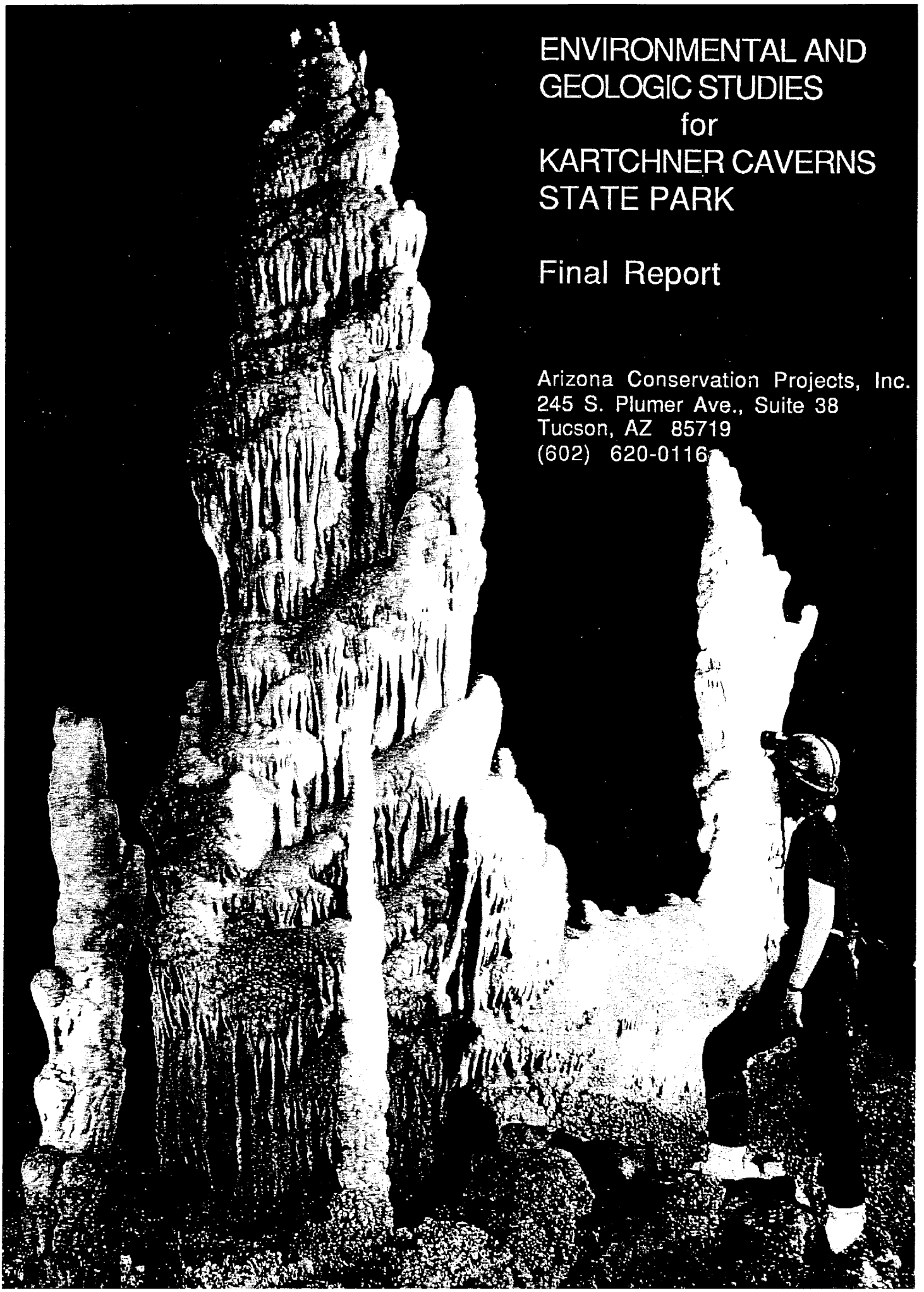

ENVIRONMENTAL AND GEOLOGIC STUDIES for KARTCHNER CAVERNS STATE PARK

Final Report

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EXECUTIVE SUMMARY

INTRODUCTION

Kartchner Caverns is a beautiful limestone cave in pristine condition, considered by experts to be the premier cavern in Arizona. It will be protected and displayed to the public as the 25th Arizona State Park. The cavern was discovered in 1974 by two Tucsonans, Gary Tenen and Randy Tufts. They kept the cave secret for fourteen years to protect it from vandalism and to maintain it in its original pristine condition. It is located approximately 8 miles southwest of the town of Benson on the west side of State Highway 90. The park site is 550 acres in size and is situated at an average elevation of 4700 feet .

The cavern is over two miles long with spacious rooms, one of which is as long as a football field. It is a wet, 'live' cave into which water still percolates from the surface and whose calcium carbonate features are still growing. It contains an unusually wide variety of multicolored cave formations – stalactites, stalagmites, flowstone, shields, helictites and soda straws - including the longest known soda straw in the world. It is also a summer home to a colony of approximately 1000 bats.

The contrast between the moist interior of the cave (over 99% relative humidity) and the dry desert above makes Kartchner Caverns particularly vulnerable to damaging changes brought about by developing the cave for public viewing. Changes in airflow, temperature, or humidity caused by improper development could quickly dry out the cave, halt speleothem growth, and diminish the cave's beauty.

To prepare for the public opening of Kartchner Caverns in an environmentally sensitive manner, Arizona State Parks has contracted for a two year pre-development study of the cave environment and geology with Arizona Conservation Projects (ACPI). This report presents the results of that 24 month study. The studies focus on four main aspects of the cave environment: (1) cave microclimate and meteorology, (2) hydrology, (3) geology, and (4) biology. Additionally a recommendation is made for the location of a new entrance into the cave.

CAVE MICROCLIMATE AND METEOROLOGY

Maintaining the moist conditions within the cave has been identified as the most important consideration in developing the cave. Drying of the cave can result in permanent damage to many of the features which make the cave so attractive. There is a marked contrast between the arid surface conditions and the moist interior of Kartchner Caverns. On the surface, the annual temperature fluctuates by 85°F, while deep inside the cave the fluctuation is less than 1°F. The difference between evaporation on the surface and in the cave is even more striking. Outside, the annual evaporation can exceed 65 inches; inside the cave it is less than 0.08 inches. The rate of evaporation outside is 800 times greater than inside the cave! If outside air were allowed to freely enter the cave, it would deplete the entire annual supply of moisture to the cave in only a few days.

The cave receives moisture from percolating rain water and infiltration from surface washes. Significant infiltration from washes is sporadic and occurs only during years with above average precipitation. It is, however, the largest source of water for the cave when it does occur. The influx of water from the washes is very important in maintaining the microclimate of the cave. Not only does infiltrating water bring moisture into the cave, but the temperature of the water has a controlling influence on the microclimate of the cave. Precipitation and the subsequent percolation of water

into the cave is highly variable from year to year. Percolation is still the most reliable source of moisture for the cave: of the 16.5 inches of rain which falls on the hill above the cave each year, only 0.3" (2%) reaches the cave. Water which does reach the cave leaves by a system of natural drains and by direct percolation through the floor of the cave. Evaporation from cavern surfaces and the subsequent removal of the moist air from the cave by air exchange with surface air is presently responsible for only a small fraction of the moisture loss. However, development of the cave will unavoidably increase the air circulation within the cave, resulting in increased evaporation. Surface climate measurements indicate that, because of the desert environment, the exchange of outside air with cave air always has a drying effect on the cave.

