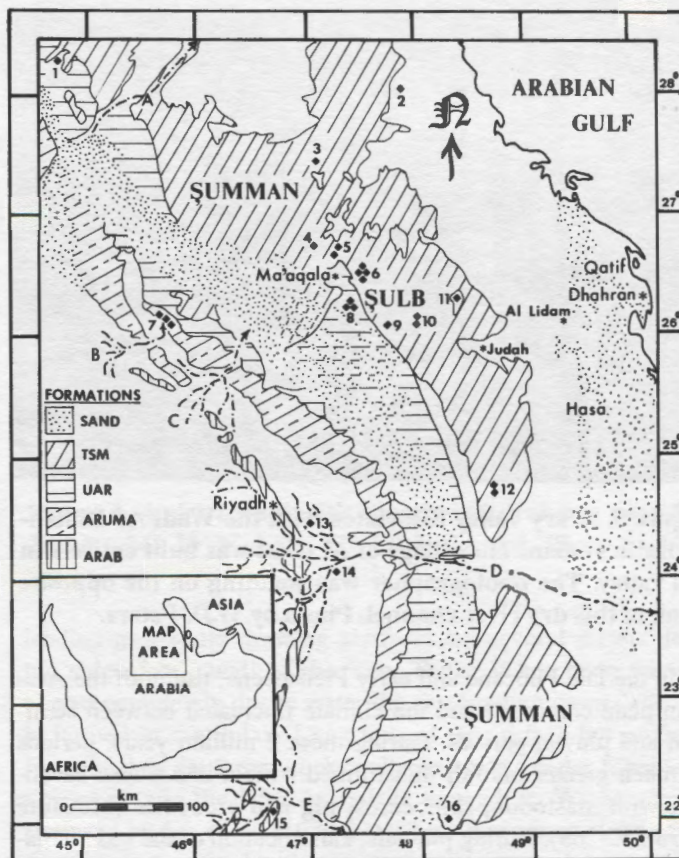


Figure 2. Generalized geological map of northeastern Saudi Arabia. Karst features are shown by number: 1. Unnamed dahl, 2. Dahl Al 'Khaliqah As Shamaliyah, 3. Dahl Abu Sukhayl, 4. Dahl Al Furayy, 5. Two nidw: Abu Sudayrah, Abu Khurjayn, 6. Four dahl: Umm Hujul, Al Khafaq, Abu Harmalah, Suraywilat, 7. Three unnamed dahl, 8. Three dahl: Iftakh, Dhiba, 'Azari, 9. Dahl Matar, 10. Two dahl: Jibbu Al Khaliqah (collapse doline), Daban, 11. Dahl Sab-sab, 12. Two dahl: Abu Sawadah, Al Kherran, 13. Dahl Hit, 14. 'Ayn Ad Dil, 15. 'Ayn Al Burj, 16. Ghar Mushay'ib.

Major wadis are shown by letter: A. Al Batin, B. An Namil, C. Al 'Atk, D. As Sah 'ba, E. Al Jadwal.

Karst springs are found in Al Qatif and Al Hasa along the Arabian Gulf Coast.

Refer to Table 2 for descriptions of geological formations.

These karst features are shown on Arabian American Oil Co. (ARAMCO) F-series maps 1118, 1162, 1227, 1128; on Bramkamp and Ramirez (1957) and on USGSARAMCO (1963) maps.



**Figure 3.** A dry valley associated with the Wadi Ar Rimah-Al Batin system. The village of Al Ghat was built entirely in the valley. The photographer was standing on the opposite bank of this dry river channel. Photo by W.D. Peters.

In the late Pliocene and early Pleistocene, tilting of the Arabian plate continued and the climate fluctuated between semi-arid and pluvial periods. During these 2 million years, periods of much greater rainfall transformed Arabia into a lush savannah with mastodon, rhinoceros, pig and crocodile (McClure 1978:252-263). During pluvials, karstification of the sedimentary regions was intense. The ghar caves in Al Hasa's escarpments were greatly enlarged by underground erosion of joints (Chapman 1971). Wadis draining the uplands of western Arabia (Fig. 1) caused heavy erosion in the Precambrian highlands, the development of gorges and deep river channels in the sedimentary regions and deposition of extensive deltaic fans along the coast (Holm 1960, Powers et al. 1966 and Hötzl et al. 1978:292-301). The As Summan TSM caves (Fig. 2) were undoubtedly strongly karstified at this time. During the semi-arid intervals, a calcrete duricrust cap developed on exposed bedrocks throughout the sedimentary region (Chapman 1978:77-84). With the exception of pluvial periods during the Holocene, the climate of Arabia has been predominantly semi-arid to arid since the early Pleistocene (Hötzl and Zötl 1978:301-311).

In modern times, eolian deposition and deflation shape the landscape. Brief torrential rains may cause local flooding and pooling of water or may infiltrate into the sedimentary rock surfaces. Most of this surface water evaporates with the onset of hot weather. When runoff enters sinkholes it may stand for some time before percolating to greater depths (beduoin wells) or flow through cave systems depositing surface sands and clastics. Where cave walls and floors have been undercut by vadose flow, breakdown may occur. Salt crystal wedging plays an important role in eroding cave surfaces and causing breakdown in some caves.

In Koppen's climate classification system, most of Arabia is classified as hot, dry, desert (Bwh). The mountainous region along the Red Sea coast experiences cooler temperatures and higher rainfall than the rest of the peninsula and is classified as semi-arid (Bs). The following climatic patterns are typical for the region shown in Figure 2:

Annual rainfall averages 100 millimeters over most of the area and falls between November and May. Heavy rains of short duration typically fall over a limited area. This area may have rainfall which greatly exceeds the yearly average in the course of a few hours and then go without significant rains for several years. Localized flooding frequently accompanies episodes of heavy rainfall.

Summer months are typically hot and dry. Normal daily temperatures range from 24° to 42°C, but may exceed 50°C. The average relative humidity is approximately 13% inland and increases to about 60% along the coast. Winter days are pleasant. Normal temperatures range from 8 to 23°C but may drop below freezing. Relative humidity averages about 45% inland and increases to about 70% along the coast.

A more detailed account of the climate of Saudi Arabia is found in Schyfsma (1978:31-44).

#### VEGETATION

The vegetation of the sedimentary regions is typical of arid steppes. Drought-adapted, perennial shrubs grow singly or in isolated patches which may cover vast areas. Dominant species include saltbushes (*Zygophyllum sp.*, *Tribulus sp.*), hamd (*Rhazya stricta*) and arfaj (*Rhanterium epapposum*). This type of vegetation is generally limited to undulating sand sheets and areas which are subject to periodic flooding. Broad expanses of gravel plains, rocky plateau and areas of shifting sands are almost completely devoid of perennial plant life. The desert thorn (*Lycium shawi*) is frequently found at the mouth of caves near Ma'aqala (Fig. 2). After a period of rain, a wide variety of drought-evading ephemerals spring up quickly in every habitat. These include annuals such as composites and mustards; and perennials such as grasses and sedges. Date palms (*Phoenix dactylifera*) are common in oasis areas. The largest oases in the Kingdom are near the Arabian Gulf coast and are associated with karst springs. These are the Al Qatif oasis and the oasis of Al Hasa (Fig. 2).

#### KARST LANDFORMS

The principal karst features of Saudi Arabia include dry valleys and gorges cut by extinct river systems, karst lakes and springs, an extensive field of collapse and solutional dolines, and cave systems.

Three major wadi systems dissect the Kingdom: 1. Wadi Ar Rimah - Al Batin, 2. Wadi Al Birk - As Sah'ba 3. Wadi Ad Dawasir (Fig. 1). These wadis exist today as a series of discon-

nected dry valleys and gorges which act as accumulation basins for local runoff and eolian deposits. During the late Pliocene and early Pleistocene these wadi systems functioned as active rivers which drained rainwaters from the peninsula.

Dendritic drainage patterns developed mainly on the igneous and metamorphic rocks of the western highlands. Through-flowing drainage in the sedimentary regions was limited to the deep channels of the Wadi Al Batin (Fig. 1 #4 and Fig. 3) and the Wadi As Sah'ba (Fig. 1, D). Sedimentary region runoff was carried only short distances, in isolated wadis, before infiltrating into the bedrock.

Impressive karst gorges exist where large wadis breached the steep limestone escarpments of the central Arabian region. For example, the Wadi Ad Dawasir system cut a 20 kilometer-long gorge through the Tuwayq escarpment near the village of Tamrah (Fig. 1 #2). This gorge is 25 kilometers wide where it enters the escarpment and narrows to 8 kilometers wide near Tamrah. Here the gorge walls tower over 250 meters above the wadi floor. The wadi channel has an average width of 3 kilometers near the mouth of the gorge and decreases in width towards the east where it empties into a gravel delta. The decreasing channel width may be due to subsurface infiltration of the runoff waters. Other gorges were cut through the central Arabian escarpments by the Wadi Al Hinw (Fig. 1 #1), Wadi Al Birk (Fig. 1 #3), Wadi Al 'Atk (Fig. 2C, through Aruma rocks) and Wadi Ar Rimah (Fig. 1 #5).

Numerous short wadis with westward flow can be found along escarpment faces in central Arabia. These range from narrow gullies cut steeply into the cliff face, to wider channels several kilometers in length. They all have their origin as runoff channels which drain limited local areas on top of the escarpment. The larger wadis are typically widest where they breach the escarpment and they taper to narrow channels near the top (Fig. 4).

#### NORTH CENTRAL ARABIA KARST LAKES

'Ayn Al Burj (Fig. 2 #15) is an immense karst lake found in the Al Aflaj oasis. 'Ayn Al Burj (Fig. 5) is a roughly cylindrical pit with a surface width of over 100 meters and a similar depth. The water level has decreased by about 3 meters since the installation of a pumping station in 1981.

The Al Aflaj region is covered with lag deposits and gravel from the Wadi Al Jadwal. This deposition must have occurred during the late Pliocene - early Pleistocene pluvials since the gravels in the eastern part of the wadi cover clastics of Miocene to Pliocene age. 'Ayn Al Burj and several small 'ayns occur where the Arab Formation outcrops in the gravel plain. The probable origin of these lakes is due to solution of the anhydrite layers in the formation and subsequent collapse of the marine limestone during the Plio - Pleistocene pluvial periods.

'Ayn Ad Dil' (Fig. 2 #14), in the Al Kharj oasis, is another karst lake of dimensions similar to 'Ayn Al Burj. In historical times this lake was also full, as witnessed by a series of steps



**Figure 4.** A short wadi with a westward drainage near Abu Jiffan ( 24° 30' N. Lat., 47° 43' E. Long.). Photo by W.D. Peters.

leading to a water drawing platform cut several meters down the side of one wall of the 'ayn. Today it has been pumped almost completely dry to water the surrounding oases. The 'ayn is formed in the Sulaiy Limestone at the surface but probably formed when the Sulaiy rocks collapsed into a water-filled solution pocket in the Hith Anhydrite beneath it. Water samples analyzed by Job et. al. (1978:221) show that waters drawn from the 'ayn are saturated with respect to gypsum.

#### DAHL HIT

Dahl Hit (Fig. 2 #13) is located along the course of the Wadi As Sulaiy at the base of the Hit escarpment. Davis (1983) described the cave as a single chamber full of breakdown, with



**Figure 5.** Part of the karst lake 'Ayn Al Burj in the Al Aflaj region. Photo by J. Briggs.

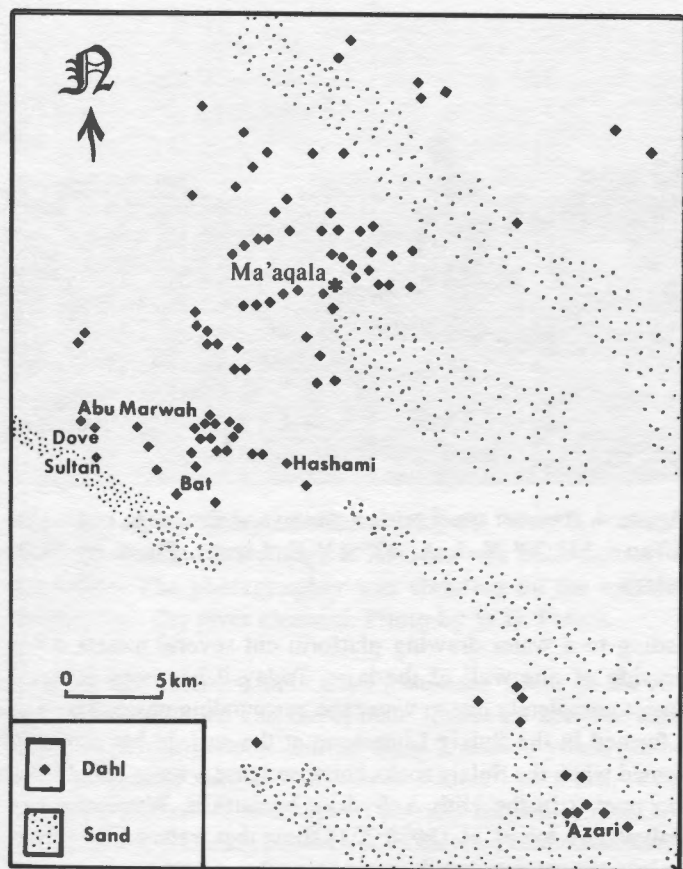


Figure 6. The doline field around the village of Ma'aqala. The figure is modified from the Defense Mapping Agency's Ma'aqala map (1974).

an opening 30 meters high by 60 meters wide, which enters the base of the Hit escarpment at a 45° incline. He noted a crescent shaped lake, approximately 30 meters long by 10 meters wide, 150 meters from the entrance.

The land surface to the east and west of the Hit escarpment is limestone of the Sulaiy Formation. To the east this formation is a gently tilting, slightly dissected plateau underlain by the Hith Formation. To the west the Sulaiy rocks are badly slumped and contorted due to solution of the underlying Hith Anhydrite by numerous wadi systems. In the area surrounding Dahl Hit, many solutional pits penetrate the wadi floor. Dahl Hit represents a solutional pocket at the contact between the Hith and Arab Formations.

Job et al. (1978:221) analyzed waters collected from Dahl Hit in 1973 and found them to be chemically related to those of 'Ayn Ad Dil' in Al Kharj. In 1983, Davis noted that the water level in Dahl Hit had been dropping recently. Today, Dahl Hit is dry. Considering that no water has been pumped directly from

Dahl Hit, the low water level in 'Ayn Ad Dil,' and the extremely limited aquifer recharge by modern rainfall, the aquifer in the Al Kharj region is apparently being rapidly depleted to water the oases and farm projects.

#### ARUMA DAHLS

Three unnamed dahls are shown by Bramkamp and Ramirez (1957) where the Aruma Formation meets a small escarpment of the Umm Ar Radhuma Formation (Fig. 2 #7). One is a dry pit about 90 meters deep by 70 meters wide. The width decreases at the top to about 50 meters due to a projecting rim of rock near the surface. The floor of the dahl is a cone-shaped collection of breakdown and gravel. All three dahls lie in a gravel filled depression which serves as a collection basin for the Wadi An Namil and other local runoff (Fig. 2, B). These dahls appear to be of solutional origin. Since the underlying formations are primarily sandstone, anhydrite solution does not seem to be involved in the formation of these dahls.

#### AS SUMMAN PLATEAU

The As Summan (Fig. 2) is an extensive bedrock plateau which slopes gently eastward and is occasionally covered by sand sheets, or is shallowly dissected. Gravel ridges, up to 50 kilometers in length, are elevated above the landscape in parts of the plateau. These ridges are relict river channels exhumed by wind deflation of fine sediments in the surrounding area. They bear little relationship to the present drainage system (ARAMCO F-1228).

The central part of the As Summan plateau, known as the As Sulb, is one of the most interesting karst landscapes in Arabia. This region is penetrated by numerous dolines and a few cave systems. The entrance to these dahls are typically open shafts which are almost imperceptible to an observer on the flat plateau.

#### UMM AR RADHUMA KARST

The large doline field which surrounds the village of Ma'aqala (Fig. 2) is formed chiefly in the Umm Ar Radhuma Limestone. The most prominent dolines in this area are shown as possible water sources on the Defense Mapping Agency's map (1974). Figure 6 shows only a minimum number of the largest dolines. A map showing the full extent of this doline field does not exist.

The nature of these dolines is regionally variable. Dahl Al Hashami (Fig. 7), a bedouin well, is a vertical shaft 14 meters deep. Entrance to the well is gained through two 3 meter wide holes, separated by a rocky bridge. The floor of the well is breakdown and gravel. In 1984, we found 70 meters of horizontal passages leading from the bottom of Dahl Al Hashami. These passages are low, narrow crawlways which extend in a straight line along bedded clastics. In 1985, after local rains, the passages beneath the first crawlway were full of water.

## TERTIARY SANDSTONE AND MARL KARST

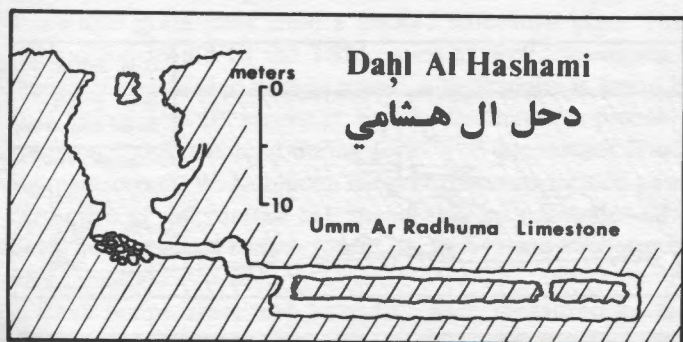


Figure 7. Section view of the bedouin well, Dahl Al Hashami. Decimeter sized holes and tubes (tafoni) are found in the thick calcrete crust at the top of the well. The horizontal passages follow well defined bedding planes. Rope marks have been cut in the limestone walls in numerous places. Drawn by W.D. Peters.