An analysis of the moisture balance of the cave indicates that air exchange is the only parameter which is likely to be altered in developing the cave. Increased air exchange due to development will unavoidably remove additional moisture from the cave. Minimizing the potential for increased air exchange should be a primary consideration of the cave development in order to maintain the moist microclimate of the cave.

Environmental Monitoring Program

The environmental monitoring system was designed to provide data necessary for determining the nature and magnitude of microclimate changes which will likely result from the development of the cave and the construction of one or more man-made entrances. The microclimate studies at Kartchner Caverns have measured the following parameters:

- Air Temperature
- Soil Temperature
- Relative Humidity
- Evaporation Rates
- Air Trace Gasses
- Airflow

ACPI has installed a total of 22 environmental monitoring stations distributed throughout the cave. These stations have been placed so that the existing and future impact of an entrance or proposed entrance on the microclimate of the cave could be assessed. In addition to the manual measurements taken at each station on a monthly basis, two computer systems record temperatures on an hourly basis.

Temperature

The temperatures of large caves are generally considered to be at the same temperature as the mean surface temperature. At Kartchner Caverns State Park, the mean surface temperature is 62.5°F. Inside the cave, temperatures vary from 69.7°F to 65.5°F, with a mean temperature of 67.7°F. The discrepancy between the temperatures inside the cave and the surface is primarily due to regional geothermal heat flow which warms the cave and to flooding of the cave during the winter which cools portions of the Back Section.

Evaporation

The moisture content of the air within the cave can become a critical management issue. At the present time, evaporation from cave surfaces is the major source of moisture in the air. The rate at which water evaporates within the cave is very low. The rate of evaporation within the cave is largely determined by the relative humidity of

the air. It is important to understand that evaporation is proportional to the difference in relative humidity from 100%. If the relative humidity changes from 99.5% to 99.0%, the evaporation rate will double! This means that very small changes in the relative humidity will have major impacts on the moist conditions in the cave. The relative humidity inside the cave presently ranges from 96.32% to 100.00% and averages 99.42%. Calculations indicate that the cave would dry out if the relative humidity is allowed to fall below 98.5%.

Under present conditions, evaporation plays a minor role in removing moisture from the cave. This is because the present entrance is quite small and there is relatively little air exchange with the surface. Development of the cave for public viewing can potentially greatly increase the amount of evaporation. Poorly located or constructed entrances can induce a strong airflow pattern which in turn will greatly increase the evaporation. This has been observed in many other developed caves but is aggravated by our arid climate. These problems can be lessened by care in locating or enlarging entrances and connecting tunnels. Steps can also be taken to control the airflow entering the cave. Entryway doors can be constructed to act as airlocks and prevent the entry of outside air. Developing the cave so as to prevent increased airflow and evaporation is the most easily controllable part of the moisture balance.

Air Exchange

Air exchange between the cave and the surface has been identified as one of the major routes by which moisture is lost from the cave. For this reason, controlling the rate of air exchange is one of the most important tasks in developing the cave. Airflow is also strongly related to other processes within the cave such as the concentration of carbon dioxide and radon gas. Unfortunately, the concentrations of these trace gases is also an important management issue. Artificially increasing rates of air exchange would have the benefit of lowering the concentrations of these gases but would also result in increased evaporation, drying of the cave and potentially irreparably damaging the beauty of the cave. A knowledge of how these three parameters - evaporation, carbon dioxide and radon - are related to airflow is necessary in order to predict the likely effect of development. The maximum concentrations of both gases is determined by the air exchange rate. Estimates of the rate at which air is exchanged have been made by several different approaches. These range from direct measurement of airflow to estimates based on concentrations of trace gases, and models of air exchange. No one method has given a clear-cut picture but together they give a consistent overall estimate of the air exchange rate.

The air exchange rate can be determined by measurement of the properties of the air. The amount of alpha radiation particles, relative humidity and CO_2 in the air are all indications of how long the air has been in the cave and how frequently it is exchanged with outside air.During all periods of measurement, the direction of airflow was overwhelmingly into the cave (97%). The simplest explanation for this would be the existence of another opening(s) at an elevation above the natural entrance. No evidence of such an opening has been found within the cave. It is thought that the upper opening(s) is either very small or partially blocked by rubble. It appears that the size of this upper opening is what controls the volume of air entering the natural entrance.

The quantity of carbon dioxide (CO_2) gas contained in the cave air has been used to approximate the rate of air exchange between the cave and the surface.

The outside air contains approximately 300 parts per million (ppm) CO_2. Carbon dioxide concentrations have been measured in the cave at two locations on a monthly basis and range from 850 to 5400 ppm. CO_2 concentrations vary seasonally from a minimum in late winter to a maximum in late summer. A relatively simple model of CO_2 concentrations in the cave can be constructed from a knowledge of the cave volume, the rate at which CO_2 enters the cave and the ventilation rate. This model predicts that CO_2 concentrations are likely to double or triple once the cave is open to the public. The increase will be due to exhaled CO_2 from visitors. Levels should remain well below dangerous concentrations but should be monitored to identify small localized areas of high concentrations. Higher levels of CO_2 may have a greater impact on cave features. The higher CO_2 levels may shift the chemical equilibrium of water entering the cave so that it will dissolve cave formations. Continued drip water collection and photographic monitoring should be used to document any changes.

The annual pattern of air exchange can be qualitatively understood by computing the density of the surface air and the cave air during winter and summer. Assuming that a higher opening exists, the cave will then act as a chimney. During the winter, cold surface air is denser than air in the cave and flows into the cave. During the summer, surface air is warmer and less dense and air flows out the natural entrance. This simple relationship is complicated by two other effects. First, the cave is several degrees warmer than the average surface temperature. As a result, winter air exchange is twice as great as summer and summer air flow out of the cave lasts for only 4 months. This asymmetric reversal of airflow creates the second effect. Because more winter air, which is cooler, enters the cave, the entrance passages become quite chilled. This in turn creates a pocket of cool dense air which partially blocks the summer airflow out of the natural entrance.

Alpha Radiation

Alpha radiation levels in all caves are elevated and Kartchner Caverns is no exception. While the level is higher in Kartchner Caverns than in most developed caves , it must be emphasized that it is not a hazard for the public visiting the cave. The Environmental Protection Agency (EPA) has determined that there is little danger to the public from alpha radiation in National Park Service caves due to the short time visitors spend underground. However, the levels are high enough to be of concern for employees who may work in the cave for many years. Alpha radiation in caves is primarily due to radon gas.

Recommended guidelines for permissible exposure levels for the general public are $^1/_{30}$ of the permissible occupational exposure. Applying the above guidelines to Kartchner would allow the general public to spend up to 25 hours within the cave based on a permissible standard of 3.5 working level months (WLM) for employees. A tour of the cave is anticipated to take less than 2 hours. It would appear that the visitors to the cave would experience less than one-tenth of the guideline for public exposure.

The National Park Service is now in the process of adopting regulations for the protection of employees working in caves. The proposed standard would limit employee exposure to 3.5 Working Level Months per year. If adopted at Kartchner Caverns, this standard would allow employees to spend approximately 750 hours per year underground.

The radon levels within Kartchner Caverns average approximately 100 pCi/l and vary by a factor of two on a seasonal basis. Radon daughters resulting from the

radioactive decay of radon average approximately 0.8 Working Level. These concentrations are high enough to be of concern to those who will work within the cave for many years. Prolonged exposure to radon daughters for many years has been linked to increased rates of lung cancer. Radiation exposure to human lung tissue results from inhalation of radioactive radon-decay products that adhere to lung tissue or to airborne particles that become trapped in the lungs. Due to inhalation of these products, the lungs of most people receive more radiation than any other body organ.

Most estimates of lung-cancer risk due to low-level radon daughter exposure use a linear extrapolation from high exposure rates experienced by some groups of underground miners. In a linear extrapolation, exposure and risk are proportionally related; for example, half the exposure would constitute half the risk. There is some question about whether the exposure rates determined for miners are applicable to the much lower exposures encountered in caves. Mines typically contain large amounts of dust and exhaust fumes from equipment and miners are not a representative sample of the general population. Despite these differences, most risk assessments continue to be based on studies of uranium miners.

The Environmental Protection Agency (EPA) has used the risk coefficients determined for uranium miners to project lung cancer rates to lower exposure levels. Other studies have generally recommended somewhat lower risk estimates.

If we use the NPS proposed guidelines which allow a lifetime maximum of 105 WLM as a reasonable maximum exposure estimate, we can calculate the increased lifetime risk of contracting lung cancer from radon daughter exposure. The increase is between 2.5% and 9.9% based on EPA risk coefficients and 2.2% based on the average of 7 other studies. The low end of the estimate (2.2%) is slightly greater than the lifetime risk of dying in an auto accident or working in a hazardous industry such as mining. The high end of the estimate (9.9%) is comparable to the risk associated with cigarette smoking. These comparisons indicate that exposure to the levels of radon daughters expected to be found in the cave are a small but significant risk for those working in the cave for many years. Exposure and risk to the general public is very much smaller because they will be in the cave for a very short period of time. Based on a one and a half hour tour length, the risk to the public is approximately the same as that associated with a 60 mile automobile trip.

It is recommended that the proposed NPS regulations regarding allowable exposure be adopted. Alpha radiation monitoring should continue for two years after the cave has been developed. Arizona State Parks should maintain records of employee exposure.

BIOLOGY OF KARTCHNER CAVERNS

Bats

Among its many other values, Kartchner Caverns is important because it is a natural refuge for a large colony of bats. From May to mid-September of each year, the cave is home to 1000 to 2000 Myotis velifer, a species of insectivorous bat. These bats, primarily pregnant females , faithfully return each year to Kartchner Caverns to rear their young. These bats provide an important link between the ecosystem of the cave and the surface. The bat guano introduces a rich food source for Kartchner's cave limited organisms. During the summer, bats are usually found roosting together in a small cluster on the ceiling of the Big Room. Accumulations of bat guano in other

parts of the Big Room indicate that they may occasionally use different parts of the room. There is no indication that bats presently use any other part of the cave.

The principal species of bat found within the cave is the "Cave Bat" (Myotis velifer). Two other species of bat have been observed in the entrance passages. Two additional species of bat are known to have used the cave in the past and have been identified from bones found in the cave. Ancient guano piles in the Throne Room indicate that bats used this area of the cave 40,000 to 50,000 years ago. There is no indication that bats have used the Throne Room in more recent times.

No endangered species of bat has been found to be using the interior of the cave. On the surface, an endangered species of nectar feeding bat was netted at the cattle tank. These bats may use some of the smaller caves on the park during the summer.

The importance of the bats to Kartchner Caverns State Park is three-fold. For Arizona State Parks, they are an exciting educational experience for the park visitor. The public has become increasingly aware of the many benefits provided by this often misunderstood animal. Cave parks such as Carlsbad Caverns fill an amphitheater on summer evenings for a natural history talk about bats during the bats' nightly emergence. The bats also act as a natural insecticide for the park property. A conservative estimate indicates that the bats roosting in Kartchner devour approximately one-half ton of insects every summer. The third benefit of a healthy bat roost within Kartchner Caverns is its introduction of excrement (guano) below the roost. This bat guano is the primary source of food for the permanent organisms in the cave and supports the ecosystem of the cave. These invertebrates are sensitive indicators of the conditions in the cave. The uniquely cave-adapted organisms utilize the bat guano in different ways but all depend on it for their survival. A loss of the bat roost would cause a collapse in the entire cave ecosystem and the destruction of a healthy cave environment.

Bats have particularly good hearing and can sense intrusion into their roost just from the sound of movement through the cave. As a result, tours will have to be carefully designed to avoid driving the bats from Kartchner Caverns. Options for maintaining the bat population after development are to restrict visitor use of the Big Room while bats are present or attempt to entice the bats to use another portion of the cave. It should be noted, however, that the literature does not support the second option. We do not totally understand what conditions bats need in their roost and relocation has not been generally successful in the past. In Arizona, there are very few known bat roosts in caves, especially with this many individuals. The bats are a valuable resource to be protected because serious bat population declines have been documented throughout Arizona during the last twenty years. Arizona State Parks has a wonderful opportunity to utilize this facet of a unique cave. The interpretive possibilities of incorporating the bats into the cave development outweigh the problems of working around the bats.

From both public-interest and scientific viewpoints, Kartchner Caverns is even more exciting as a bat roost because it houses a maternity colony. This means also that continued responsible and knowledgeable management is necessary for the bats. From our observations, we know that the period from mid-June to early August is the time when females are in late stages of pregnancy, they give birth, nurse their young, and juveniles are developing and fledging. This is the critical period of time when the bats require non-disturbance to assure healthy behavior and, in turn, successful reproduction and a stable population.

The presence of a healthy bat population in Kartchner Caverns provides much potential for scientific interest. For a state park, however, what is perhaps more important is that the bat population provides the opportunity for public education about these increasingly popular animals and about the exciting and interesting ecology of a subterranean ecosystem. Our studies have shown that Myotis velifer are easily disturbed by lights and noise. The presence of tours and general lighting of the areas of the cave which they use will almost certainly make them abandon the cave. To maintain the bat population will require that development of the cave not disturb the bats or drive them from the cave. Options for maintaining the bat population after development are, in order of preference:

- Limit visitor use of the Big Room while bats are present .
- Attempt to entice the bats to use another portion of the cave.
- Mitigate the impacts of development on the bats by trail alignment, low level lights and providing a bat house on the ceiling.