Between Dahl Al Hashami and Dahl Abu Marwah (Fig. 6) lies a group of blowholes which narrow with increasing depth (Fig. 8). Shallow, sand-filled shelter caves (Fig. 9); and sinks which channel local runoff beneath the surface are also found in this area. Around the village of Ma'aqala, the dolines are typically vertical shafts with openings of 2 meters or less in diameter and depths of 4 to 15 meters. Many shafts terminate in sand, gravel, garbage and animal remains. Horizontal passages may extend from some shafts at various depths, but are usually blind cul-de-sacs or connect to nearby shafts. To the south of Ma'aqala, another group of dolines cluster around Dahl 'Azari (Fig. 6).



Figure 8. Two field investigators occupy the upper parts of blowholes near the village of Ma'aqala. Photo by J. Pint.

A few caves to the southwest of Ma'aqala are formed in the TSM formation. These caves differ dramatically in structure from the UAR dolines. Typically, a maze-like system of horizontal passages lies 10 to 15 meters below the surface. We explored over 2 kilometers of passage in Dahl Sultan (Fig. 10), 500 meters of passage in Bat Cave and 300 meters of passage in Dove Cave (Fig. 6). These investigations in no way exhausted all possible leads, and it is likely only a small part of each cave system was seen.

Upper level chambers are found at a depth of 7 to 8 meters at or near the entrance of the deeper TSM caves. Typical of these chambers is Fox Hole, 300 meters northwest of Dahl Sultan.

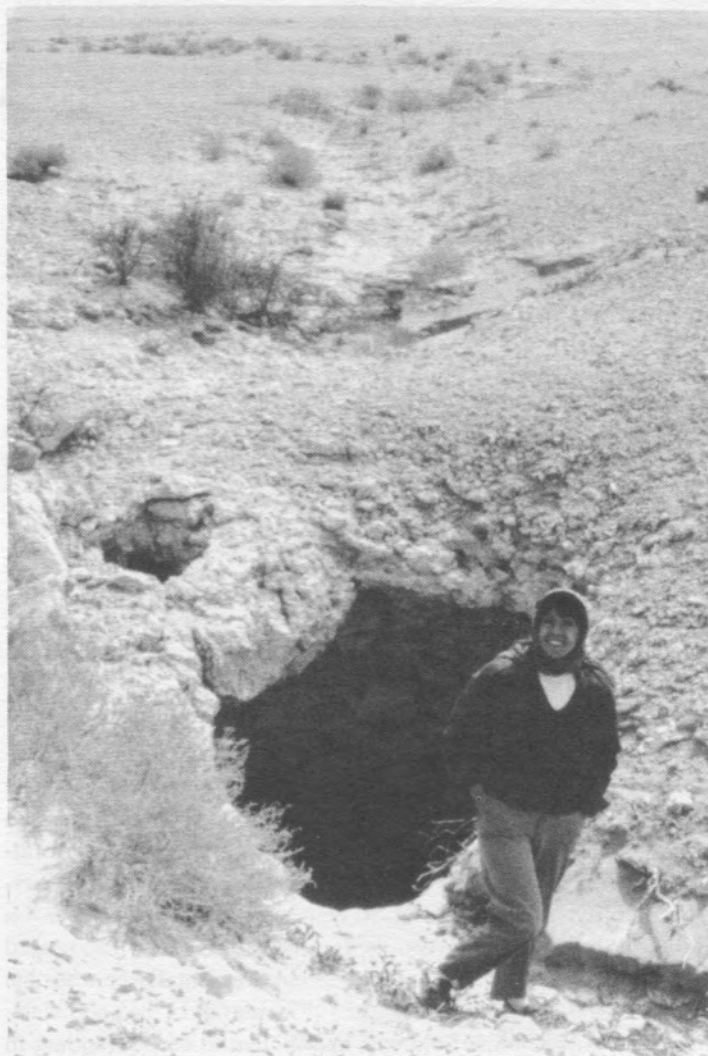
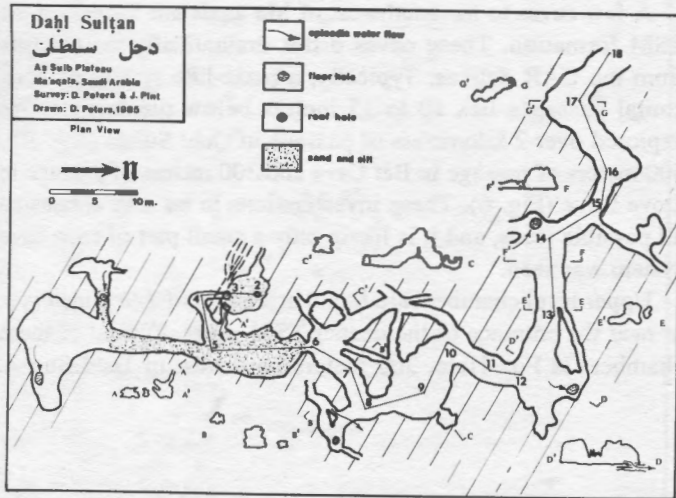


Figure 9. A shallow solutional doline which collects local runoff near the village of Ma'aqala. Photo by W.D. Peters.

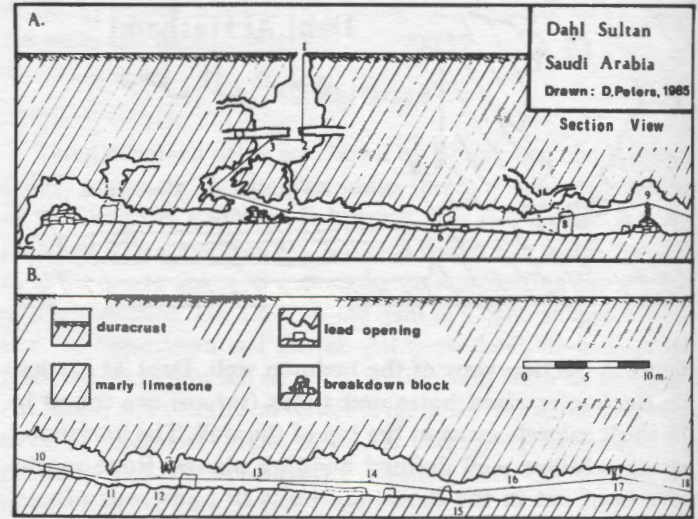


**Figure 10. Plan and section views of the entrance to Dahl Sultan. This is the “blowhole cave” of Pint and Peters (1985). The initially low passages and crawlways lead to large and repeatedly branching passages and rooms deeper into the cave. This represents the only accurately surveyed section of the cave.**

The entrance to this cave is a 7.5 meter deep by 3 meter-wide shaft partitioned in several places by rock bridges. Twenty meters of sand-filled horizontal passage, averaging 1.5 meters high and 3 meters wide, terminate in two low rooms. A 0.2 meter diameter solutional pipe leaves each room in the direction of Dahl Sultan’s entrance. Similar pipes intersect Dahl Sultan’s upper chamber at the same depth (Fig. 10). Numerous small holes, ranging from 5 centimeters to 1 meter, are found between the two cave entrances. All of these entrances collect local runoff after heavy rains and channel it to greater depths.

Partially-sand-filled crawlways at the lower level cave entrance give way to repeatedly branching and interconnecting passages as large as 11 meters wide by 4 meters high. Large breakdown rooms are common. A dome-shaped room measuring 15 meters high by 60 meters wide with a cone of massive breakdown blocks on the floor is found in the Bat Cave (Fig. 6). Small solutional pipes that intersect the ceilings and sediment-free vadose tubes that intersect the walls at various levels channel local surface runoff from the upper level passages into the larger rooms below. Shallow stream channels and dessication cracks in the floor sediments indicate the presence of intermittent running or pooled water in some larger rooms and passages. High water marks of 50 centimeters or less are seen on the walls of many large rooms. In other areas, water has passed through tight floor drains, and then ran horizontally beneath the present floor. Between 1984 and 1987, rainfall in the southwestern part of the doline field was insufficient to cause flooding in these caves.

The walls of these caves have a rather surrealistic texture of rough, irregular pockets and odd, angular projections. Many of



these projections are flat or amorphous masses of porous chalcidonic quartz, usually 1 meter or less in length (Fig. 11). The walls and ceilings are encrusted with a wide variety of calcite and gypsum speleothems. Nowhere are these speleothems better developed than in Dahl Sultan.

Clastic floor sediments away from the cave entrances include individual blocks or conical piles of breakdown and insoluble residues of red clay, sand and silt. Conical sediment piles up to 3.5 meters high are found in several locations in Dahl Sultan and near the entrance of the Dove Cave. Jennings (1971:33) reports a similar finding in an Australian cave. He



**Figure 11. Chalcidonic quartz wall projection found in Dahl Sultan. Photo by W.D. Peters.**

suggests the cone's origin is due to the collection of dry soil fed in a single grain state from a choked solutional pipe. This explanation would fit the TSM caves as well. An unusual deposit of quartz sand thickly coated with limonite is found in Dahl Sultan (Fig. 10, survey pt. 6). The limonite was probably precipitated onto the sand during periods of intermittent flooding (pers. comm. W. Kubilius). Biogenic deposits include powdery piles of dehydrated bat guano and bat mummies (Bat Cave) and skeletons of fox, rodent, rock dove and beetles near cave entrances.

Cave temperature and humidity were measured by the authors over a two-year period in Dahl Sultan. A maximum-minimum thermometer and a hygrometer were placed 150 meters away from the entrance in the lower level caves. These were checked and reset four times each year. The cave temperature varied between 25° and 26° C and the relative humidity remained a constant 100%.

Dahl Abu Marwah (Cave of the Father of Flint) is atypical of the TSM caves near Ma'aqala. It is a collapse doline (Fig. 12) with a roughly rectangular surface plan measuring 47 by 22 meters. The doline is 11 meters deep and has breakdown covering over half of the floor. The doline has retained its original collapse form with the exception of eolian sand infilling which has choked a horizontal passage and obscured some of the breakdown floor. It was formed by collapse of the roof into a large cavern below.

Dahl Suraywilat (Fig. 2 #6) is an outlier of the Ma'aqala doline field. The entrance to this bedouin well is a 1.5 meter wide by 8 meter deep vertical shaft. A 0.5 meter high by 4 meter wide crawlway leads 2 meters to another vertical shaft similar to the entrance. This lower shaft is partitioned by rock bridges and was full of water 8.5 meters below the crawlway in February 1985. The walls of all passages have been deeply rope-scored by countless generations of bedouin hauling water from the lower level well.

Dahl Abu Sukhayl (Fig. 2 #3) is the deepest sinkhole recorded in the TSM Formation. Davis (1983) presented a memory sketch of the cave and described it as a 2 meter diameter shaft which drops 46 meters to a 30 meter long by 15 meter wide by 15 meter high room. A second drop of 8 meters leads to a system of horizontal passages up to 10 meters lower, and to a solutional dome 15 meters wide by 35 meters long which rises 45

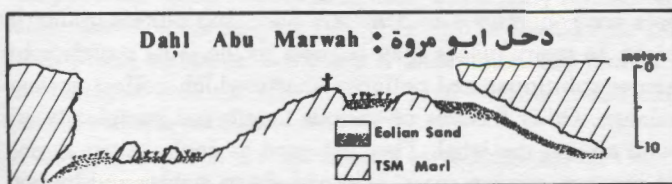


Figure 12. Section view of Dahl Abu Marwah. This doline has retained its original collapse structure and angular plan. Drawn by W.D. Peters.

meters above the floor. Most of these lower leads remain unexplored. He noted the presence of standing water on a return trip which blocked the entrance to the lower level system. Although he stated that the cave was formed in Paleocene age rocks, this is unlikely. The TSM beds are quite thick in this area. Davis (1983) and Bramkamp and Ramirez (1957) note the presence of other dolines in the area.

Dahl Sabsab (Fig. 2 #11) is typical of the As Sulb caves. It is formed in compact grey limestone (Hadrukh Formation?). Davis (1983) presented a memory sketch of the system which is roughly accurate. The cave has 3 openings along a distance of 73 meters in a straight bedrock joint. Twenty meters to the west, two even narrower entrances are found in a parallel joint which appears to connect through subsurface crawlways to the main



Figure 13. A vadose passage in Dahl Sabsab. The passage is two meters high and has a shallow pool on the floor. Photo by W.D. Peters.



Figure 14. A ghar cave near the village of Judah. This shallow fissure is 15 meters high. Photo by W.D. Peters.

system. Both joints have a northerly bearing. The 3 entrances descend through winding tubes (Fig. 13) and vertical shafts to a common point about 25 meters below the surface. Here they enter a 0.5 meter high horizontal passage full of mud which was impassable after 20 meters in November 1984. In April 1985, the lower crawlway was half full of standing water. Dahl Sab-sab drains an 18 square kilometer basin and may flood partially or completely after heavy local rains.

#### COASTAL REGION OF THE ARABIAN GULF

Clusters of karst springs are found at the Al Qatif and Al

Hasa oases (Fig. 2). Over 140 perennial 'ayns (springs) water the 75 square kilometer oasis in Al Qatif (ARAMCO F-2910). These 'ayns are vertical pits several meters in diameter and up to 35 meters deep. They may be non-flowing wells or artesian springs. The largest karst spring, 'Ayn Al Labaniyah, has an average discharge of 40 liters per second. Total karst water discharge from the 'ayns, drilled wells, submarine springs and groundwater evaporation is estimated at 14 cubic meters per second for the Al Qatif oasis (Job 1978:93-135).

In Al Hasa, 16 principal artesian springs clustered in two locations water the vast 200 square kilometer oasis. The largest of these springs, 'Ayn Al Khudud, has an output of 1700 liters per second (Hötzl et al. 1978:58-77). It is a vertical shaft 7 meters in diameter and 11 meters deep fed by a system of phreatic tubes. Divers equipped with SCUBA gear surveyed over 60 meters of the lower system of caves. They found horizontal tubes at a depth of 8 to 10 meters and at 23 meters connected by vertical shafts (Hötzl et al. 1978:58-77). Similar situations are found at the other springs in Al Hasa. These cave systems are formed in the Dam Formation and have a total discharge of about 13 cubic meters per second (Hötzl et al. 1978:58-77).

The Umm Ar Radhuma Formation is the most important aquifer in eastern Arabia. Waters which infiltrated strata in the As Sulb region flow by gravity to the karst springs of Al Qatif and Al Hasa. Here the UAR waters use the intervening karstified aquifers and tectonic faults as conduits for emergence as artesian springs and wells (Job 1978:93-135). This aquifer has been heavily developed for domestic and agricultural projects throughout the eastern region.

Vertical fissures (ghar) of various dimensions are a common feature in the east-facing escarpment and its outlying benches to the west of Al Hasa. One of these benches, Jabal Al Qarah, is formed in Hofuf Formation sandy marl. It has a surface area of 1.7 square kilometers and rises 70 meters above the surrounding oasis in Al Hasa. Its sides are eroded into step-like, small plains and steep rises. The jabal's face is dissected in some places by a series of ghar fissures which follow a NW-NNW trending joint system and extend various distances into the jabal. Ghar An Nashab, located on the east side of the jabal, is a maze-like fissure system which branches along rectangularly crossing joints. Its 746 meters of passage extend about 220 meters into the jabal. The relatively flat floor of these fissures is found at 20 to 25 meters beneath the jabal's surface. The fissures are generally 1 to 5 meters wide and quite variable in height. In many places they connect to the jabal's surface by narrow solutional and collapse shafts which collect surface drainage. Other fissures of various length and complexity are found around the jabal. They are used as cool shelters during hot weather, storage areas, goat and sheep stables and by pot-terers.

Shallow ghar fissures (Fig. 14) are also found in benches of the Al Lidam escarpment ( Fig. 2) and the Jabal Shadgam near Judah (Fig. 2).



At Dhahran (Fig. 2), Jado and Johnson (1983) noted the presence of blind solutional caverns in exposed Rus rocks. These lenticular cavities were 1 to 2 meters wide, 3 to 5 meters high and several meters in length. There was no apparent grouping or alignment of these solutional cavities.

#### WESTERN SAUDI ARABIA

Karstification of landforms in the western part of the Kingdom is quite limited due to the igneous nature of most rocks in the region. However, Ivan Miller (pers. comm.) has reported caves in the region of Khamis Mushayt (Fig. 1 #9).

Also, the Koran mentions that the Prophet Muhammad sheltered from his enemies in the Cave of Thaur, near Mecca (Fig. 1 #8). These caves are formed in granite which is known to weather into pits and caves (USGSARAMCO 1963). Outcrops of these rocks are widespread in the western mountains.

Dahl Hamdah (Fig. 1 #7) is the only recorded cave (USGSARAMCO 1963) in the northwestern region. It is formed in the Raghama Formation of Miocene age. These limestone, gypsum and calcareous conglomerates of marine origin are quite limited in distribution along the Red Sea coast. Dahl Hamdah is close to several important archaeological sites and may be of historical interest itself.

#### UNEXPLORED KARST FEATURES

The following is a list of karst features which the authors did not visit: Dahl Jabana is located at 28° 46' N. Lat., 43° 11' E. Long. on a Bartholomew (1982) map ( Fig. 1 #6). It appears to be in the Aruma Formation. Northwest of the 'Wadi Al Batin (Fig. 1), the Umm Ar Radhuma Formation is dissected by a well-developed system of short wadis which drain to the northeast. This area is marked by numerous small sinks and slumping due to anhydrite removal (Powers et al. 1966). Bartholomew (1982) records an unnamed dahl at 28° 21' N. Lat., 44° 44' E. Long. ( Fig. 2 #1). Ghar Mushay'ib ( Fig. 2 #16) is located in the southern As Summan on the USGSARAMCO (1963) map.

#### SMALL-SCALE KARST FEATURES

Case-hardening of exposed rocks due to calcite enrichment has led to the development of a duricrust (calcrete) cap on many sedimentary formations. This duricrust is thinly bedded on marl, nodular on calcareous sandstone, and thickly bedded with tafoni development on pure limestone (Hötzl et al. 1978: 284-290). Minor solutional sculpture is uncommon and limited to smoothing of rock surfaces in some karst wells or meandering runnels on some rock surfaces.

Cave decorations are uncommon in Arabian caves. Only a few caves, to the southwest of Ma'aqala, are endowed with calcite and gypsum speleothems. These reach their best development in Dahl Sultan (Fig. 6 and 10), and the surrounding Tertiary Sandstone and Marl caves. In these caves, gypsum

flowers and crusts and selenite crystals are common. Short calcite stalactites, short soda straws and thick helictites decorate the walls in many rooms. In the areas where intermittent water pools form, calcite has been deposited in the form of coralloid, crusts and rarely, dogtooth spar. Calcite in the form of flowstone and stalagmites is quite uncommon.