The first option is clear but would limit visitation to the Big Room from May to the middle of September. This is the only option which appears to be likely to succeed. The second option has never been successfully implemented in any other cave. Suggestions were made regarding the use of bat houses, in order to provide alternate roost sites for the bats, so that the Big Room might be developed without detriment to the bats (i.e., the bats could be moved into houses and placed elsewhere). Unfortunately, bat houses have shown minimal success in the United States (and no success in desert scrub or desert grassland environments in Arizona). The two bat houses that were placed in the cave provided the best possible chance for occupation by bats; i.e., they were placed in an area where conditions were known to be acceptable to the bats and yet these structures were never inhabited by the bats. The preliminary results from the bat houses placed in Kartchner Caverns indicate that there is little reason to expect that the bats could be successfully relocated.

The third option, of routing the trail away from the bat roost and utilizing low level lights, is also unlikely to succeed. Our experience in observing these bats is that they are easily disturbed by sound and light, even at low levels. The last two options could be combined. A bat house could be constructed which could be sound proofed and also provide shelter from light, but there is no evidence that it would be successful. This indicates that it is unlikely that attempts to relocate the bats to other areas of the cave would be successful.

A set of guidelines for working inside the cave while bats are present has been developed as part of the study of the bats. These were developed to minimize the possibility of disturbing the bats and driving them from the cave. They are based on our experiences and observations of the behavior of the bats. Each and every cave visitor should receive instruction in these guidelines, at least on an annual basis. Noise and other effects of workers and casual visitors to the cavern are potential sources of disturbance to bats residing within the cave that could cause pregnant females to abort fetuses or abandon young. Whatever the causes, caution and the least amount of disturbance possible should continue to be the rule. Eight months (September through April) are available during which few bats are in residence and most disturbing cave work may be accomplished.

Bats, like many other mammals, can carry rabies. It is, however, unlikely that any visitor would come into contact with a bat. Five bats from the cavern were tested during 1991 for rabies and all were negative. Visitors should be warned and instructed about the hazards of handling bats or any other wild animal. Suitable

warning signs should be placed in the visitor's center, campgrounds, nature trails and in the cave.

Arizona State Parks should write a "Long-Term Management Policy Regarding the Status of Bats at Kartchner Caverns." Four years of data collection have contributed much baseline information regarding the several species of bats that roost inside the cave. There is more baseline information for KCSP than has been available for most state and federal parks prior to the development of their properties. This information should be used to write a long-term management policy of how these animals will fit into the proposed cave development. With a policy in hand, there would not be a crisis situation whenever something happens regarding the bats. A number of items are suggested in this report for inclusion in the policy.

Survey of the Invertebrate Cave Fauna

The invertebrate fauna of Kartchner Caverns is unique with several new species that may be endemic to Kartchner Caverns. Invertebrates, especially arthropods, make up the majority of all known cave organisms. The cave biota constitute a sensitive, indigenous monitoring system of conditions in the cave. The relative simple ecology of the cave should be integrated into the overall interpretation of the cave.

Preliminary work indicates there are several new species of cave adapted invertebrates, including at least one new species of cave isopod and a new mite species.

Thirty three invertebrate species were found in Kartchner Caverns during this study. Of the 33 species, 5 (15%) are considered to be obligate cave dwellers (troglobites) and 16 (48%) are facultative cave dwellers (troglophiles). The camel cricket, Ceuthophilus pima, is a trogloxene because they leave the cave to feed. The remaining 11 (33%) species are either accidentals (10) or obligate parasites (1).

All of the troglobites and troglophiles in Kartchner Caverns are dependent on organic material from the surface. Most of this organic material is deposited as Myotis velifer bat excrement (guano) every summer. Small amounts of organic matter carried into the cave by periodic flooding of the Back Section provide a limited food supply in that area. The camel crickets are the only cave arthropod that is not dependent on organic material carried into the cave.

Development of Kartchner Caverns must be scheduled in a way to preserve the bat population in the Big Room. The loss of the bats from the Big Room in Kartchner Caverns would result in the extinction of most of the arthropod fauna in the cave. Development in the Back Section, especially the Throne and Rotunda Rooms would have the least impact on the cave fauna.

Care must be taken during construction and subsequent tours to insure that the cave environment remains unchanged and that exotic surface species are not introduced into the cave. A change of the environment and/or the introduction of surface species could result in the disruption of the cave community and eventually the loss of cave species.

HYDROLOGY

Two off-site drainage areas, Guindani Wash and Saddle Wash, have been shown to be the source of the water which sporadically floods the back portions of the cave. Two flooding events occurred during the course of our study. In August 1990 and during the winter of 1991, the back section of the cave was flooded. The cave was found to respond slowly to the runoff on the surface. The adjacent washes must flow

for several days before water begins to enter the cave. Once surface water infiltrated the cave passages, the flooding was still rather slow, taking a week or more to flood the back sections. This indicates that rapid flooding of the cave is highly unlikely. Only a portion of the cave is subject to flooding; mainly the areas in the back sections of the cave.

An analysis of weather records at nearby surface stations indicates that, while flooding of the cave has been rare in recent years, historically it is a common occurrence. Flooding of portions of the back areas of the cave occurs in 2 out of every 3 years, usually during the winter. Winter floods have a lasting impact on the cave microclimate because cold water is entering the cave. This creates a zone of cold, dense air which has a controlling influence on airflow patterns in the cave.

The source of water which floods the cave was determined by dye tracing to be Guindani Wash and Saddle Wash. These two surface streams appear to be one of the most significant sources of water for the cave. Changes in land use within these drainage areas can directly affect the quantity and quality of water entering the cave. These watersheds are located on Coronado National Forest lands. Arizona State Parks should take steps to see that the cave is adequately protected from detrimental changes in these watersheds.

Areas on the park which are important for recharging water into the cave have been identified. These are of two types: areas along the washes where water infiltrates into the cave when the streams carry water and areas above the cave where precipitation percolated down into the cave.

GEOLOGIC STUDIES

The geologic study was conducted to provide a detailed understanding of the geologic setting of Kartchner Caverns and the surrounding area. The objectives of the surface and subsurface geological investigations are twofold: (1) to provide geological engineering information critical to the evaluation of potential visitor access points and (2) to provide a detailed understanding of the geological setting and speleogenesis of the cave.

The geologic mapping of the Kartchner Caverns State Park revealed a highly faulted and fractured block of Paleozoic limestones. These limestones, consisting of Pennsylvanian Horquilla Limestone, Pennsylvanian Black Prince Limestone, Mississippian Escabrosa Limestone, Devonian Martin Formation, and Cambrian Abrigo Limestone, have a general dip to the west ranging from 10 to 45 degrees. The fractures or joints have been solutionally enlarged near and at the surface. These minor fractures were probably formed in conjunction with the major normal faults which cut through the limestone with displacements up to several hundred feet. The rock units have been covered in many places by unconsolidated sediments of varying ages from very recent back to Late Tertiary/Quaternary time. This outlying block of limestone has both an east-bounding fault (revealed by geophysics) and a west-bounding fault.

A more detailed map of the geology of the cave and surface geology of the area overlying the cave was performed in conjunction with the study of three potential entrance sites. This study focused in greater detail on the structural geology and subdivisions within the Escabrosa Limestone block that contains Kartchner Caverns. The cave is contained entirely within a highly faulted and fractured block of Escabrosa Limestone. Identification of key marker beds allowed the surface and interior geology to be closely correlated by projecting surface features into the cave.

MINERALOGY

The mineralogy of Kartchner Caverns is both diverse and significant. It is diverse in that six different chemical classes are represented by the cave mineralogy: the carbonates, nitrates, oxides, phosphates, silicates and sulfates. It is significant for a number of reasons:

- World's longest soda straw 21'-2". "The Soda Straw" in the Throne Room measured at 6.45m (21.16 ft) long. This length beats the previous world of 6.24 m (20.47 ft) in a western Australian cave.
- Largest and most massive column in Arizona - 58 foot high column, named Kubla Khan, in the Throne Room.
- First cave occurrence of the "birdsnest" form of quartz needles.
- Rare occurrence of nitrocalcite "cotton" as a cave mineral. First modern description of this mineral.
- One of the most extensive occurrences of brushite moonmilk in the world.

Ages of several cave formations were determined. These range from 194,000 years to as recent as 41,000 years. Cave formations in the Big Room were found to be 70,000 to 83,000 years old.

The diverse and interesting mineralogy of Kartchner is due to an unusual set of circumstances. Unlike most limestone caves, Kartchner Caverns is located near igneous terrain. The dry Arizona desert supplies another condition: the low relative humidity allows nitrocalcite cotton to form in the entrance zone of the cave. Bats add the third ingredient, phosphates and nitrates.

POTENTIAL ENTRANCES

At the present time there is only one entrance into Kartchner Caverns, the original discovery entrance. To reach the main rooms of the cave, one must crawl for several hundred feet through small passages. In order to develop the cave for public viewing, a new entrance will need to be constructed or the existing entrance passages enlarged. Introducing new access points into the cave should not be taken lightly because we must insure that they will not adversely affect the microclimate of the cave. The overall goal of these studies is to identify the location which will have the smallest impact on the conditions in the cave. Furthermore, we would also like to identify the site which appears to be the most practical from the standpoint of developing the cave for the public.

Initially a total of 10 different locations for constructing a new entrance into the cave were investigated. For each location, three schematic designs were considered: a wheelchair-accessible ramp, a flight of stairs and an elevator. For each of these 30 combinations, an assessment was made of the potential for disrupting the microclimate of the cave. Results from the microclimate study indicate that the potential for increasing airflow and subsequent moisture loss is the most important issue to be considered. Other factors included in the assessment were impacts on the supply of moisture to the cave and impacts on the biota. The biota are not only an important feature of the cave but also provide a sensitive indicator of the conditions within the cave. In the analysis of the potential entrances, a number of sites were found to have undesirable characteristics and were rejected. These sites had impacts

associated with a particular entrance configuration which would jeopardize the integrity of the cave if that entrance were to be constructed.

Each potential entrance site was also evaluated with a series of criteria for judging the suitability of each entrance for developing a suitable tour of the cave. Factors which were identified as influencing the ease of development are: Length of access tunnel and elevation difference, geologic hazards, distance from the entry point to major features of the cave and the distance the visitor must travel between the Visitor's Center and the starting point of the tour must also be considered.

Based on a weighted point system, the following three potential entrance locations were judged to be the most favorable:

- Echo Passage
- Throne Room
- Tarantula Room

Geologic evaluation of these potential entrance locations was carried out in two phases. The first part focused on the detailed geology above the cave. The second part entailed construction of detailed geologic cross-sections at each proposed entrance. Based on the geologic investigations, the ramped tunnel and elevator shaft at the Tarantula Room were dropped from further consideration.

A more complete review of the advantages and disadvantages of using elevators was made. This indicated that elevators had many disadvantages and should not be considered for the following reasons.

- Dependent on a reliable source of power
- May be source of damaging air exchange if not properly constructed
- Require specialized maintenaince
- Limit the movement of materials into the cave during construction
- Not economically justified

A desirable goal for the development of the cave is to allow access to the cave by the handicapped. Use of stairways on the entrance would limit the use of the cave by the handicapped. Under the assumption that State Parks intends to provide handicapped access, if possible, the use of stairs as an option was eliminated.

The recommended location for a new entrance into the front section of the cave is a ramped tunnel into the Echo Passage. This would result in an entrance which is located close to the proposed visitor's center, would be handicapped accessible and would preserve several options for interior trail routing.

The recommended location for a new entrance into the rear of the cave is the alternate ramped tunnel alignment into the Throne Room. This entrance could also be used as an exit portal if the cave were designed as a one-way through-trip.

CONSTRUCTION IMPACTS AND MITIGATION

During the exploration and scientific study of Kartchner Caverns, great care was taken to conserve the mineral resources. Many of the features in the cave are very fragile or are dependent upon the stable climatic conditions found in the cave. Potentially, the construction phase of the project can be the most damaging to the cave. While it is certainly the goal of Arizona State Parks to protect the cave a contractor will be primarily interested in completing the work. It will be necessary to

insure that the contractor understands the reasons for certain approaches and the necessity of protecting the cave features.

Control of airflow should be one of the highest priorities in the construction of a new entrance into the cave. Prior to completing the last few feet of tunnel the air control doors should be in place and operational. Uncontrolled air exchange through a newly opened tunnel can potentially dry out the cave within a few days.

Underground construction must be scheduled so that it does not interfere with the bats' use of the cave. Bats are present in the cave from May to the middle of September, so this leaves almost 8 months for construction in the Big Room. Construction can take place in other areas of the cave, such as the Throne Room, while bats are present.

Other issues which have been identified are the control of exotic plant growth during construction. Temporary lighting for construction will be brighter and less carefully placed than the display lighting system. Unless carefully controlled, exotic plants can gain a start during construction. Alpha radiation levels will also need to be monitored during construction. Some types of construction activities can potentially increase alpha radiation levels.

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FOREWORD

Arizona Conservation Projects, Inc. (ACPI)

ACPI is a non-profit corporation whose exclusive goal is to aid the development of Kartchner Cavern in a manner that will preserve the pristine quality of the cave while providing an enjoyable and informative experience for the public. In addition to the tasks required by the scope of services, ACPI has recruited volunteers to provide assistance on other tasks which have enhanced our understanding of the cave. Since the first trip into the cave in February 1989, ACPI has taken a total of 375 trips into the cave through September 1991. This total does not include trips to the park for surface monitoring, bat counts or surface surveying. A total of 141 individuals have participated in these trips. The number of hours spent in the cave by these individuals totals 6069.25 hours.

Much of the material for this report has been freely drawn from the reports submitted by many individuals. However, the interpretations, conclusions and recommendations contained in this report represent the opinions of Arizona Conservation Projects, Inc. The reader who is interested in more specific details of a particular aspect of this study is encouraged to obtain the original report. All data collection and analysis has been performed by ACPI unless otherwise noted.