A variety of monocrystalline forms are found in these caves. Six-sided calcite crystals with a pyramidal apex are found in a few areas. These crystals are typically 3 cm. long by 0.6 cm. in diameter with their long axis at 90° to the stalactite face. Two longer calcite crystals are found hanging from a low, undercut wall in Dahl Sultan. These prismatic crystals are up to 27 cm. long and 1.5 cm. in diameter, and have a pyramidal apex. Dogtooth spar scalenohedrons, up to 2.2 mm. long, are found on the faces of the crystal's barrel. Monocrystalline gypsum crystals, up to 5 cm. long, by 1.5 cm. wide, are found on the tips of calcite stalactites in some parts of these TSM caves. These monoclinic crystals are colorless and translucent. Strong air flow is common in all areas where these gypsum crystals are found.

All of the caves where speleothems were encountered are formed in highly porous, sandy marl (TSM). Water enters these caves as runoff after infrequent, heavy rains. The primary effect of this brief but rapid inflow of water is erosional. This is evidenced by the lack of flowstone and the deposition of surface sediments at water entry points. Calcite deposition may occur later as standing pools evaporate. Pools of water trapped in upper level caves may percolate through the floor and emerge through capillaries as thin films or trickles in the lower caves. Calcite and gypsum deposition may occur when this water evaporates from wall surfaces and speleothems. Dripping water was encountered in only one room in Dahl Sultan and was not associated with speleothem development. The lack of stalagmites in these caves indicates that dripping water has been uncommon in the past.

#### SUMMARY

The study of karst landforms in Saudi Arabia is in its infancy. Historically, geological investigations were aimed at locating the oil and mineral wealth of the Kingdom. Little time or effort was spent on projects which did not have immediate economic applications.

Initially, our interest in this topic was peaked by the study of a USGS geographical map which showed a cluster of caves near Ma'aqala. Due to the constraints of conflicting work schedules and the difficulties involved in deep desert travel, our explorations were limited to occasional long weekend and national holiday trips. The excitement of finding and exploring a huge field of virgin caves enticed us to spend many long hours pouring over any map of the peninsula we could find. These maps led us to new caves, dry river valleys, karst lakes, artesian springs and towering gorges through steep escarpments. The project grew from an occasional caving trip to a survey of karst in Arabia. We decided to criss-cross Saudi Arabia

to see what was there rather than spend all of our limited time in a detailed study of any one area. This paper is an account of our travel in Arabia and a subsequent literature search. Two references provided most of our information on Arabian karst: *Sedimentary Geology of Saudi Arabia* (Powers et al. 1966) and *Quaternary Period in Saudi Arabia* (Al-Sayari and Zötl 1978).

In this article, we barely touch the surface of the exciting discoveries which await future explorers and researchers of Arabian karst. Detailed studies of the Ma'aqala and coastal karst are now in progress as a joint venture between the Research Institute of the King Fahd University of Petroleum and Minerals and the Austrian Academy of Sciences. These and future studies will greatly extend our knowledge and understanding of Arabian karst.

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# MEANDER CUTOFF CAVES AND SELF PIRACY: THE CONSEQUENCES OF MEANDER INCISION INTO SOLUBLE ROCKS

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*When meander incision occurs into soluble rock materials such as limestone, karst processes can alter river flow patterns in a manner, and with a rapidity, that is not available on insoluble rocks. The development of dissolution conduits or caves through meander necks is especially important. Efficient self-piracy of a stream through a meander cutoff cave causes abandonment of the meander loop. Abandonment of the meander loop will inhibit further development of any meander cutoff cave draining the abandoned meander loop to the next meander downstream. Sedimentation of the abandoned meander loop may choke both the meander cutoff cave feeding the abandoned meander loop, as well as tributary caves draining the surrounding upland to that meander loop. The relative efficiency of meander cutoff caves will control which meander loops and meander cutoff caves become abandoned.*

*Examples of meander cutoff cave formation from flatlying Paleozoic limestones in Kentucky, and from glaciated Precambrian marbles in New York demonstrate the complex interaction of meander cutoff cave development. Structure, carbonate lithology and climate in this type of speleogenesis is subordinate to the geomorphologic and hydrologic setting of the surface meanders.*

## INTRODUCTION

The development of free meanders in river or stream channels formed on easily eroded materials in wide valleys is a well documented and understood phenomena. Common morphological features such as meander loops, oxbow lakes, point bars and meander necks are present. Rapid incision of a meandering stream into underlying, resistant bedrock results in incised or entrenched meanders, where the original meandering channel pattern is locked into rock banks as base level lowers. Meander migration, and associated neck cutoff and loop abandonment, is greatly slowed due to the resistant rock walls.

When entrenchment occurs into a soluble rock material, such as limestone, channel modification occurs more slowly than in unconsolidated material, but more rapidly than in non-soluble rocks. Although water is held within mechanically resistant rock walls, it has the capability to cut through meander necks by dissolution, diverting water flow and producing self-piracy. The dissolution conduit developed through a meander neck is

called a *meander cutoff cave* (Fig. 1). The literature on this subject is exceedingly sparse. Jennings (1985) referred to "meander caves" as features developed by the lateral undercutting of the caving bank of a meander loop. He also described natural bridges as possible from the development of a short dissolution conduit through a meander neck. In an earlier work, Jennings (1971) presented a classic example from Burra Creek in New South Wales. Trudgill (1985) also discussed meander caves in terms of natural bridges. The term natural bridge is vague when applied to karst processes and geomorphology; the specific term meander cutoff cave avoids confusion. Examples of meander cutoff caves in the literature include Malott's (1922) work from Indian Creek in Lawrence County, Indiana, and Fridley's (1939) work from the Cloverlick Valley in Greenbrier County West Virginia, subsequently expanded on by Werner (1972). Examples used as case histories in this report come from Kentucky (Moore and Myloie, 1979; Mason, et al., 1983) and New York (Myloie, 1979a; 1979b).

Incision of meanders into soluble rock has other conse-

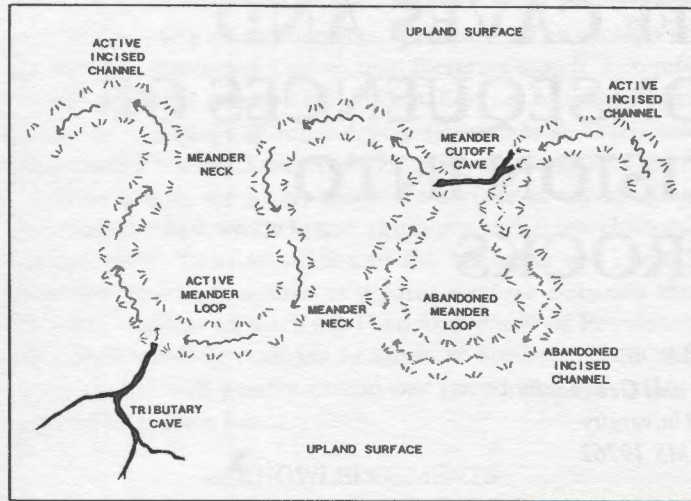


Figure 1. A diagrammatic representation of the features formed by incision of a meandering stream into a limestone surface. The terms displayed here will be used consistently throughout the paper.

quences for karst development. Besides the obvious implications of the lowered base level represented by stream incision, the position of meanders with respect to regional structure and the potentiometric surface can influence where cave systems draining the surrounding limestone upland will develop. Kastning (1983) demonstrated the production of deep cave systems in the Langtry area of southwest Texas as a result of meander incision. Quinlan and Ray (1981), in the Mammoth Cave, Kentucky region, have demonstrated the focus of flow from the sinkhole plain north under the ridges of the Crawford Upland to the southern portions of incised meander loops on the Green River.

Meander cutoff caves develop because they provide an appreciable increase in the local stream gradient. This steeper gradient has sufficient advantages that part or all of the surface flow may eventually be diverted through the meander neck. Streams meandering on floodplains made of unconsolidated material usually produce meander cutoffs as the result of a single flood event, changing the stream flow path abruptly. Meander cutoff caves develop slowly by dissolution, and the stream flow path also changes slowly. The extended time frame of meander cutoff cave development allows meander cutoff caves to compete for recharge sources and discharge points.

Entrenchment of a stream channel into soluble rock removes the stream from continuity with its former flood plain. Flood events produce dramatic rises in stream level, and can result in the development of "bank flow" mazes in the channel wall (Palmer, 1975). During flood events, solutionally aggressive flood waters are forced into the joints, bedding and other openings in the soluble rock of the channel wall. Because recharge is equally available to all openings from the stream, maze caves

develop. Upland cave systems that are tributary to the incised stream channel, and meander cutoff caves can both be modified by backflooding and integration with bank flow maze caves.

### SELECTED CASE HISTORIES

The following case histories are used to illustrate the consequences of meander incision in soluble rocks. Two examples from Kentucky and one example from New York are presented (Fig. 2). These examples show not only how meander cutoff cave development works, but also illustrate the commonality of the process under different geologic settings.

#### SINKING FORK AREA, TRIGG COUNTY, KENTUCKY

Sinking Fork is a major stream draining west-central Christian County and east-central Trigg County, Kentucky (see Figures 2 and 3). This area is part of the Shawnee Hills section of the Interior Low Plateau Province (Whaley and Black, 1978). The entire drainage of Sinking Fork from its headwaters in the east to its discharge into the Little River in the west is developed on and in Mississippian (Lower Carboniferous) limestones (with associated Quaternary alluvium).

The incision of Sinking Fork into the limestones has resulted in extensive cave formation. This cave formation has taken two basic patterns: development of meander cutoff caves, and development of tributary caves. Continued incision by Sinking Fork has led to a complicated history of abandonment and piracy in both types of caves.

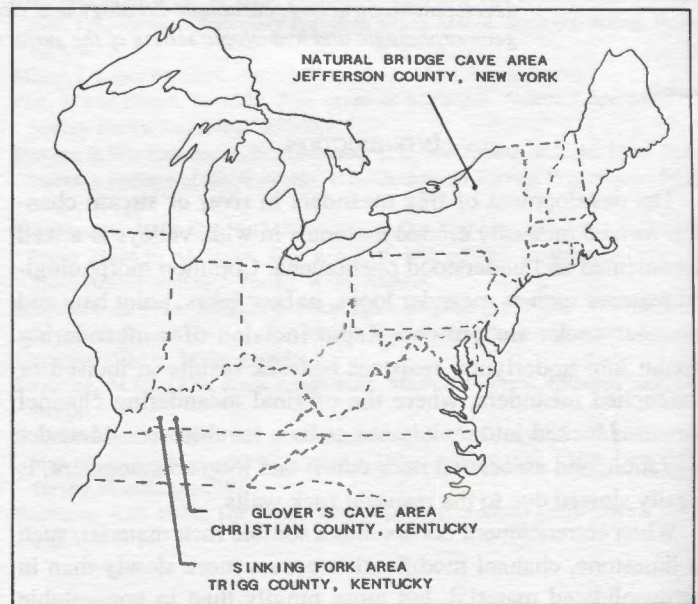


Figure 2. Location of the three case histories presented in this paper.

### Geologic Setting

The Mississippian St. Genevieve Limestone covers almost the entire area. It is a light to medium-gray limestone with varying degrees of finely crystalline and dolomitic beds to coarse grained bioclastic and oolitic beds. Chert is common, often comprising 50% of some beds. A fine-grained oolitic limestone occurs at the base, providing a conformable and well-defined contact with the lithologically similar underlying St. Louis Limestone. A total available thickness of 75 m is exposed (Ulrich and Klemic, 1966). Quaternary alluvium is found throughout the Sinking Fork valley floor, especially in the downstream section. The alluvium is unconsolidated clay, silt and sand, with abundant chert gravel. The material tends to merge imperceptibly with the residual soil and colluvium of the valley walls (Ulrich and Klemic, 1966).

The limestones dip gently to the north-northeast at approximately 1/2 degree or less. The dip is undulatory, with subtle structural highs and lows. These subtle features exercise some local control over speleogenesis (Kastning, 1984). Jointing occurs as orthogonal sets developed along approximate NE-SW and NW-SE trends. Joint influence is obvious in some cave passages. Some normal faults of small displacement occur in the area. One known normal fault occurs at a major resurgence of Sinking Fork and a tributary stream, implying structural control at sites J and K of Figure 3.

The plateau surface is undulatory but fairly uniform at an elevation of 150 m above sea level. Small hills reach 166 m. The bed of Sinking Fork, in its downstream end, is at 120 m elevation. The plateau surface is dotted with closed contour depressions up to 20 m deep with bottoms as low as 130 m elevation. Many of these lead through smaller openings in their floors or walls into cave conduits (Pipeline Cave and Boatwright Hole, see items H and I, Fig. 3). Despite the extensive karst development on the plateau, very few large streams sink in blind valleys. Sinking Fork sinks in its own bed, but three tributary stream valleys all join Sinking Fork at grade although they flow through to Sinking Fork only under high water conditions. Many small sinking streams exist, and their total summed catchment area is appreciable.

### Cave Descriptions

The Cutoff Caves are located on the South bank of Sinking Fork at the western edge of the study area (item B, Fig. 3). Sinking Fork has abandoned a large meander (item A, Fig. 3) by developing a meander cutoff cave through a meander neck. This conduit has enlarged and collapsed, leaving an open channel through the meander neck, and remnant cave passages in the cliff on the south bank. The Cutoff Caves are a series of tubes that occur over a 78 m horizontal and a 10 m vertical range. The passages range from small tubes 0.3 m in diameter to larger passages 3 m wide and 4 m high. Scalloping shows that the

large openings at the upstream end of the cliff accepted water from the river, and the caves at the downstream end of the cliff discharged water to the river. The caves are relatively free of breakdown, but contain large amounts of sediment and flowstone, which eventually chokes off most of the passages.

River Road Cave is located on the south bank of Sinking Fork just upstream of its junction with Steele Branch (item C, Fig. 3). Sinking Fork flows along the south side of its valley at this point, forming steep bluffs. In these bluffs are the three entrances to River Road Cave, stretched along a 90 m section of the bluffs. The main entrance is the most upstream or eastern one, located 3 m above normal water level in Sinking Fork.

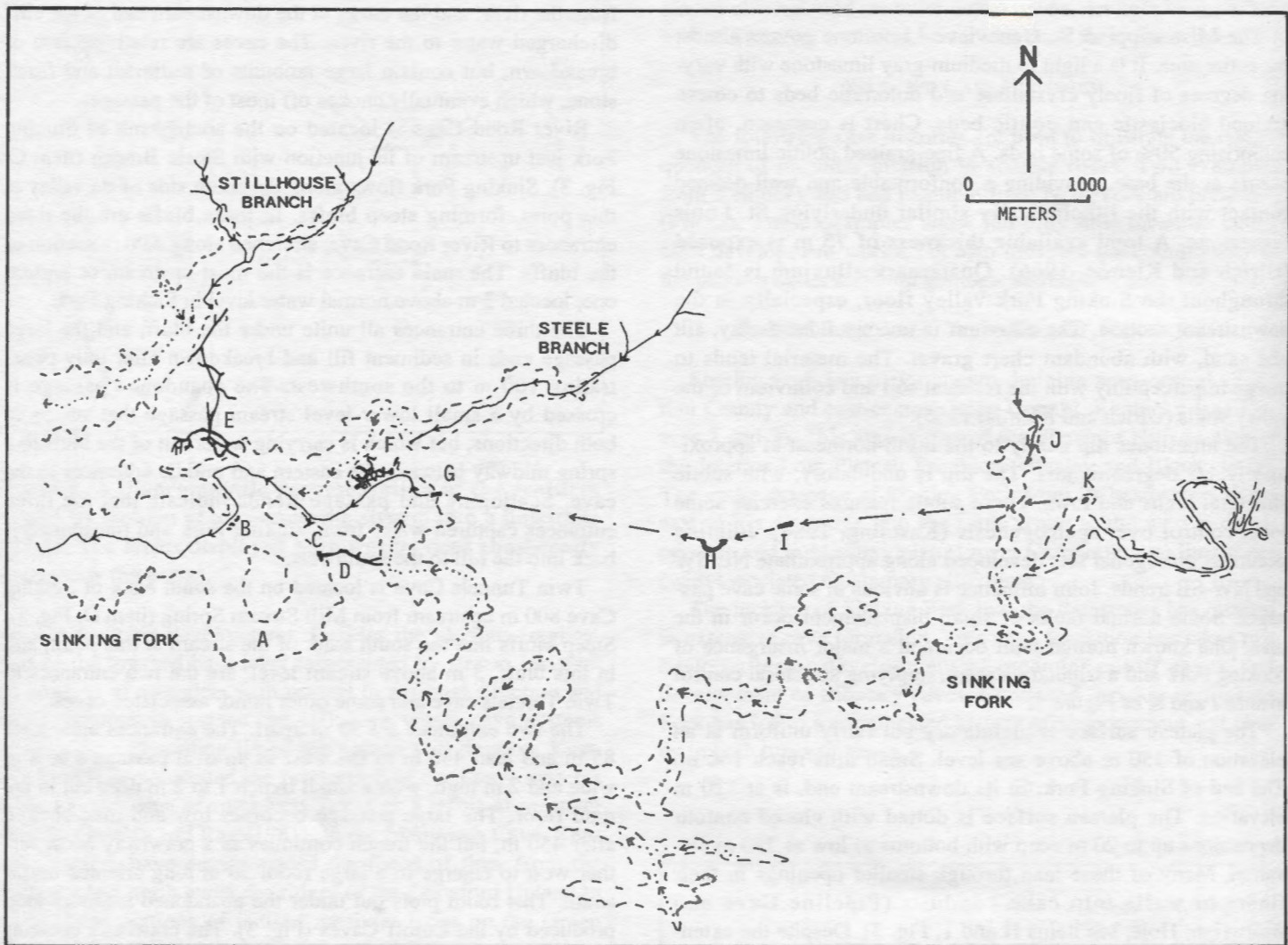
The three entrances all unite under the bluff, and the large passage ends in sediment fill and breakdown after only penetrating 100 m to the southwest. The abandoned passage is crossed by a small lower level stream passage that sumps in both directions, but which is carrying water out of the bluff to a spring midway between the eastern and middle entrances to the cave. Scalloping and passage trends indicate that the three entrances captured water from Sinking Fork and transported it back into the hill to the southwest.