Specific sections of this report have been drawn largely from the reports by the following individuals.

Cave Description - Chuck Graf
History - Randy Tufts
Surface Climate - Bob Buecher
Cave Environmental Monitoring - Bob Buecher
Cave Airflow - Bob Buecher
Alpha Radiation - Bob Buecher
Drip Water Measurement - Bob Buecher
Cave Flooding - Bob Buecher
Cave Moisture Balance - Bob Buecher
Well Monitoring - Chuck Graf & Bob Buecher
Surface Hydrology - Debbie Buecher & Bob Buecher
Bats - Ronnie Sidner
Invertebrate Cave Fauna - Dr. W. C. Welbourn
Plant Growth Potential - Ozark Underground Laboratory
Small Mammals - Tom Valone
Ornithology - Tom Valone
Amphibians and Reptiles - Brent Martin & Peter Holm
Survey and Mapping - Bob Buecher
Impact Assesment - Hans Bodenhamer
Photomonitoring - Steve Holland
Unimproved Trails - Bob Buecher
Mineralogy, Sediments and Speleogenesis - Carol Hill
Detailed Surface Geology - David Jagnow
Potential Entrances - Bob Buecher

Volunteers

ACPI's work has been enhanced by the contributions of many individuals who have donated their time and expertise to this study. A total of 2,290.45 hours were

donated to ACPI by over 100 individuals. For these people, the satisfaction of helping to open the cave to the general public has been their only reward. I would especially like to thank the following individuals who have made outstanding contributions to this study and the many others who have donated their time.

Deborah Buecher donated many hundreds of hours to all facets of the project. She has drafted maps and figures, helped on the theodolite and compass survey, collected data from environmental stations, bat counts and collected samples for the bat guano study, performed hydrology calculations for the surface drainage report, and contributed to many other tasks.

Ron Bridgemon continuously helped throughout the project, both in the cave and in overseeing the review of all reports. He also helped on the geophysics, compass and theodolite surveys. David Dalton helped on all aspects of the project, airflow measurement, surveying, collecting data, and establishing stations. But most of all, he initially recommended the Owl data loggers and continued efforts in installing and maintaining the computer systems. Chuck Graf gave advice and insight on the hydrology and speleogenesis of the cave, aided in the collection of geologic samples, trail survey and well monitoring. John Garrison was always willing to help out on any task and particularly helped in data collection and bat studies. Scott Gibson showed interest in the geology of the cave and its relationship to the regional geology. Also, he helped in reviewing the geology, mineralogy and geophysics reports. John S. McLean gave insight and advice on the microclimate studies. Dr. Todd Rasmussen brought the soil psychrometer to our attention and provided new insight into the airflow and relative humidity within the cave. Steve Holland took charge of the photo-monitoring program, arranged trips and managed the additional photographic work done in the cave. Tom Strong devoted his time to organizing the biological studies and helped in surveying the cave. Art Christiansen was always willing to help no matter what the job was, from surveying to establishing monitoring stations to hauling supplies. Randy Gruss helped with the photomonitoring and with the trailer. Ben Watkins helped in constructing equipment for the computer systems and aided in maintaining them. Leonard Swanson helped install the computer systems in the cave, constructing temperature probes and aiding on the theodolite survey. Cyndi Mosch gave help with the mineralogy, geology and contributed her keen observations. Mike Doe provided geologic expertise both above and below ground. Ken Byrd and Liz Hamilton-Byrd helped in data collection. Gary Tenen supported our efforts and printed our reports. Henry Schneiker helped in the cave and gave of his expertise with Macintosh computers. Ginny Dalton aided in the bat studies, airflow studies and data collection. Bob Pape helped with the compass survey, construction of environmental stations, and review of the invertebrate studies. Tom Harris helped in building mud bridges and surface surveying. Bill Grimes provided welcome help in collecting data from the environmental stations. Thanks go to Johnson, Brittain and Associates for the advice of Mike Johnson, continued support and loan of survey equipment. Thanks also go to members of the Cave Research Foundation Science Committee for their review of our reports.

Subcontractors

ACPI's approach to these studies has been to assemble a team with specific expertise in cave studies where each member has an understanding of the relationship between study areas. The studies were performed by a team of experts whose combined knowledge and experience in cave-related studies totals over 240

years. This team offers the most productive possible match between the study requirements and the nation's foremost cave scientists - individuals who have proven themselves on cave management projects of this kind and who have become directly involved in the investigations. A total of 723.25 hours were spent in the cave by ACPI's subcontractors.

Many of these experts share our interest in Kartchner Caverns and have performed outstanding work far in excess of the requirements of their contracts. In particular, I would like to thank the following:

The inventory of the minerals and speleothems in Kartchner Caverns was performed by Carol A. Hill, co-auther of the book "Cave Minerals of the World". Carol was extremely helpful in guiding us to understand the complete development of the cave.

Ronnie Sidner was the Mammologist and consulting biologist on bats. She has continued support of the study of the bats at Kartchner Caverns. For all of her help on many nights studying the bats.

David H.Jagnow, Consulting Geologist, produced an outstanding report and extremely detailed map of the geology of the cave and surface.

Dr. Cal Welbourn, Curator, Acarology Lab, The Ohio State University, provided an inventory of the invertebrates and comparisons with other caves.

Dr. Edgar J. McCullough, Jr., for his oversight and review of the geologic studies.

Dr. Owen Davis, Department of Geosciences collection, carbon-14 age dating and analysis of bat guano samples from the Throne and Rotunda Rooms.

Staff

Work on the project was directed and supported by the staff of ACPI. During the study, a total of 2,580.75 hours of in-cave work were performed by the two ACPI full-time and two part-time staff members.

Bob Buecher was manager of the Kartchner Caverns project for ACPI. Other duties included data analysis, report preparation, geophysics control survey, data collection, contract administration, compass and theodolite survey, surface hydrology study.

Anita Pape assisted in the surface geophysics survey, collected environmental station data, was responsible for database organization and maintenance, report preparation and day-to-day office operation.

Hans Bodenhamer was employed part-time and produced the comprehensive impact mapping of the cave, aided in the geophysics survey, theodolite survey and contributed to general equipment maintenance.

During the first year of the project, Bruce R. Tufts was responsible for researching and writing the history of the cave, contract preparation and aiding on survey and photomonitoring trips to the cave.

Bob Buecher

Bob Buecher
ACPI Project Manager

KARTCHNER CAVERNS STATE PARK
ENVIRONMENTAL AND GEOLOGIC STUDIES

INTRODUCTION

Kartchner Caverns is a beautiful limestone cave in pristine condition, considered by experts to be the premier cavern in Arizona. It will be protected and displayed to the public as the 25th Arizona State Park. The cavern was discovered in 1974 by two Tucsonans, Gary Tenen and Randy Tufts. They kept the cave secret for fourteen years to protect it from vandalism and to maintain it in its original pristine condition. It is located approximately 8 miles southwest of the town of Benson on the west side of State Highway 90. The park site is 550 acres in size and is situated at an average elevation of 4700 feet (Figures 1 and 2).

The cavern is over two miles long with spacious rooms, one of which is as long as a football field. It is a wet, 'live' cave into which water still percolates from the surface and whose calcium carbonate features are still growing. It contains an unusually wide variety of multicolored cave formations – stalactites, stalagmites, flowstone, shields, helictites and soda straws - some of which are among the best examples in the United States. It is also a summer home to a colony of approximately 1000 bats. The contrast between the moist interior of the cave (over 99.5% relative humidity) and the dry desert above makes Kartchner Caverns particularly vulnerable to damaging changes brought about by developing the cave for public viewing. Changes in airflow, temperature, or humidity caused by improper development could quickly dry out the cave, halt speleothem growth, and diminish the cave's beauty.

The overall goal of the Kartchner Caverns State Park project is to preserve the pristine nature of the cave while displaying it to the public. Meeting this goal requires taking advantage of the growing body of research from both show caves and wild caves about techniques used for minimizing the impact of show cave development while maintaining the integrity of the delicate cavern environment. The environmental and geologic studies now being undertaken will make it possible to avoid the costly and damaging mistakes made at other caves.

In order to maintain the cave environment, it is first necessary to understand the significant aspects of that environment. Technical studies of the cave must precede development to provide the information needed for comprehensive planning. The non-renewable and fragile nature of the cave features and microclimate means that any mistakes made during development may have a permanent impact.

To prepare for the public opening of Kartchner Caverns in an environmentally sensitive manner, Arizona State Parks has contracted for a two-year pre-development study of the cave environment and geology with Arizona Conservation Projects (ACPI). The results of that 24-month study are presented in this report. The studies focus on four main aspects of the cave environment: (1) cave microclimate and meteorology, (2) hydrology, (3) geology, and (4) biology. This report summarizes the findings of those studies and makes specific recommendations regarding the impact of development on the cave and methods of minimizing those impacts.

CAVE MICROCLIMATE AND METEOROLOGY

Of all the studies, cave microclimate and meteorology will be the most critical in designing an environmentally-sound cave development and management plan. In order to preserve the unique features of the cave, Arizona State Parks intends to maintain existing humidity, temperature, and airflow in the cave . The contrast

between the moist interior of the cave (over 99% relative humidity) and the dry desert above (46% relative humidity and 16" annual precipitation) make Kartchner Caverns particularly vulnerable to damaging changes. Large parts of the cave are still live. In the live areas, calcite is still depositing from water dripping into the cave and forming beautiful cave formations. Changes in airflow, temperature, or humidity caused by improper development could quickly dry out the cave, halt speleothem growth, and diminish the cave's beauty. The most likely cause for damaging changes would be an improperly designed and located entrance for visitors which could potentially dry out the cave. The parameters being investigated in this study include evaporation rates, air quality, water drip rates and the relationship to surface meteorology. A total of 22 environmental monitoring stations were installed throughout the cave and one weather station was installed on the surface.

HYDROLOGY

Kartchner Caverns was formed thousands of years ago by the slow dissolving of the limestone rock by percolating water. Even today the presence of water in the cave and elsewhere on the park plays a vital role in maintaining the conditions in the cave. The hydrologic studies aim to understand the relationship between the cave and the surrounding groundwater. As a part of this study, frequent measurements were taken at each of several water wells located on the Park. The impact of surface water and precipitation on conditions within the cave was also assessed.

GEOLOGIC STUDIES

The objectives of the surface and subsurface geological investigations are twofold: (1) to provide geological engineering information critical to the evaluation of potential visitor access points and (2) to provide a detailed understanding of the geological setting and speleogenesis of the cave.

The geological studies include investigations of the surface geology, subsurface geology, speleothems (cave decorations), mineralogy, speleogenesis and geophysical explorations to identify unknown extensions to the cave.

Speleothems and Mineralogy. The mineral deposits within Kartchner Caverns give it much of its beauty. The quality and diversity of these speleothems decorating the cave is one of the primary attractions of the cave. Proper display and protection of these features should be of prime concern in the development of the cave.

Geology and Speleogenesis. Understanding the geology of the cave through detailed geologic mapping will aid in developing new entrances into the cave and understanding how the cave was formed.

Geophysics. The primary purpose of the geophysical study was to determine if additional large, unknown cave chambers are located within the Park boundaries. A second objective was to aid in the placement of surface facilities to minimize impact on the cave.

BIOLOGY

The most visible sign of biological activity in the cave is the presence of bats. Kartchner Caverns is the summer migratory and maternity home for about one thousand Cave bats (Myotis velifer). The bats begin arriving from their winter range in Mexico in May, have young about the third week of June (which begin flying the first week of August), and leave by mid-September. In their nightly forays for insects, the bats navigate deftly through the series of small rooms and passages connecting the

Big Room to the Entrance Sinkhole. Bats occupy a vital niche in the cave ecosystem. Therefore, much effort is being devoted to understanding their habits and requirements.

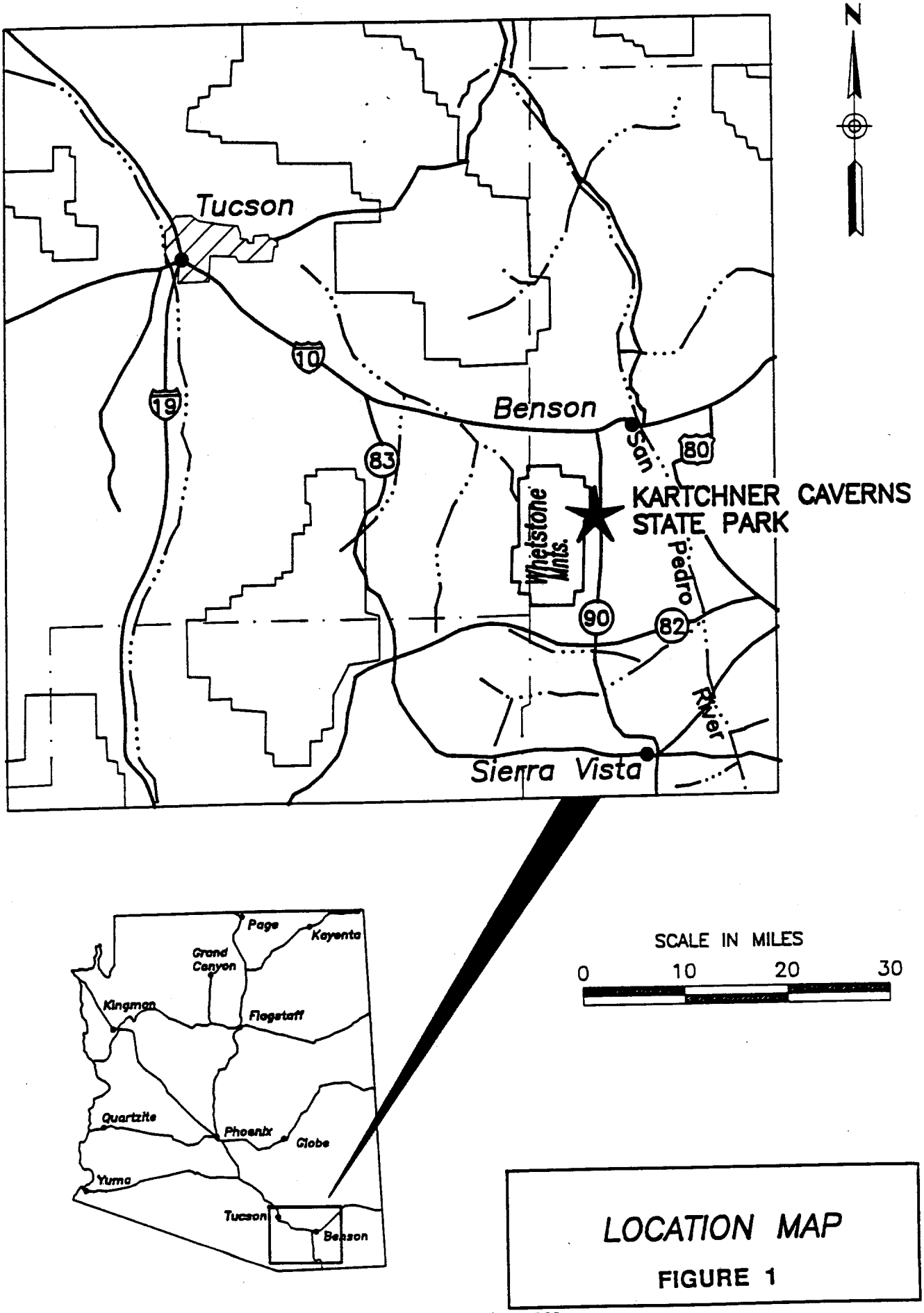
Invertebrates make up the majority of all known cave organisms, but tend to be overlooked during cave inventories. The dark, generally nutrient-poor habitat of caves gives rise to interesting invertebrate-dominated ecosystems and unique cave-limited species have been found in Kartchner Caverns.