Twin Tunnels Cave is located on the south bank of Sinking Fork 800 m upstream from Mill Stream Spring (item D, Fig. 3). Steep bluffs line the south bank of the stream at this point, and in this bluff, 3 m above stream level, are the two entrances to Twin Tunnels cave and some other minor associated caves.

The two entrances are 30 m apart. The entrances unite after 85 m and lead 450 m to the west as an oval passage 4 to 8 m wide and 2 m high, with a small trench 1 to 2 m deep cut in the mud floor. The large passage becomes low and mud-choked after 450 m, but the trench continues as a crawlway 60 m further west to emerge in a large room 50 m long oriented north-south. This room plots out under the abandoned meander loop produced by the Cutoff Caves (Fig. 3). The crawlway contains a low drain that trends northeast towards River Road Cave, feeding the lower level stream crawl of that cave. Flow scallops in the main tube show flow into the twin entrances towards the west.

In the eastern part of the Sinking Fork drainage (item K, Fig. 3) is a bend of Sinking Fork which the topographic map shows as an alcove in the channel wall. Some of the water in the river at this point disappears here into a massive logjam. In dry weather all of Sinking Fork insurges here. This water resurges at Mill Stream Spring, via Boatwright and Pipeline Cave segments noted (items H and I) on Figure 3 (Moore and Mylroie, 1979). About 500 m northwest of this major resurgence is a disappearing tributary surface stream (item J, Fig. 3).

The incision of Sinking Fork resulted not only in the self piracy of the meander cutoff caves previously described, but in the development of traditional tributary caves (Fig. 3). The caves are part of systems that deliver (or delivered in the past) water to Sinking Fork from areas not in the bed of the stream itself. Complete descriptions of these caves are available in Moore and Mylroie (1979).



**Figure 3. Map of the Sinking Fork area, Trigg County, Kentucky. The Sinking Fork stream and two major tributaries, Stillhouse Branch and Steele Branch, are labeled. The dashed line is the 137 m (450 foot) contour, and displays the meandering, incised course of Sinking Fork. The thin solid line with arrows are the year-round active stream courses; the dotted lines with arrows are seasonal flood routes. The bold solid lines are mapped cave passages. The dot/dashed line is the underground dye test route of Sinking Fork from its headwaters through Pipeline Cave and Boatwright Hole to Mill Stream Spring. Major features and caves are shown by letter designations as follows: A - abandoned meander loop of Sinking Fork; B - Cutoff Caves; C - River Road Cave; D - Twin Tunnels Cave; E - Cool Spring Cave; F - Decibel Cave; G - Mill Stream Spring; H - Boatwright Hole; I - Pipeline Cave; J - small sinking tributary stream; K - upstream sink point of Sinking Fork.**

Four tributary cave systems are known. The tributary cave system underlying River Road Cave and Twin Tunnels Cave has been previously discussed. It is the only tributary cave of any size that is found on the south side of Sinking Fork, despite the fact that the regional dip is from southwest to northeast. The dip is fairly undulatory, and the larger, older Little River is incised to an elevation of 118 m, 3 km south of Sinking Fork. These factors may be the reason for a lack of tributary caves on the south bank of Sinking Fork.

The second tributary cave system is a large cave just downstream of Mill Stream Spring, Decibel Cave (item F, Fig. 3). The entire known cave is located in a hill projecting from the main plateau. Sinking Fork forms the southern boundary of the projection, and the surface tributary valley of Steele Branch forms the northern and western boundary. The cave consists of a series of passages, divided into four main groups, that show water transmission from the northwest to the southeast. The passages total 2,000 m in length. The three most southwesterly

passage series are dry, but the most northeasterly series is active. The southeast end of all these passages are very maze-like, ending in mud, breakdown, and flowstone blockages at the edge of Sinking Fork. Steele Branch sinks in its bed in dry weather only 300 m north of the upstream end of the active stream passage in Decibel Cave, and flows through the active passages to Sinking Fork. The size of the Steele Branch valley indicates that it has continued to incise its valley downward, despite the loss of some water into the cave. Large scale collapse has occurred in the active portion of the cave, breaking to the surface in two locations.

The third tributary cave system is the sinking stream just north of the Sinking Fork resurgence shown as item "J" on Figure 3. This cave cannot be explored beyond its sink alcove, but delivers its water to Mill Stream Spring. The cave's proximity to the Mill Stream Spring flow path indicates that it is probably not an extensive system.

The last major tributary cave to Sinking Fork is Cool Spring Cave. With over 5200 m mapped, with more remaining, this is the second largest cave in western Kentucky. The cave has three distinct levels of development. From the entrance area in a spring alcove just north of Sinking Fork (item E, Fig. 3), the cave trends west and north. The area to the west is entirely middle and upper level abandoned passage, developed at an approximate elevation of 130 m and 137 m, respectively. The lower, active level is developed at approximately 125 m elevation, and trends north for over 1200 m (straight line distance), with another portion of the middle level crossing overhead. Like Decibel Cave to the east, Cool Spring Cave is isolated in a projection of the plateau surface, only on a larger scale. The projection is bounded on the south and west by Sinking Fork, and on the north by Stillhouse Branch, a tributary to Sinking Fork. The middle and upper levels of the cave imply a significant age to Cool Spring Cave. Again, like Decibel Cave, Cool Spring Cave apparently transmits portions of the flow of a tributary surface stream, in this case Stillhouse Branch, south to Sinking Fork.

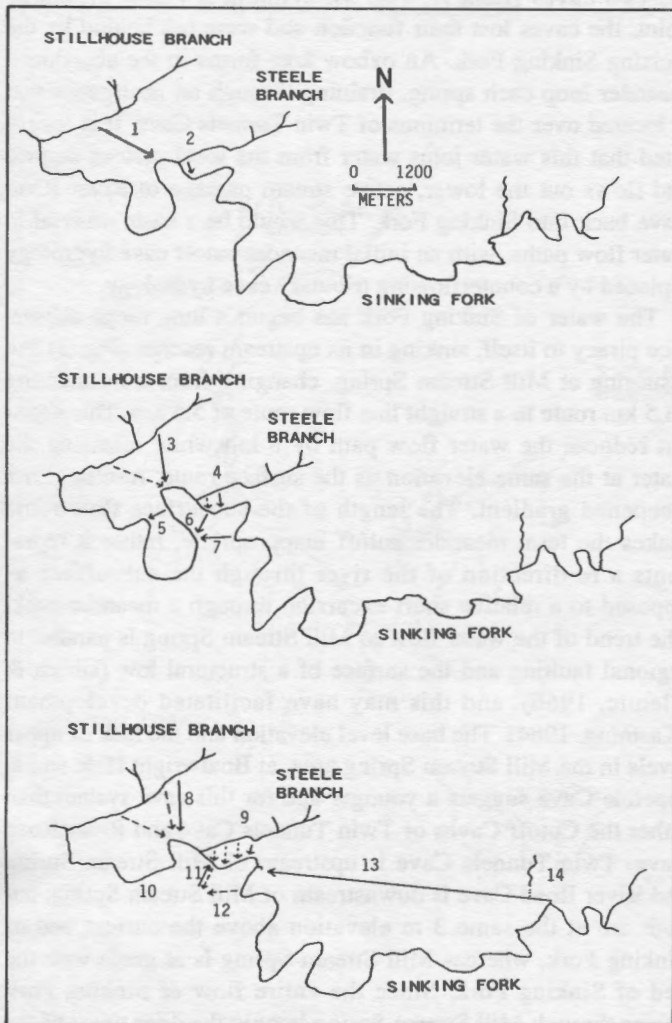
#### *Discussion of the Sinking Fork Caves*

The entrenchment of the meanders of Sinking Fork has resulted in the development of cave conduits in the meander necks, bypassing the meander loops and following the shorter, steeper gradient to the far side of the meander necks. This process has reached a terminal stage at the Cutoff Caves (Fig. 3), and the main solution conduit has been breached, leaving only remnant caves in the open channel cutting across the meander neck. Farther upstream, River Road Cave and Twin Tunnels Cave are abandoned meander cutoff caves perched 3 m above the normal flow level of Sinking Fork. These caves fed water to a common discharge point through their meander necks to the next meander downstream. River Road Cave and Twin Tunnels Cave were abandoned when the Cutoff Caves formed, creating a dry, abandoned meander loop at the downstream terminus of

the two caves (item A, Fig. 3). Without a viable discharge point, the caves lost their function and were left behind by the incising Sinking Fork. An oxbow lake forms in the abandoned meander loop each spring, draining through an resurgence that is located over the terminus of Twin Tunnels Cave. It is speculated that this water joins water from the local plateau surface and flows out the lower, active stream passage of River Road Cave back into Sinking Fork. This would be a basic reversal in water flow paths, with an initial meander cutoff cave hydrology replaced by a counterflowing tributary cave hydrology.

The water of Sinking Fork has begun a long range subsurface piracy to itself, sinking in its upstream reaches (Fig. 3) and resurging at Mill Stream Spring, changing from a meandering 13.5 km route to a straight line flow route of 5.5 km. This shortcut reduces the water flow path by 8 km while releasing the water at the same elevation as the surface route, resulting in a steepened gradient. The length of the subsurface flow route makes the term meander cutoff inappropriate, rather it represents a re-direction of the river through the subsurface as opposed to a relative short excursion through a meander neck. The trend of the water flow to Mill Stream Spring is parallel to regional faulting and the surface of a structural low (Ulrich & Klemic, 1966), and this may have facilitated development (Kastning, 1984). The base level elevation and the lack of upper levels in the Mill Stream Spring area, at Boatwright Hole and at Pipeline Cave suggest a younger age for this cave system than either the Cutoff Caves or Twin Tunnels Cave and River Road Cave. Twin Tunnels Cave is upstream of Mill Stream Spring and River Road Cave is downstream of Mill Stream Spring, but both are at the same 3 m elevation above the current bed of Sinking Fork, whereas Mill Stream Spring is at grade with the bed of Sinking Fork. Since the entire flow of Sinking Fork passes through Mill Stream Spring in only the drier times of the year, this cave system may still be in the development stage. The partition of water flow through Mill Stream Spring may reduce the rate of headward incision of Sinking Fork in that portion of its surface course upstream of the spring, but downstream of the resurgence.

The incision of Sinking Fork into the plateau surface resulted in cave development through subsurface self-piracy, and subsurface capture of tributary streams. The history of cave development in the area is shown diagrammatically by Figure 4 A-C. In Figure 4A, the initial meander pattern of Sinking Fork is incised into the plateau surface, and initial cave formation began in Cool Spring Cave and Decibel Cave, by their capture of Stillhouse Branch and Steele Branch, respectively. Further incision by Sinking Fork resulted in the situation pictured in Figure 4B. Cool Spring Cave and Decibel Cave captured water further upstream in the tributaries, abandoning earlier, higher levels to the southwest. Decibel Cave has a complex, maze-like character in its southeastern portions, produced by backflooding from the Sinking Fork. The Cutoff Caves pirated water through a meander neck, as did River Road Cave and Twin Tunnels Cave. Continued incision of Sinking Fork resulted in Figure 4C,



**Figure 4.** Representation of the evolution of surface and subsurface drainage patterns in the Sinking Fork area. 4 A - initial incision of Sinking Fork locks in the meander pattern. The upper levels of Cool Spring Cave (1) and Decibel Cave (2) develop by the respective piracy of Stillhouse Branch and Steele Branch. 4 B - Continued incision results in the development of lower levels in Cool Spring (3) and Decibel (4) caves as they pirate water from further upstream in the tributaries. Meander cutoff cave development begins at the Cutoff Caves (5), River Road Cave (6), and Twin Tunnels Cave (7). 4 C - current status of cave development in the Sinking Fork area. Cool Spring Cave (8) and Decibel Cave (9) have continued their piracy upstream in Stillhouse Branch and Steele Branch, respectively, abandoning early higher levels. The Cutoff Caves have breached to the surface (10), shifting the Sinking Fork flow entirely through the meander neck and producing an abandoned meander loop (see figure 3). River Road Cave (11) and Twin Tunnels Cave (12) have become abandoned by loss of their discharge point, and flow reversal has occurred back to Sinking Fork from the abandoned meander loop. A major self-piracy of Sinking Fork has occurred through Mill Stream Spring (13), intercepting a surface tributary (14).

Twin (Double) Level, Buzzard's Folly and others are found along the banks of the West Fork of the Red River in the southeastern portion of Christian County, Kentucky (Fig. 2 and 5), and have been described in Mylroie (1984).

#### *Geologic Setting*

The area is a gently rolling sinkhole plain averaging 165 to 175 m in elevation. The West Fork of the Red River and a tributary, Montgomery Creek, are incised to an elevation of 140 m down to 135 m, providing a relief of approximately 30 to 40 m.

The Mississippian Ste. Genevieve Limestone covers almost the entire area, with underlying St. Louis Limestone being found only in the southern portion of the West Fork of the Red River Valley (Klemic, 1966). A thick residual soil covers most of the sinkhole plain surface, and unconsolidated alluvium floors parts of the bottom of the main river courses. The regional dip is approximately 1 degree or less to the north but is very undulatory and locally variable. High angle normal faults are documented both immediately north and south of the Glover's Cave area, striking west to west northwest with a displacement of several meters or more (Klemic, 1966). The degree to which the faulting has influenced the area's cave development is not known. A review of the regional geology can be found in Whaley and Black (1978). The overall geologic setting is essentially the same as described for the Sinking Fork area of Trigg County to the west.

analogous to the present, in which Cool Spring Cave and Decibel Cave have continued their process of capturing water from even farther upstream in the tributaries to the northeast. The efficiency of the Cutoff Caves meander by-pass caused the abandonment of the meander loop fed by River Road Cave and Twin Tunnels Cave, with subsequent abandonment of those caves by Sinking Fork with a small scale water flow reversal from the abandoned meander loop back to Sinking Fork. The Mill Stream Spring system is established, with concurrent capture of a small surface tributary.

Sinking fork demonstrates the effect of master stream incision on cave development. As shown here, self-piracy by meander cutoff, or by larger scale conduit formation, can in turn affect previously established tributary caves and meander cutoff caves.

#### THE GLOVER'S CAVE AREA, CHRISTIAN COUNTY, KENTUCKY

The Glover's Cave area of eastern Christian County and extreme western Todd County, KY is well known for its extensive cave development. Caves such as Glover's, Dry Cave,



The incision of the West Fork of the Red River below the sinkhole plain surface has resulted in entrenched meanders with a vertical relief of around 30 m. Mason (1982) and McDowell (1983) have noted that two major types of caves have developed: first, major dendritic tributary caves draining adjacent expanses of the sinkhole plain, and second, simple conduits, often with backflood mazes, acting as meander cutoffs within the West Fork itself. The situation is similar to that described for Sinking Fork of the Little River discussed above.

#### Cave Descriptions

The dendritic tributary caves draining the sinkhole plain are characterized by two major caves, Glover's Cave with 3.25 km of passage (item E, Fig. 5) and Twin Level Cave (Payne, 1981), with over 5 km of passage (item I, Fig. 5). Both caves consist primarily of a major conduit trending east from the banks of the West Fork under the sinkhole plain. Other smaller examples include Dry Cave (item F, Fig. 5), a 1.2 km long truncated portion of Glover's Cave, and Gates Cave (item D, Fig. 5) and Cedar Bluff Church Cave (item C, Fig. 5), both small caves on the west bank of the West Fork. These sinkhole plain caves are similar to Cool Spring Cave on the Sinking Fork in Trigg County (Moore and Mylroie, 1979).

As is shown in Figure 5, the West Fork of the Red River undergoes several meander self-piracies or cutoffs below the junction with Montgomery Creek. The first cutoff occurs at Buzzard's Folly (item A, Fig. 5), and is unusual in that the water re-appears on the surface at Murphy's Spring (item B, Fig. 5) and sinks again before returning to the West Fork. Water not sinking at Buzzard's Folly continues downstream and is partially lost to the Rick's Rise meander cutoff cave (item G, Fig. 5). The remaining surface water is joined further downstream by the resurging Buzzard's Folly/Murphy's Spring cutoff water; this combined flow sinks (except in high water) at the Dry Ford Cave meander cutoff cave (item H, Fig. 5). The water resurging at Rick's Rise continues downstream and joins the water resurging at Dry Ford Cave, re-establishing the normal surface flow of the West Fork. Further south, just before leaving the Glover's Cave area, part of the water sinks and then rises at the Turner's Blue Hole meander cutoff cave (item J, Fig. 5).

The efficiency of these cutoffs varies. The Turner's Blue Hole, Buzzard's Folly/Murphy's Spring and Rick's Rise meander cutoff caves appear to handle only 5% of the average West Fork flow. On the other hand, the Dry Ford Cave meander cutoff handles 100% of the West Fork flow 95% of the time, allowing only flood water to continue down the surface channel to the resurgence of Rick's Rise (McDowell, 1983).

#### Discussion of the Glover's Cave Area

If the Buzzard's Folly/Murphy's Spring meander cutoff cave system became 100% effective, no water would reach the resurgence point of the Rick's Rise meander cutoff cave, which

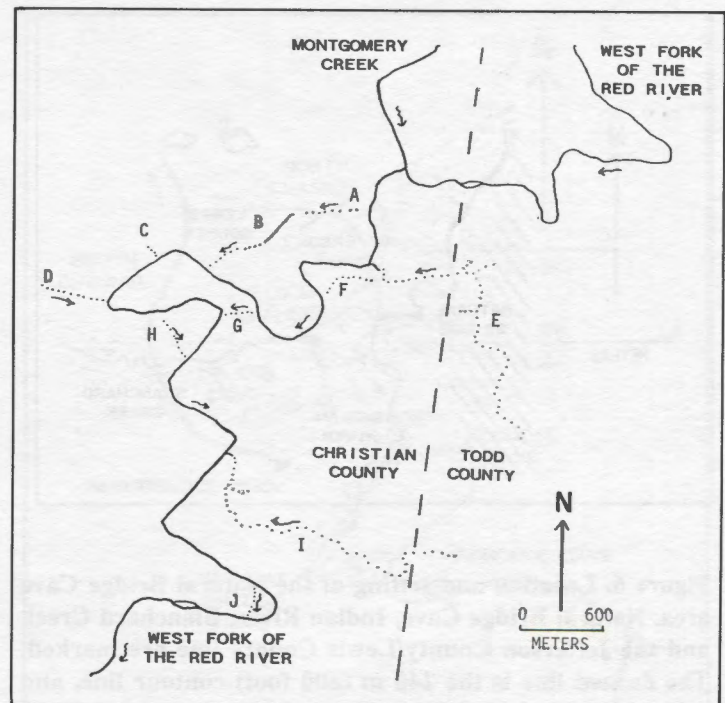
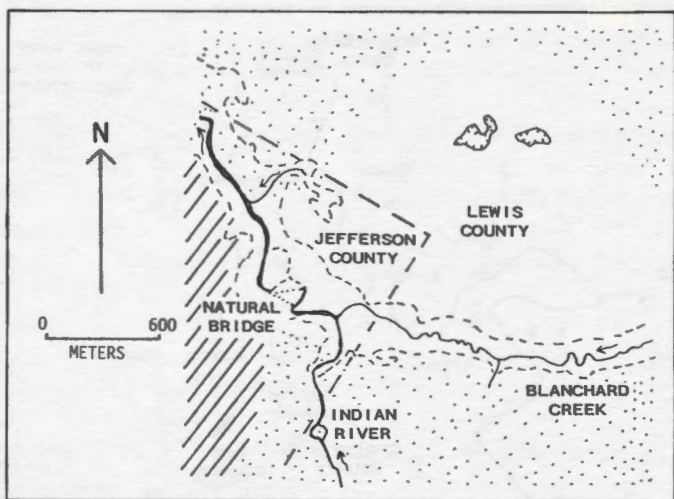


Figure 5. Simplified representation of the Glover's Cave area, Christian County, Kentucky. Montgomery Creek, West Fork of the Red River, and the Christian County/Todd County line are labeled. Solid lines are surface flow paths, dotted lines cave passage and underground flow paths. A - Buzzard's Folly Cave; B - Murphy's Spring; C - Cedar Bluff Church Cave; D - Gate's Cave; E - Glover's Cave; F - Dry Cave; G - Rick's Rise; H - Dry Ford Cave; I - Twin Level Cave; J - Turner's Blue Hole.

would then become abandoned. So the most upstream meander cutoff cave can effect the future of the meander cutoff caves immediately downstream. If the Dry Ford Cave meander cutoff continues to be efficient, it may result in the abandonment and sediment infilling of the meander loop fed by Rick's Rise, choking the Rick's Rise meander cutoff cave unless the flow there is enough to keep the channel open (in the Sinking Fork area, the flow from River Road Cave and Twin Tunnels Cave was not enough to keep their resurgence channel in the abandoned meander loop open, and those caves became senescent). In this case, the most downstream meander cutoff cave can control meander cutoff caves immediately upstream. Finally, Rick's Rise, by becoming very efficient, can cause abandonment of meander cutoff caves both upstream and downstream. If Rick's Rise became very efficient, it would pirate water away from the Dry Ford Cave cutoff, which would then have as its only water supply the Buzzard's Folly/Murphy's Spring water, plus water gained from tributary caves such as Gate's Cave. The surface course of the West Fork upstream of the Dry Ford



**Figure 6.** Location and setting of the Natural Bridge Cave area. Natural Bridge Cave, Indian River, Blanchard Creek and the Jefferson County/Lewis County line are marked. The dashed line is the 240 m (800 foot) contour line, and defines the incised valley. Two closed depressions are shown. Diagonal lines are Quaternary glacial sediments; dotted area is noncarbonate metamorphic rocks, white area is Precambrian Grenville marble.

cave resurgence but downstream of the Buzzard's Folly/Murphy's Spring resurgence would be abandoned by much of the West Fork flow, and would become a minor surface course much like the present surface flow between Buzzard's Folly and Murphy's Spring. In addition, the normal surface flow path of the West Fork water from the Buzzard's Folly resurgence and through the Rick's Rise cutoff to the Dry Fork Cave resurgence is slightly less distance than the flow path to the same point by way of Murphy's Spring and Dry Ford Cave. Since most West Fork water currently bypasses the Buzzard's Folly resurgence, an efficient Rick's Rise cutoff would cause faster valley deepening for the Rick's Rise route compared to the Buzzard's Folly to Dry Ford Cave route. The result would be the abandonment of both the Buzzard's Folly/Murphy's Spring meander cutoff cave system as well the Dry Ford Cave meander cutoff. This scenario of the meander cutoff caves influencing other meander cutoff caves is similar to that earlier described from the Sinking Fork area of Trigg County. The interaction of meander cutoff caves may have impact on the formation and development of tributary caves under the adjacent sinkhole plain, as certain river meanders may silt up as nearby ones undergo deeper entrenchment, affecting tributary caves which resurge at those localities. The truncation of Dry Cave from Glover's Cave was produced by valley wall retreat of a meander (Fig. 5). The present resurgence of the Glover's Cave water closer to the input point for the Buzzard's Folly/Murphy's

Spring meander cutoff cave system has potential to reverse flow in the West Fork north into Buzzard's Folly.

The similarity in geologic conditions between the Sinking Fork area and the Glover's Cave area has resulted in similar meander cutoff cave development. The question becomes to what extent is meander cave cutoff development independent of minor variations in local geology.

#### THE NATURAL BRIDGE CAVE SYSTEM, JEFFERSON COUNTY, NEW YORK

The Natural Bridge Cave system is located in Jefferson County in northwestern New York on the western flank of the Adirondak Mountains (see Fig. 2 and 6). The cave system is developed in marble of Precambrian age and depending on the season diverts part or all of the Indian River through meander cutoff caves. Figure 6 shows the basic topography of the area, with the Indian River and Blanchard Creek flowing west off of the Adirondak uplands at an elevation of about 240 m, uniting and flowing underground at the village of Natural Bridge, NY. A small area of closed depressions exists 1200 meters northeast of Natural Bridge, and along with the Natural Bridge Cave System constitutes the known karst features of the immediate area.

#### *Geologic Setting*

The caves are developed in Precambrian marble, the calcitic and dolomitic Grenville Marble, which occurs as a band running east-west through the area of Figure 6. The marble contains numerous insoluble inclusions and boudinage features, but discernable relict primary features are absent (Smythe and Buddington, 1926). The marble is bounded on the north, east and south by a variety of gneisses and related metamorphic rocks, and on the west by a thick overburden of glacial sediments that obscures the underlying bedrock (Rickard and Fisher, 1970). Figure 6 shows the relationship of the major geologic features with the surface landscape in the Natural Bridge area. Unlike the Paleozoic limestones of the Helderberg Plateau to the south or the Watertown area to the west, the marbles of the Natural Bridge area are the weakest rocks in their location (excluding the glacial sediments). Instead of weathering as strong, resistant uplands as seen in the Helderbergs and in Watertown, they weather to produce lowlands about 255 m in elevation surrounded by low hills approximately 275 m in elevation, composed of more resistant gneisses. This differential in erosion resistance results in a large outcrop of marble which is not very far above base level, restricting cave development in the area, similar to the situation in the Cambro-Ordovician marbles of western Massachusetts (Cullen, et al., 1979). The main drainage of the area, Indian River and Blanchard Creek, have oriented their flow along the southern edge of the marble outcrop, entrenching a valley approximately 15 m deep into the marble. The Indian River has been captured underground by dissolution conduits which conduct the river water through the meander necks of the river, as shown in Figure 7.

### Cave Descriptions

There are four basic parts of the Natural Bridge Cave System. The cave system was first described by Carrol (1969), and his nomenclature will be used in this discussion. A more detailed description and interpretation is available in Mylroie (1979a). The first cave system met by the westward flowing Indian River is the Pancake Cave area, which once captured water from the upstream side of a meander (Fig. 7) and conducted it to the downstream side of that meander. Pancake Cave, Hornet Cave and other smaller caves clustered nearby are the relict input points for this section of Indian River, the water resurging 100 meters to the northwest as a series of springs. The caves consist of wide, low tubular passages which end in sumps, sediment and breakdown. Pancake Cave, the largest of the group, is typical, 75 m in length, 3 to 4 m wide, and 0.5 to 2 m in height.

Continuing downstream from the Pancake Cave area, the second part of the cave system is reached, Natural Bridge Cave itself. Natural Bridge Cave is a large cave conduit carrying part of the water of Indian River through the neck of the next meander west of the Pancake Cave meander (Fig. 7). The passage averages 10 m wide and 2 m high for 215 m, terminating in a deep, debris clogged sump only 30 m from the resurgence. The cave trends west for 80 m, then north-northeast for 135 m. The cave is basically a wide, low oval tube with occasional enlargement and subsidiary tube development along a fracture plane.

Only part of the Indian River enters Natural Bridge Cave itself, the rest flows downstream to insurgue at Flooded Cave, a large entrance chamber (Fig. 7) that soon sumps. Directly between Flooded Cave and the downstream end of Natural Bridge Cave is Siphon Cave, a large entrance leading to a single room that sumps immediately upstream and downstream. The water seen in Flooded Cave, Siphon Cave and Natural Bridge Cave all resurges at the Resurgence Pool, where it flows northwest in the South Channel of Indian River. In flood times, the Indian River carries too much water for Natural Bridge Cave and Flooded Cave to accept, and the excess water flows down the North Channel of Indian River, sometimes joining the South Channel by way of the Flood Channel (Fig. 7).

In the topographic high formed by the South, North and Flood Channels of Indian River is the third part of the Natural Bridge Cave System, Island Cave. Island Cave (Fig. 7) consists of a single large oval tube averaging 3 m wide and 1.5 m high, with subsidiary tubes and passages. The cave trends 60 m from its breakdown choked upstream end along the Flood Channel west southwest through the southeastern portion of the topographic high to sediment chokes along the north bank of the South Channel. Island Cave is an abandoned cave, probably having formed prior to Natural Bridge Cave itself, and acted as a meander cutoff cave for meander formed by the Flood and South Channel of Indian River (Fig. 7). Loss of the water of the Flood and North Channels to Natural Bridge Cave and the South Channel resulted in abandonment of the large upper

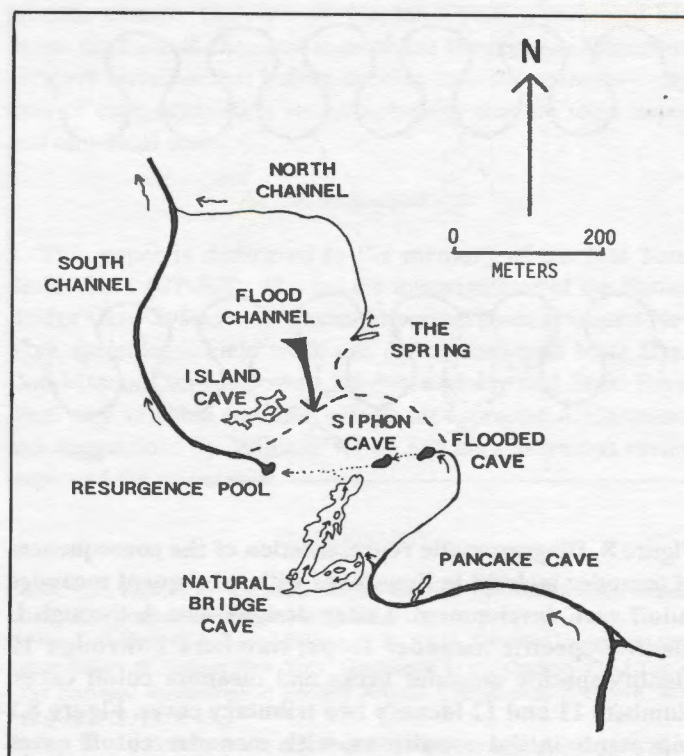
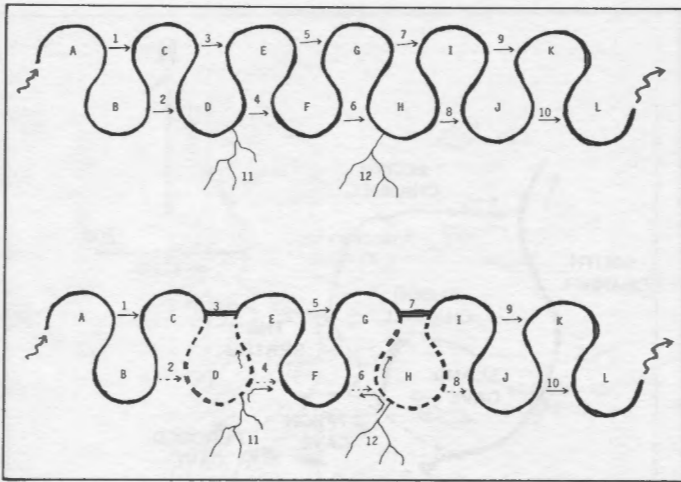


Figure 7. Major features of the Natural Bridge Cave area. Caves and channels are marked. Solid black lines are surface flow paths; dashed lines are surface overflow/abandoned flow paths; dotted lines are subsurface flow paths.

levels of Island Cave. Local drainage still provides water for the smaller, flooded lower levels of the cave.

West along the North Channel of Indian River downstream from the Flood Channel is the last portion of the Natural Bridge Cave System, The Spring. This small cave (Fig. 7) is located on the north bank of the North Channel, and its source of water has not been determined. It doesn't carry a large volume of water and it is not known if the cave receives its water from inputs in the stream bed of the North Channel, as a meander cutoff cave for the meander formed by the North Channel, or if it derives its water from karst areas in the marble to the northeast of the cave. As mentioned earlier, a series of large sinkholes and closed depressions lie on a small plateau of marble some 900-1200 m northeast of this location (Fig. 6). The cave is a low, wide passage with a series of partially flooded tubes averaging 0.6 m high and 2.5 m wide. The cave trends east 45 m before ending in sumps and breakdown.

Immediately downstream of The Spring in the North Channel and Island Cave in the South Channel the marble outcrop is lost under thick glacial sediments to the west and karst development is obscured (Fig. 6).



**Figure 8.** Diagrammatic representation of the consequences of meander incision in limestones with subsequent meander cutoff cave development. Letter designations A through L identify specific meander loops; numbers 1 through 10 identify specific meander necks and meander cutoff caves. Numbers 11 and 12 identify two tributary caves. Figure 8.1 represents initial conditions, with meander cutoff caves developing in competition with each other. Figure 8.2 shows the results of the disproportionate success of meander cutoff caves 3 and 7. Meander loops D and H are abandoned. Meander cutoff caves 2 and 6 are abandoned because of loss of a discharge point; caves 4 and 8 are abandoned because of loss of recharge. Tributary caves 11 and 12 have been placed to show some of their possible responses. Cave 11 may utilize the abandoned surface channel of loop D to reach meander loop E, or may reactivate meander cutoff cave 4 to reach loop F. Cave 12 may utilize the abandoned channel of loop H by reversing the original flow direction to reach loop G and meander cutoff cave 7, or may reactivate cutoff cave 6 by flow reversal to reach loop F.

#### *Discussion of the Natural Bridge Area*

The conduits of the Natural Bridge Cave System have the distinctive passage morphology typical of caves developed in marble (Hauer, 1969), that is, the twisting, multi-level semi-random trend of the passages on the local scale. Without consistent joint and bedding planes as are found in undeformed limestones, the groundwater initially flowing through the marble must utilize whatever faults, joints, lithologic boundaries and openings it can find. As these structures are not regularly placed in the marble, the cave passages also tend to lack a systematic morphology and orientation, especially on the small scale. Despite the lack of regular flow paths, the enterable cave passages in this cave system generally trend in straight line or straight line segments on the large scale. The caves go from

their insurgences to their resurgences in a very short, straight forward manner within a relatively thin set of vertical limits. The flow gradient between the insurgences and the resurgences and the water table position at the time of cave formation apparently prevented any exceptional deviation of passage orientations, either vertically or horizontally, from a single direct route between water input and output.

The Natural Bridge Cave System is a collection of horizontal and sub-horizontal oval cave conduits developed in Precambrian marble, that lie in the meander necks of the Indian River, transporting the river water through the steeper stream gradients of these meander cutoff caves. The caves show evidence of past competition that has resulted in abandonment of some meander cutoff caves. Some of the caves are competing in the present, and the future sequence of cave development and abandonment can be determined. Pancake Cave is abandoned, but shows evidence of flooding. Whether this flooding is backflooding, or actual transmission across the meander neck is not clear. Natural Bridge Cave is immediately downstream of Pancake Cave. Part of its input has been deflected by an artificial dam downstream to Flooded Cave. Before the emplacement of the dam, Natural Bridge was capable of handling all but flood inputs. Therefore the discharge point for Pancake Cave was an abandoned (at least seasonally) meander loop, and Pancake Cave has undergone abandonment as well. Flooded Cave was an early meander cutoff cave that has lost flow to the more upstream position of Natural Bridge Cave. The dam at Natural Bridge Cave has reactivated Flooded Cave and its flow path through Siphon Cave to the Resurgence Pool. Island Cave acted as a meander cutoff cave until the success of Flooded Cave and Natural Bridge Cave removed its source of water. Continued entrenchment of the stream from the Resurgence Pool has left Island Cave's large upper levels dry and abandoned. It is possible that The Spring was a meander cutoff cave that has lost recharge because of Flooded Cave and Natural Bridge Cave, but its current discharge and passage size are more in agreement with a water source on the limestone bench north of Indian River. The success of the Natural Bridge Cave meander cutoff has resulted in the abandonment of other meander cutoff caves both upstream (Pancake Cave) and downstream (Island Cave) of its position, by removal of discharge and recharge points, respectively.

#### CONCLUSIONS

The three case histories presented demonstrate how the development of incised meanders leads to the production of meander cutoff caves. Once initiated, meander cutoff caves compete for recharge waters, and for sites to discharge those waters. The meander cutoff cave that develops most rapidly, or with the greatest efficiency in terms of water capture and delivery, will control the future of its competitors.

Successful meander cutoff cave development can also influence the nature of discharge of tributary caves to incised mean-

ders. The production of abandoned meander loops by meander cutoff cave formation can result in hydraulic inefficiencies for tributary caves draining to that abandoned meander loop. Conversely, tributary caves may keep abandoned meander loop channels functional over a portion of the loop, maintaining flow through meander cutoff caves downstream that otherwise might lose all recharge. Depending on the location of the tributary cave resurgence in an abandoned meander loop, reversal of flow in the loop may result. This reversal of flow may occur in the subsurface, involving previously abandoned meander cutoff caves, or it may be surface flow reversal along the paleo-upstream direction in the abandoned meander loop.

The result of meander cutoff cave development can be presented diagrammatically, as in Figure 8. Though highly idealized, the figure has direct application to the three case histories previously discussed. The "domino" or cascade effect of meander loop abandonment, with subsequent meander cutoff cave abandonment, that results from hydrologic success of a single meander cutoff cave is illustrated. The abandonment of meander loops has consequences that can ripple outward from the incised channel to the subsurface karst hydrology of the adjacent uplands, primarily by controlling the efficiency of resurgences. Understanding the influence on meander cutoff caves in time and space has broad implications for conduit flow in karst areas.

The pattern of meander cutoff cave and tributary cave development that results from the incision of a meandering stream into soluble rock can be influenced by pre-existing conduits below the initial position of the meandering stream. Bathypneatic or deep phreatic conduits may be intercepted by stream incision, and distort the later development of meander cutoff caves by providing an open conduit, even if it is not in the most direct flow route. No evidence of pre-existing conduits were noted in the Kentucky or New York examples.

The overall similarity of the development of meander cutoff caves and associated features in the widely different geologic settings of the three examples presented deserves comment. The relative uniformity of meander cave development in the flatly-laying Paleozoic limestones of Kentucky versus the glaciated Precambrian marbles of New York emphasizes the primary hydrologic advantage of the meander cutoff cave compared to the importance of carbonate lithological variation, geologic structure and climate. The Kentucky examples could perhaps be considered "classic" examples, directly comparable to many lowland karst areas around the world. The glaciated Precambrian marbles of New York represent an example greatly removed from the classic case. Billion year old marbles that have undergone glaciation only 15,000 years ago could well be expected to produce karst features of a different nature from those in Kentucky. Yet both areas have shown a similar response to a similar recharge/discharge environment. The overall role of the geomorphic setting, as it interacts with the soluble rock outcrop to produce major subsurface conduit drainage trends is often overlooked during detailed examinations of subtle lithologic

variations, minor dip flexures, joint and fault orientation, and climatic change. The cave development pattern presented here draws attention to the need to establish the regional framework for cave development before delving into the secondary controls of cave orientation and morphology that are most important on a local scale.

#### ACKNOWLEDGEMENTS

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# METEOROLOGICAL OBSERVATIONS OF ICE CAVE, TROUT LAKE, WASHINGTON

KYLE MARTIN

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*Ice Cave is a segmented lava tube that traps cold air during winter permitting the development of ice speleothems. Four separate daily visits from Jan. 1986 through July 1987 allowed weather data collection in this cave.*

*Winter visits in 1986 and 1987 revealed cool temperatures of  $-4^{\circ}\text{C}$  and  $+1^{\circ}\text{C}$ , respectively in the stable cave interior in response to differing weather regimes. Spring and summer observations in 1987 indicated a transitional gradient of temperature from cave entrances to the deep interior. Stability in temperature and relative humidity increased with distance into the cave. Small temporal variations in temperature ( $0.5\text{-}1^{\circ}\text{C}$ ) and relative humidity were detected at all stations, indicating turbulent processes did on occasion extend throughout the cave. Ice speleothems manifested strong seasonal and spatial variation in growth and decay. From May through July of 1987 ice melted four times faster near the east cave entrance compared to the cave interior. Our spring and summer observations roughly agree with profiles generated by the Wigley-Brown model.*

## INTRODUCTION

Atmospheric observations were collected from January 1986 through July 1987, in Ice Cave, near Trout Lake, Washington. Ice Cave is a collapsed lava-tube noted for near-freezing temperatures and perennial ice features.

Such cave features persist because cold dense winter air sinks into a cave and strong density stratification between this cool air and lighter summer air prevents the warmer air from entering the cave. The primary objective of the study is to examine the spatial and temporal (diurnal and seasonal cycles) distribution of three atmospheric variables: temperature, relative humidity (RH), and air flow.

Limited quantitative studies of ice cave meteorology exist (Kovarick, 1898), although qualitative studies abound (Balch, 1900; Halliday, 1954; Merriam, 1950; Harrington, 1934). For general cave meteorology, refer to Ford and Cullingford (1976), Davies (1960), and Geiger (1965).

## REGIONAL GEOLOGY, GEOGRAPHY, AND CLIMATE

Ice Cave is associated with Quaternary volcanism of the Cascade Mountains in southwest Washington (sec. 35, T.6N., R.9E., Willard Quadrangle, 858 m asl). The cave is located in a mature coniferous forest ~31 km south-southwest of Mt. Adams (Fig. 1). Ice Cave is ~200 m long with four entrances permitting

a modest influx of outside air. A speleographic description of Ice Cave is given in Halliday (1963, 1954).

Ice Cave is located on the lee side of the Cascade Mountains in a humid microthermal climate defined where the average temperature of the coldest month is below  $0^{\circ}\text{C}$  and the average

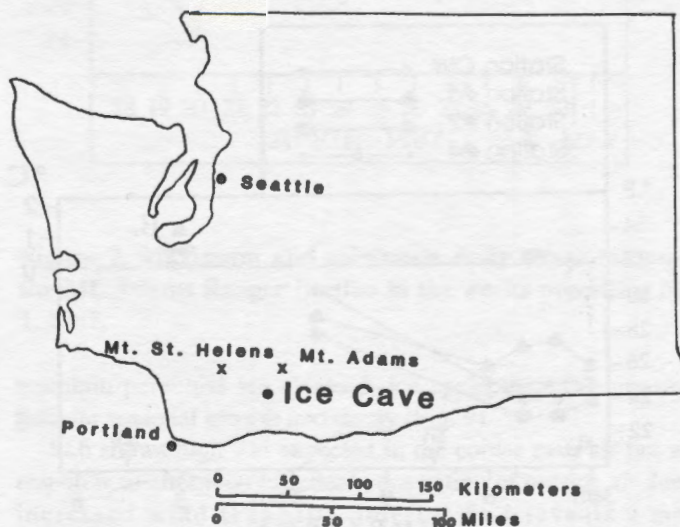


Figure 1. Map of Washington state showing location of study area (modified after Kiver and Steele, 1975).

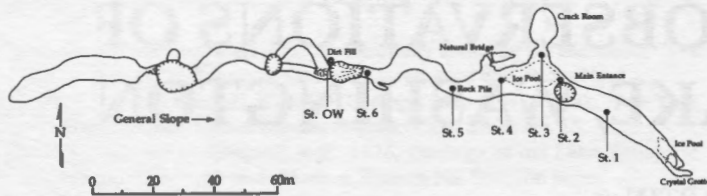


Figure 2. Plan view (A) and longitudinal cross-sectional profile (B) of Ice Cave (modified after Halliday, 1963).

temperature of the warmest month exceeds 22°C. Over 70% of the normal annual precipitation occurs during October-April with summers being warm and dry. The coniferous forest creates a microclimate moderating extremes in temperature, humidity, wind, and direct solar exposure.

FIELD METHODS

The study period includes daily visits on 2 January 1986, 31 January 1987, 1 May 1987, and 29 July 1987. Ideally, data should be collected for at least one week to compute daily averages but time constraints prevented that option. A November 1985 pilot study dictated the placement of sample stations. For all visits, data from only a few stations are shown to promote clarity. Ice Cave contains four segments with the longest segment, the subject of this study (Fig. 2), aligned east-west. The vertical scale is estimated.

Temperatures were measured 1 m above the active surface. Two people, well clothed to minimize the effect of body heat, took readings within the span of 15 minutes. Sling psychrometers measured dry bulb and wet bulb temperatures with ± 0.28°C (± 0.5°F) error. Mt. Adams Ranger Station, located 12.9 km (8 miles) east of Ice Cave, provided maximum/minimum daily air temperatures.

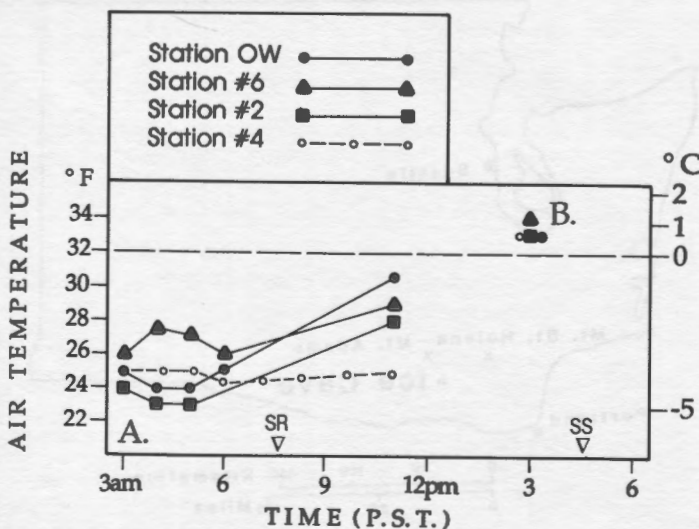


Figure 3. Temperatures at select stations at Ice Cave on January 2, 1986 (A) and January 31, 1987 (B).

Air flow was gauged by timing drifting smoke along a meter stick. The wind speeds appear "clustered" because distance was fixed and time varied (error ± 0.5 sec).

On May 1 ice features were cored at a slight down-dip angle to allow melt water to freely drain. The depth of penetration was measured. The same cored holes were remeasured three months later to compute melting rates.

RESULTS

Due to frigid conditions only limited temporal sampling was possible during winter (Fig. 3). Determining the RH for winter visits proved futile because the wet bulb constantly froze and gave misleading high (>100%) relative humidities.

On 2 January 1986, observations at St. OW (outside of west entrance), St.6, and St.2 indicate a modest diurnal signal. St.4 (interior) reveals a cold, stable temperature regime (Fig. 3 A). Mt. Adams Ranger Station data (Fig. 4 A) show colder antecedent weather and may explain why St.4 was cooler. Ice speleothem development was extensive (Fig. 5).

In contrast to the cold and dry Jan. 1986 visit, the one set of observations (Fig. 3 B) taken on 31 Jan. 1987 follows a period of mild and moist weather (Fig. 4B). Thus, wide variations in

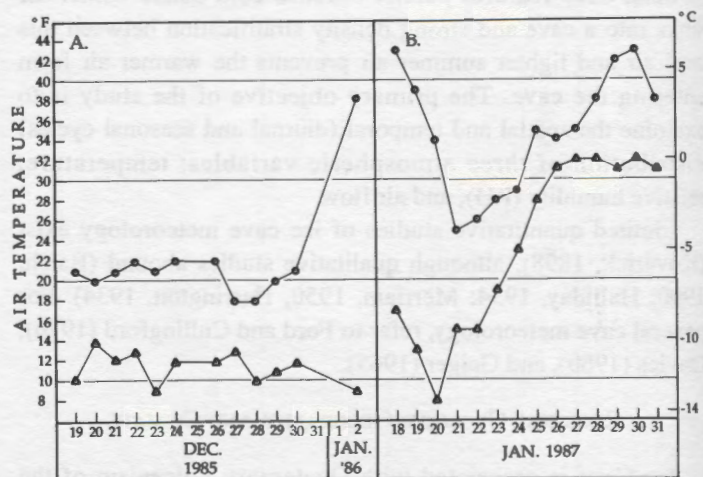


Figure 4. Maximum and minimum daily temperatures at the Mt. Adams Ranger Station in the weeks preceding January 2, 1986 (A) and January 31, 1987 (B).



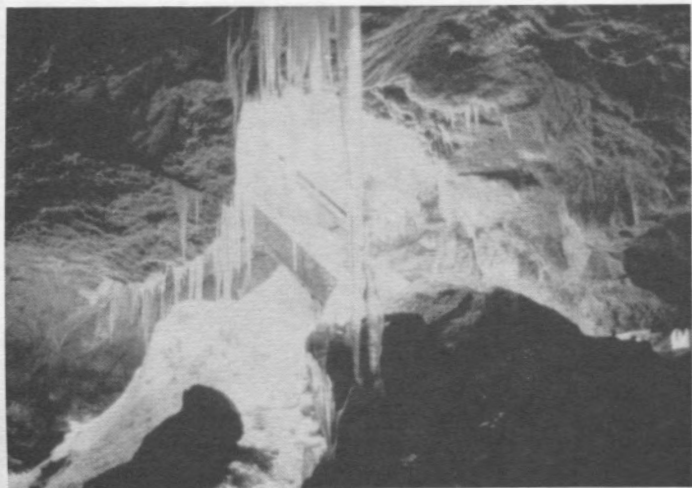


Figure 5. Ice speleothems near the east entrance of Ice Cave on January 2, 1986. Photo by Kyle Martin.

winter equilibrium temperatures at Ice Cave are possible under contrasting weather regimes.

On 1 May 1987, St.OW shows a moderate diurnal temperature mean and range despite the forest microclimate (Fig. 6). Anomalous warm weather preceded the sampling date (Fig. 7). Entrance stations (#6, #2) reflect cooler transition.

Interior cave locations (#5, #4, #1) show short-term 0.5-1°C (1-2°F) variations and reflect the dynamic nature of the middle section of the cave. Interior cave wind speeds of May were far more pronounced than the July visit (Fig. 8).

Ice speleothems were melting near St.1 in the isolated east end (coldest location). Ice speleothems existed near the main entrance but had noticeably melted. Isolated areas of Ice Cave

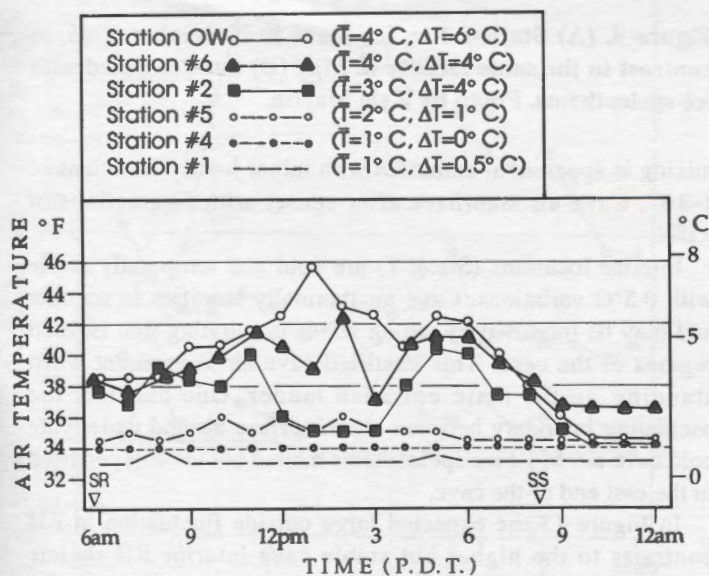


Figure 6. Temperatures at representative stations from 6 a.m. to 12 midnight (PDT) at Ice Cave on May 1, 1987.

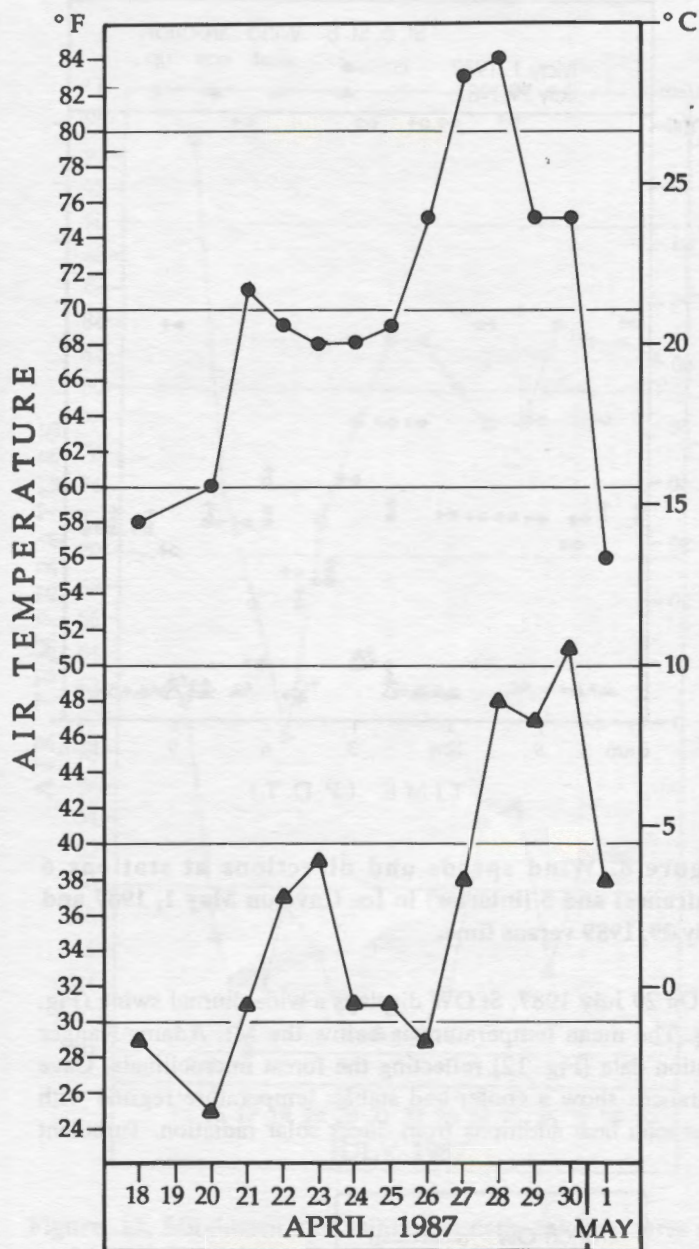


Figure 7. Maximum and minimum daily temperatures at the Mt. Adams Ranger Station in the weeks preceding May 1, 1987.

maintain perennial ice although ice speleothems demonstrate definite seasonal growth and decay (Fig. 9).

St.6 shows high RH expected in the cooler cave air but also responds to afternoon turbulent penetration of outside air due to increased wind (Fig. 10). Interior St.4 reveals a more temporally stable pattern. A decrease in RH in the evening hours may reflect a subtle flow of drier air between cave entrances as thermal resistance is minimized.

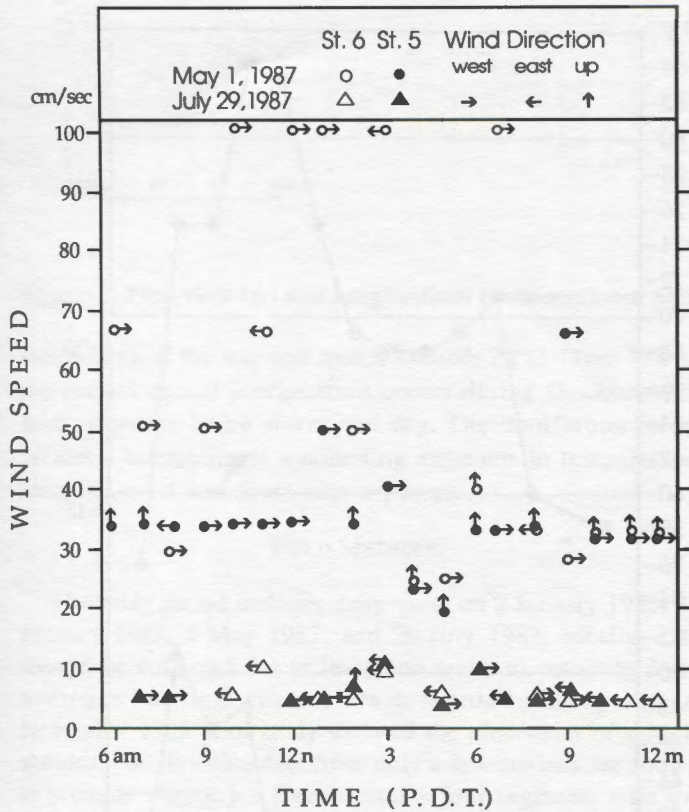


Figure 8. Wind speeds and directions at stations 6 (entrance) and 5 (interior) in Ice Cave on May 1, 1987 and July 29, 1989 versus time.

On 29 July 1987, St.OW displays a wide diurnal swing (Fig. 11). The mean temperature is below the Mt. Adams Ranger Station data (Fig. 12) reflecting the forest microclimate. Cave entrances show a cooler and stabler temperature regime with afternoon heat additions from direct solar radiation. Turbulent

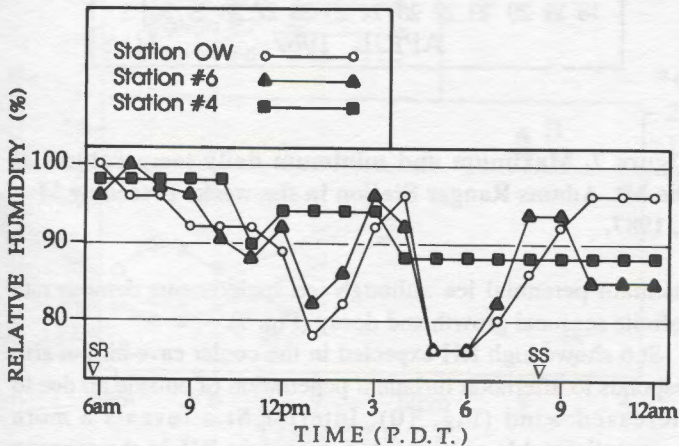


Figure 10. Relative humidity at representative stations from 6 a.m. to 12 midnight (PDT) at Ice Cave on May 1, 1987.



Figure 9. (A) Station 3 in Ice Cave in November 1985, in contrast to the same locality in May (B) but decorated with ice speleothems. Photo by Kyle Martin.

mixing is apparent at entrances with minor hourly variations of 1-3°C. Cave air stabilizes after sunset with fluctuations of <1°C.

Interior locations (Sts.4, 1) are cold and temporally stable with 0.5°C variations. Cave air thermally stratifies in summer and may be modified by strong winds penetrating into isolated regions of the cave. This stratified cave air is apparent when standing on the main entrance ladder. One can feel the oscillating boundary between warm surface air and underlying cold cave air. Most ice speleothems melted but ice still persisted in the east end of the cave.

In Figure 13 the expected large outside fluctuation in RH contrasts to the higher but stable cave interior RH regime (Sts.6, 4). Note the modest signal of drier air at St.4 during the morning hours.

Ice speleothem melt rates are given in Table 1. Two cored

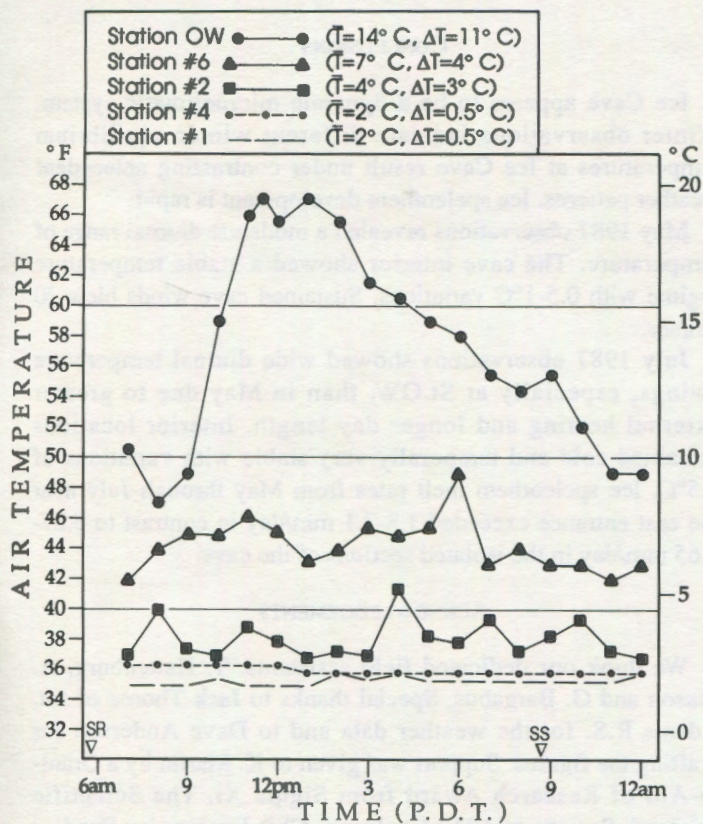
**Table 1. Rates of melting of ice speleothems.**

Location	Type of speleothem	Original depth (mm)	Final depth (mm)	Time period (days)	Rate of melting (mm/day)
St.1	Stalagmite	138	114	89	0.27
St. 2	Column	188	—	<89	>2.1
St. 3	Stalagmite	126	68	89	0.65
St. 4	Stalagmite	158	—	<89	>1.8

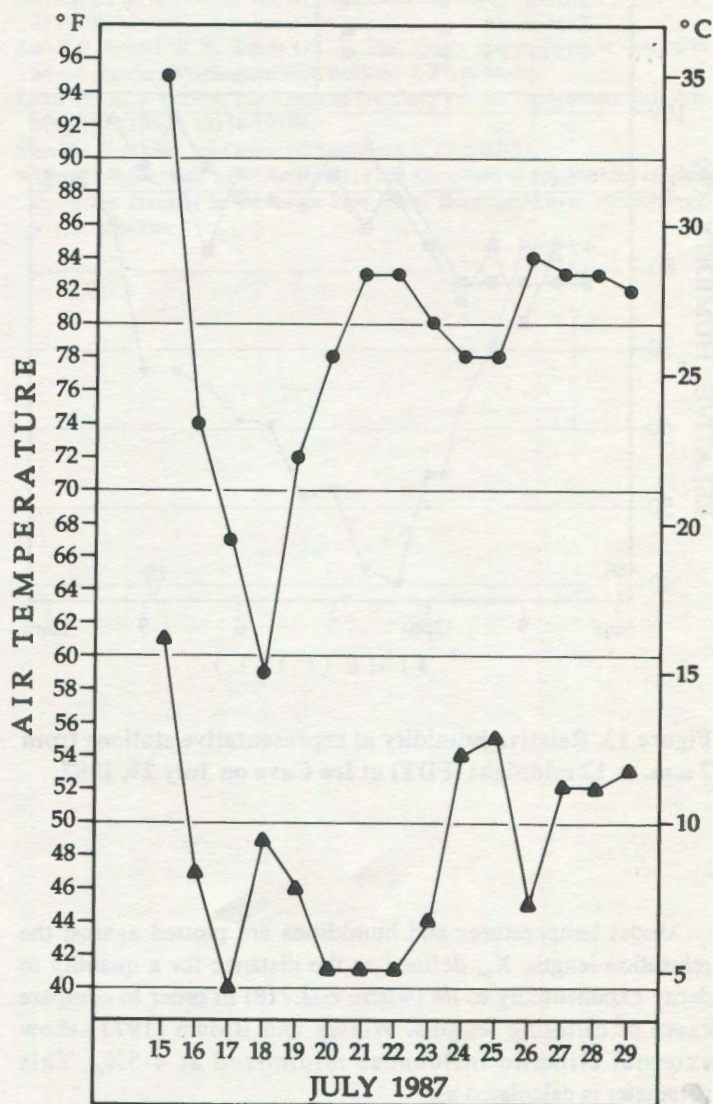
speleothems near the east entrance melted by 29 July 1987, so the computed rates of 1.8-2.1 mm/day are *minimum* melt rates near the east entrance, in contrast to slower rates of 0.27-0.65 mm/day in the isolated parts of the cave.

**DISCUSSION**

Theories abound (Balch, 1900; Halliday, 1954) for ice genesis in an "ice cave" (or glaciere) Harrington's (1934) study of the Shoshone Ice Cave demonstrates one condition conducive for ice speleothems is an intact lava-tube roof. The protected and shaded entrance to Shoshone Ice Cave and its bottle-neck shape would be conducive for trapping winter air, although Harrington (1934) did not fully elaborate on that idea. Halliday (1954) states one theory that great quantities of ice may form just after a spring thaw as seepage enters from the frozen surface.



**Figure 11. Temperatures at representative stations from 7 a.m. to 12 midnight (P.D.T.) at Ice Cave on July 29, 1987.**



**Figure 12. Maximum and minimum daily temperatures at the Mt. Adams Ranger Station in the weeks preceding July 29, 1987.**

Our winter observations expand upon Halliday's work and may indicate ice speleothem development can be rapid and early during winter. From the 15 November 1985 pilot study (no ice) to 2 January 1986, ice formed everywhere in the cave. Hence, freezing in a shallow cave occurs within days/weeks. This finding contrasts to a weeks/months time scale suggested by Balch (1900).

Can our observations be used to test a quantitative model (Wigley and Brown 1971) of cave meteorological processes? Wigley and Brown (1971) derive models based on the Equations of Continuity to define the distributions of temperature and humidity along the length of a cave.

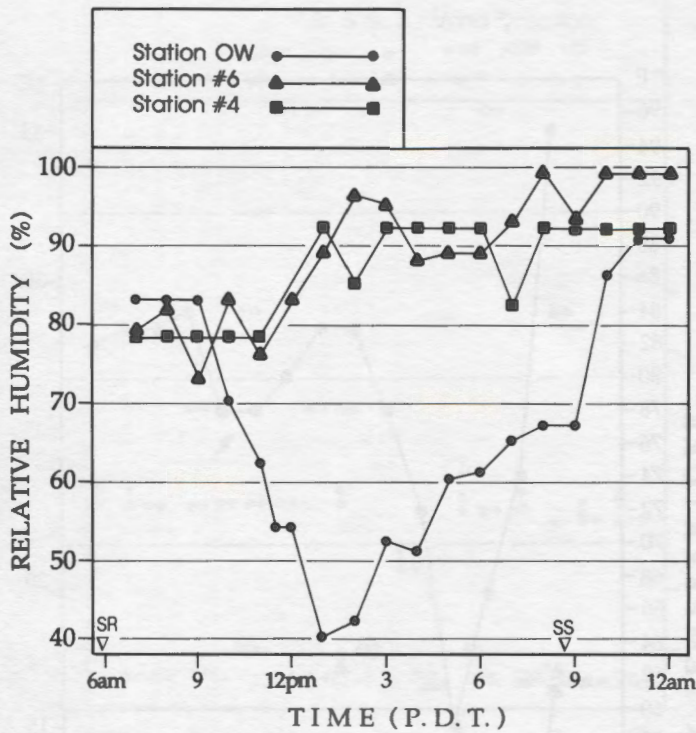


Figure 13. Relative humidity at representative stations from 7 a.m. to 12 midnight (PDT) at Ice Cave on July 29, 1987.

Model temperatures and humidities are plotted against the relaxation length,  $X_0$ , defined as the distance for a quantity to decay exponentially to  $1/e$  (where  $e \sim 2.718$ ) in order to compare caves of differing lengths. Wigley and Brown (1971) show external climatic influences minimized at  $4-5X_0$ . This parameter is calculated as:

$$X_0 = (36.44)(a^{1.2})(V^{0.2})$$

where  $a$  is radius of passage (cm) and  $V$  is air speed (cm/s).

This equation assumes a moist-walled cylinder of semi-infinite extent. Ice Cave approximates an ellipse in cross-section except at St.5 (circular).

The computed  $X_0$  for Ice Cave varies between 450-760 m, using an approximate radius of 290 cm and wind speeds at St.5 (Fig. 8), which greatly exceeds the length of this segment of Ice Cave. A non-rigorous comparison of our profiles (Fig. 14) to the Wigley-Brown model profiles (ignoring phase changes) reveal similarities during spring and summer only, where our data is relatively numerous.

Future work in ice cave meteorology needs the compilation of more temperature profiles (especially winter) at longer durations (i.e., week-long visits). More ice speleothems need to be cored and remeasured every 2-3 weeks.

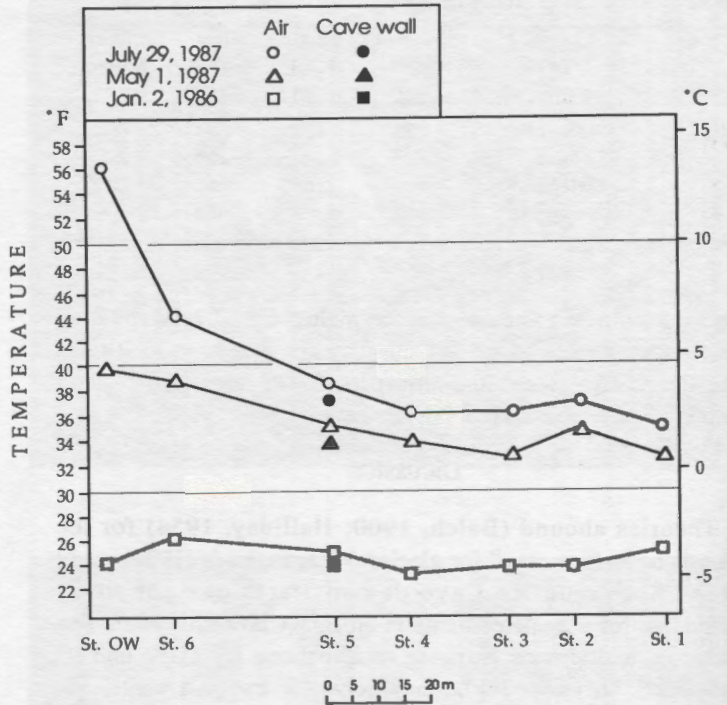


Figure 14. Time averaged air temperatures at all stations and rock-wall temperatures at Ice Cave versus distance into the cave.

### CONCLUSIONS

Ice Cave appears to be a dynamic microclimatic system. Winter observations indicate different winter equilibrium temperatures at Ice Cave result under contrasting antecedent weather patterns. Ice speleothem development is rapid.

May 1987 observations revealed a moderate diurnal range of temperature. The cave interior showed a stable temperature regime with  $0.5-1^{\circ}\text{C}$  variations. Sustained cave winds blew  $30\text{ cm/sec}$ .

July 1987 observations showed wide diurnal temperature swings, especially at St.OW, than in May due to greater external heating and longer day length. Interior locations remained cold and temporally very stable with variations of  $0.5^{\circ}\text{C}$ . Ice speleothem melt rates from May through July near the east entrance exceeded  $1.8-2.1\text{ mm/day}$  in contrast to  $0.27-0.65\text{ mm/day}$  in the isolated sections of the cave.

### ACKNOWLEDGEMENTS

We think our dedicated field assistants: T. Hattenburg, A. Mason and G. Bargabus. Special thanks to Jack Thorne of Mt. Adams R.S. for the weather data and to Dave Anderson for drafting the figures. Support was given to K. Martin by a Grant-in-Aid of Research Award from Sigma Xi, The Scientific Research Society, and The Explorer's Club Exploration Fund.



# USE OF A LOCALIZED FOOD SOURCE BY *PEROMYSCUS LEUCOPUS*, DETERMINED WITH AN HEXAGONAL GRID SYSTEM

DENNIS P. VIELE  
EUGENE H. STUDIER

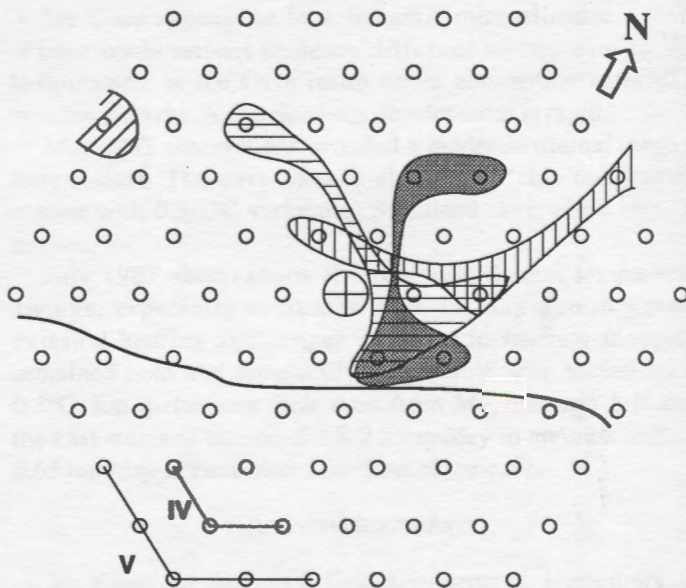
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*Nocturnal, surface foraging of cave dwelling crickets provide a consistent food source for nocturnal insectivorous mammals. Small mammals were live-trapped using an hexagonal grid centered around a cave entrance. Capture patterns for *Peromyscus leucopus* showed significant overlap at the cave entrance.*

Caves containing large populations of troglonexes, which regularly leave caves to forage outside, provide a predictable prey source which attracts predators. Such situations have long been known for cavernicolous bats as prey for raptors (Allen, 1939). Cave crickets, *Hadenoeus subterraneus*, and camel crickets, *Ceuthophilus stygius*, occur in large populations in many caves within Mammoth Cave National Park (MCNP). Crickets leave caves on warm, humid nights to feed opportunistically and omnivorously as scavengers (Barr and Kuehne, 1971), and provide potential prey for insectivorous mammals. Observations in all seasons show that *Hadenoeus* are rarely found more than seventy meters from cave entrances (Norton, 1978). Nocturnal, ground dwelling, insectivorous mammals should find foraging crickets easy prey. Hamilton (1941) examined 180 *Peromyscus leucopus* between November and April in New York and found their diet contained 72.8% arthropods. The life cycle of the parasitic nematode, *Pterygodermatites coloradensis*, in Kentucky includes *Ceuthophilus* as an intermediate host and *P. leucopus* as a definitive host (O'Brien and Etges, 1981); thus, camel crickets are eaten by *Peromyscus*. Cave cricket foraging patterns lead us to expect high concentrations of small insectivorous mammals near cave entrances.

Trapping of small mammals was conducted at MCNP, Kentucky, on the nights from 21-27 February and 28 April-2 May 1988. A hygrothermograph placed on the ground about five meters outside the Violet City entrance to Mammoth Cave provided data on temperature and relative humidity from 1800 hrs on 19 Feb. through 0800 hrs on 28 Feb. 1988. Inadequate standardization caused relative humidity measures to be inaccurate; however, relative humidity did reach 100% every night. Nighttime temperatures ranged from a low of -6.7° Celsius to a high of 3.3° Celsius. Lowest temperatures were recorded on the nights of 21, 25, and 26 Feb. Traps were set in

an hexagonal grid, consisting of ninety Sherman live traps, centered around the cave entrance (White Cave) on a generally South facing slope (Fig. 1). Each trap was set ten meters from any adjacent trap. A long axis of the grid ran through the cave entrance parallel to the South facing slope. Each trap, baited with peanut butter, was placed with its entrance directed away from the cave openings. Traps were set at dusk (checked at 10 pm in February) and then tripped at dawn for seven nights in February and four nights in April and May. Captured



**Fig. 1.** Home ranges of four male *Peromyscus leucopus* in February, using a cave (White Cave) as a localized food source. Home ranges may terminate at the edge of tested grid. Successive rings are denoted by Roman numerals and the cave entrance is denoted by a circled cross. An East/West trail runs through tested grid.

individuals were identified to species and capture sites were recorded. Sex and reproductive condition were noted. Specimens were toe clipped and released to monitor recaptures.

Statistical analysis was done using a computer generated program of Chi-square goodness of fit test.

Data were collected for a period of 630 trap nights in February and 360 trap nights in April and May. Absence of captures in the southern portion of the test grid can be explained by the presence of a large foraging mammal which tripped several traps in that region of the grid. Four scrotal male *Peromyscus leucopus* were captured a total of fifteen times in February. Surprisingly, the only small mammals captured were *P. leucopus* and few of them. Significant chi-square results ( $\chi^2 = 23.156$ ,  $dF = 4$ ,  $p < .001$ ,  $n = 15$ ) in February indicate that these captures are not randomly or evenly distributed over the tested grid. Examination of capture sites in February show that home ranges of *Peromyscus* include the cave entrance area (Fig. 1).

Captures in April and May again show extensive home range overlap with six of the seven captures located in ring one and the seventh capture located in ring five ( $\chi^2 = 70.571$ ,  $dF = 4$ ,  $p < .001$ ,  $n = 7$ ). Overlapping of home ranges are extensive at the cave entrance which indicates that *Peromyscus* use exiting

crickets as a consistent source of food.

Special thanks go to Elizabeth J. Mason for her many trips to White cave. We thank the National Park Service for allowing us to live-trap in MCNP and the Cave Research Foundation for use of its facilities in MCNP. This research was done with support of MACA-N-103 and MACA-N-128. We thank Drs. Don Wilson, Tom Poulson and Kathleen Lavoie for their comments on the manuscript and Paul Adams for generating the figure.

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# Book Reviews

*Karst Geomorphology*. Joseph N. Jennings. Oxford: Basil Blackwell, Ltd. 1985. x & 293 p. ISBN 0-631-14031.

*Karst Geomorphology* is the second edition of Joseph Jennings' earlier work, *Karst*, published in 1971 by the Australian National University Press and M.I.T. Press. The first edition went through two printings and was one of only a few English-language textbooks on karst until very recently. It had wide appeal among karst geomorphologists, cavers, and the geographic community. Understandably, after more than a decade of active work and publishing on karst by researchers worldwide, Joseph Jennings began work on a revised edition. Soon after completing the manuscript, Jennings died of a heart attack while skiing at age 68. The book was published posthumously.

Joseph Jennings was originally a Yorkshire, England speleologist and moved to Australia in 1952 where he joined the faculty of the Australian National University at Canberra. He produced over 200 papers and monographs during his career and researched karst in Australia, New Zealand, Europe, North America, the Caribbean, China, New Guinea, Malaysia, and Antarctica. Among many awards, he was the recipient of the Royal Geographic Society Victoria Medal and Honorary Life Membership in the National Speleological Society.

As might be expected, *Karst Geomorphology* retains most of the organizational format of its predecessor. There are few changes; most notably, the twelfth (last) chapter in the first edition dealing largely with practical application in karst problems has been omitted. Jennings mentions in the new preface that, owing to the recent proliferation of environmental karst studies, this subfield merits a book on its own. Given that Jennings' book is intended as an academic treatment of karst, I would agree. A second change is the addition of Chapter 11 on karst processes associated with coastal regions and islands.

The first chapter is an introduction to the nature of karst and pseudokarst. It is concise and to the point, giving definitions of the various general categories of karst. The following chapter is a brief review of rocks that typically become karsted, with emphasis on the physical and chemical character of limestone, dolostone, and evaporitic units. Lithologic variables that contribute to or control karstification are identified. Chapter 3 discusses the chemical and physical processes of karstification. Even though the discussion on geochemistry of dissolution (and precipitation) of carbonate materials is succinct and well written, the brevity of the treatment (7 pages) provides little substance to anyone wanting to become well versed in carbonate geochemistry. Again, this may be acceptable, as suitable treatises on that subject are available.

Chapter 4 is an overview of the hydrology of karstic terrains. Jennings does a commendable job in discussing *both* surficial and subsurficial flow systems in karst. Many previous texts on

karst have not adequately addressed both regimes nor the interplay of surface drainage and groundwater. Many readers will find that this topic is not covered in detail as it is in recent texts by William B. White and Alfred Bögli. However, Jennings' chapter is well referenced and current and leads the reader to most of the pertinent works in the literature.

As in the first edition, Jennings gives a very neat and orderly descriptive catalog of small-scale surficial landforms (karren) in Chapter 5. The treatment is comparable to that in Marjorie Sweeting's *Karst Landforms* (1972). The chapter also includes a discussion on covered karst and on dissolution rates on carbonate rock surfaces. Large-scale karstic surficial landforms are the subject of Chapter 6. This lengthy chapter (47 pages) is an excellent introduction to the variety of geomorphic features found in karstic terrane, including various types of dolines (sinkholes), gorges, uvalas, poljes, cockpits, tower karst, karst plains, to name a few. I recommend this chapter to anyone who needs a concise introduction to the morphology and origin of these features.

The nature and development of caves is the topic of Chapter 7. This chapter is relatively current with respect to the literature on the subject. However, cave enthusiasts will find the treatment too meager (34 pages) for their liking. Much more could have been included; but as Jennings mentions in the preface, the book is intended not solely for cavers, but for those interested broadly in karst geomorphology.

Chapter 8 covers cave deposits, including speleothems, cave ice, clastic sediments, and biogenic materials. There is also a discussion on isotopic dating and paleoenvironmental interpretation of cave deposits. Speleothem mineralogy and isotopic dating are merely reviewed in this chapter, and the reader should look elsewhere in the literature for a fuller introduction to these topics (e.g. Carol Hill's *Cave Minerals*, T. D. Ford and C. H. D. Cullingford's *The Science of Speleology*).

The following chapter on the influence of geologic structure on karst is somewhat short (14 pages) given the research expended on this topic. However, Jennings gives a good summary and leads the reader to the appropriate sources. The chapter would certainly have benefited from inclusion of additional examples showing the diversity of structural control on karst and cave origin.

One of the shining chapters in the book is Chapter 10 on the influence of climate on karst processes. This has been a topic of considerable debate for some time, but Jennings gives a fair treatment of the ideas proposed by researchers over the years. The chapter includes discussion on rates of denudation and on the role of arid, cold, and "botanic hothouse" extreme climates on karst processes.

The new material on coastal karstic phenomena of Chapter



11 includes karstification along cliffs, shore platforms, coastal dune limestones, emerged biogenic reefs and marine terraces, submerged coasts, and modern reefs. The role of sea-level oscillations is addressed. This chapter is important because it is not covered in such depth in most other current karst textbooks.

The final chapter is an historical retrospective on the development of geomorphic thought regarding karstic landforms. Jennings reviews the concept of karst "cycles" and the roles of climatic change, tectonics, and baselevel changes in the development of karst and caves. This chapter has been substantially modified from Chapter 11 in the first edition.

*Karst Geomorphology* is longer by 41 pages than the first edition and most chapters have been expanded somewhat. The list of cited references is noticeably longer, but more importantly, the percentage of British and North American karst papers cited is up dramatically, reflecting the increased activity of research in these regions. This makes the text more useful to American readers. A handy addition is a separate author index at the end of the book, facilitating finding cited references in the text.

The line drawings throughout the book are excellent—clear and concise. Most have been retained from the first edition. The photographs are generally clear, however, they are printed with a little too much contrast.

One of the best aspects of the book is Jennings' writing style. Not only are his descriptions and explanations clear, smooth, and easy to follow, but his writing is witty and humorous in places. These attributes sets the text apart from some of the others on sheer reading enjoyability. Jennings defines karst terms as he uses them, so that a reader without prior training in the field does not have to resort to a glossary. There is no glossary in the book, although one would have been convenient for looking up definitions at a later time.

Overall, I consider this to be one of the leading introductory karst books on the market today. Its availability as an inexpensive paperback makes it ideal for an introductory karst course at the undergraduate or graduate level or as one of several texts in a course in general geomorphology. It is uncluttered with technical details and terminology and it is easy to read. The citations are more than adequate for getting into the basic karst literature in monographs or journals. For the experienced karst researcher and for cavers, this text should be purchased as a complementary volume to the other leading English-language texts of recent years, most notably *Karst Landforms* by M.M. Sweeting (1971), *The Science of Speleology* by T.D. Ford and C.H.D. Cullingford (1976), *Morphogenetics of Karst Regions* by L. Jakucs (1977), *Karst Hydrology and Physical Speleology* by Alfred Bögli (1980), *Limestone Geomorphology* by S.T. Trudgill (1985), and *Geomorphology and Hydrology of Karst Terrains* by W.B. White (1988). Although the regional emphasis of Jennings' book is heavy on Australia, New Zealand, and Europe, when used with the above textbooks, it does well in

rounding out one's global perspective on karst.

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*The Management of Soluble Rock Landscapes: An Australian Perspective.* Kevin Kiernan, 1988. Sydney: The Speleological Research Council Ltd., 61 p.

Available from the Speleological Research Council, P.O. Box 183, Broadway, NSW, 2007, Australia. \$12.00 U.S. should cover the cost of the book and postage.

This book is one of the more significant contributions to cave conservation and karst management published in recent years. Its importance to the field is that it is a compilation of a tremendous amount of useful information into one volume in a readable form.

Kevin Kiernan is not well known in this country. In Australia, however, he is a leading conservationist with interests beyond caves and karst. He played an important part in saving the Franklin-Gordon Rivers wilderness in Tasmania. He discovered the archaeologically significant Kutikina (Fraser) Cave, which was important in saving the area. He is now sharing his vast management knowledge with us and we can learn much from him.

The text has been prepared in two parts consisting of seventeen chapters. Each chapter has a general global perspective followed by an Australian example. The first section is entitled, "Some Geomorphic Hazards in Soluble Rock Landscapes." It contains six chapters such as, "Sedimentation and Flooding," "Ground Surface Stability," and others. An overview is given of the hazards one might expect on karst. Specific examples are presented from around the world, such as the mine collapses in South Africa more than two decades ago. Considerable detail is given to the Australian karst scene. In a chapter entitled, unassumingly, "Other Engineering Difficulties in Karst Terrain," Kiernan provides us with anecdotes on some unusual hazards experienced on karst. He tells us of leaking dams, road design problems, and a situation where piles had to be driven 240 meters for stability! Also included is a review of geophysical methods that can be used to define the limits of a karst area.

Part two gives a vast body of information on "The Degradation of Karst Heritage Values" by human activity. Here Kiernan has separated the karst environment into its component parts (i.e., hydrology, biology, climate, geology, archaeology, etc.). He then discusses the multitude of impacts that can be visited on the terrain; mining and pollution are only two of many described.

Perhaps the greatest value of this book is as a reference source for cave and karst management. This aspect is highlighted by a fifteen page bibliography with well over three hundred entries. This makes it the most extensive karst management bib-

liography published to date. It is worth the cost for the bibliography alone.

There are no photographs or other graphics, with the exception of the cover photo. Some graphics, especially maps, would have been a helpful addition for the reader unfamiliar with the details of the Australian karst. This unfortunate omission only slightly detracts from the book's usefulness. However, the lack of graphics has kept the price low enough to warrant the inclusion of this text into the library of even the most parsimonious conservationist.

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*Paleokarst*. Noel P. James and Philip W. Choquette (editors). New York: Springer-Verlag. 1987. xi and 416 p. \$64.00 hardbound. ISBN 0-387-96563-7.

*Paleokarst* is a collection of papers largely derived from a symposium entitled "Paleokarst Systems and Unconformities—Characteristics and Significance," which was organized and held at the 1985 midyear meeting of the Society of Economic Paleontologists and Mineralogists in Golden, Colorado. Several additional papers prepared shortly after that meeting have been added to the volume.

Paleokarst includes all types of karst preserved in the geologic record as relict or fossil forms. Understanding ancient karst requires a working knowledge of modern karst processes and how karst features become fossilized. Therefore this volume is organized in two parts. Part I addresses the general features and processes of karst and Part II consists of geologic studies of paleokarst from a variety of locations and geologic settings.

The first seven papers (Part I) discuss the development, preservation, modification, and recognition of karst terranes. The lead-off paper by Derek Ford, entitled "Characteristics of dissolutional cave systems in carbonate rocks," is a synthesis and summary of modern views on cave development. Of all the papers in the book, this may be the most interesting to speleologists, although most researchers on cave origin are probably familiar with the published work that is summarized in this paper. Nevertheless, this 33-page contribution is a valuable introduction to contemporary ideas on speleogenesis. Readers will find the lengthy list of bibliographical citations to be highly useful.

Geochemists working with karst waters will find the second chapter by Kyger C Lohmann of particular interest. It outlines the chemistry of circulating karst waters and discusses the controls of the saturation state on dissolution and precipitation of carbonates.

The third paper by Luis A. Gonzalez and Kyger C Lohmann on the mineralogy and geochemistry of carbonate speleothems in Carlsbad Caverns, New Mexico is also of interest to the

speleological community. The authors performed numerous petrographic and geochemical analyses on a variety of formations from the cave. The paper is well illustrated with macrophotographic and electron photomicroscopic images and with several compositional graphs. Geochemical factors of speleothem origin are discussed in detail.

The remaining four papers of Part I concern specific aspects of paleokarst: breccia-hosted lead-zinc deposits in carbonate rocks, fire-blackened limestone pebbles at subaerial unconformities, Holocene overprints of Pleistocene paleokarst in the Bahamas, and neptunian (marine) dikes and terrestrial fissure infills. The latter paper by Peter L. Smart, R. J. Palmer, F. Whitaker, and V. Paul Wright presents work on fractures and their infills in the blue-hole cave systems in the Bahama region.

The eleven papers of Part II of the book discuss documented examples of paleokarst ranging in age from Proterozoic to Cretaceous and geographically distributed among the United States, Canada, Mexico, South Wales (Great Britain), and Spain. The U.S. examples include the Appalachians from Pennsylvania to Tennessee, western Ohio, Wyoming-Montana, central Colorado, New Mexico, and west Texas.

Speleologists will find much of interest in the case studies of Part II. The papers of Mussman and others on the Knox unconformity of the Appalachians, William J. Sando on the Madison Limestone of the Wyoming-Montana region, and Charles J. Minero on the El Abra Formation in eastern Mexico concern karst regions in which caves have been explored and researched for some time. Canadian localities such as the northern Northwest Territories (paper by Charles Kerans and J. Alan Donaldson) and southeastern Quebec (paper by Andre Desrochers and Noel P. James) are not known for caves, yet the ancient karst features of these two sites are surprisingly similar to those in currently well known karst terranes.

American karst geomorphologists will be interested in the ancient karst of the Lockport Dolomite in western Ohio (paper by Charles F. Kahle), the Leadville Formation of central Colorado (Richard H. DeVoto), the Mississippian limestones of New Mexico (William J. Meyers), and the San Andres Dolomite in west Texas (Dexter H. Craig).

In total, *Paleokarst* is the first technical book on ancient karst. As such, it fills a void in the karst literature. The breadth of topics covered in the eighteen papers, the detail presented in each paper, and the overall clarity of writing make this volume highly desirable to researchers of karst. The quality of production of the book is exceptionally high with a pleasing layout and clear line drawings and photographs. Not only will this book appeal to the professional researcher of karst, but the serious speleologist and caver will find sufficient material throughout the book that is directly applicable to the geology of caves. No collection of technical books on caves and karst should be without a copy of the book.

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## GUIDE TO AUTHORS

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

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

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

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

Authors should submit two copies of their manuscript (in-

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

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

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

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

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