Lastly, the potential of the cave to support algae and moss growth is being studied. Such growth has been a common problem in electrically-lighted caves. A notable example of the problems that can be caused is Lascaux Cave in France. There, algae began to grow over prehistoric cave paintings. As a result, the cave was permanently closed to the general public in order to preserve the features of the cave.

ADDITIONAL STUDIES

Additional studies being performed as part of the pre-development studies include: monitoring trace gases in the cave air, compiling a history of the discovery and exploration of the cave, a program of systematic photo documentation to record existing conditions and monitor changes in cave features, surveying and mapping the cave in support of the other studies and a study of the small animals that utilize the cave entrance.

The following sections of this report elaborate on each of these areas of study in greater detail.



LOCATION MAP

FIGURE 1

A.C.P.I. © 1991

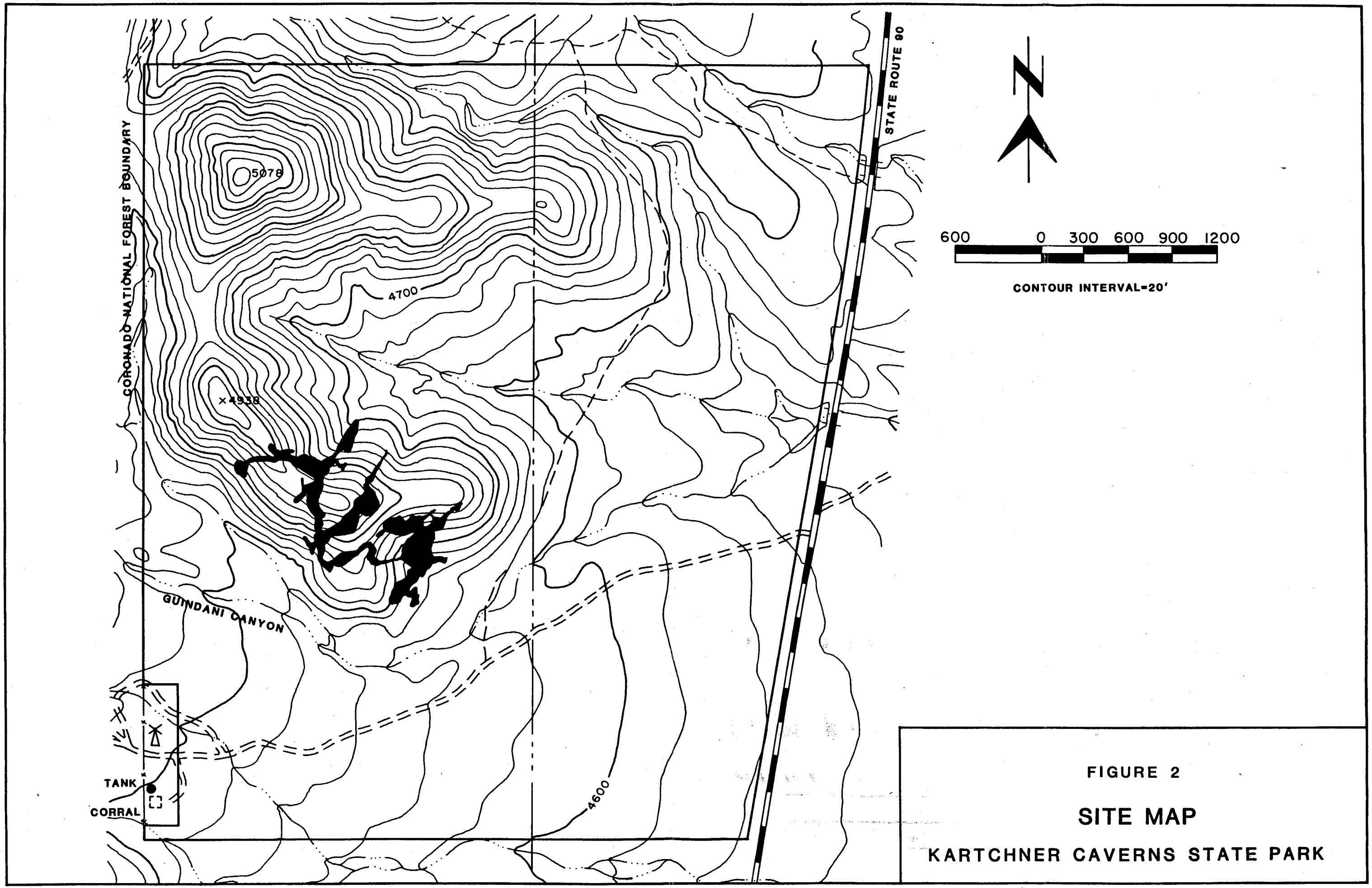


FIGURE 2

SITE MAP

KARTCHNER CAVERNS STATE PARK

A.C.P.I. 1991

DESCRIPTION OF THE CAVE

Before proceeding further with this report, the reader should be acquainted with the overall layout of the cave. Much of the material presented in the remainder of this report can only be understood in the context of its location within the cave. A small outline map (Figure 3) provides the names of many of the primary features of the cave. Following is a brief description of some of the major parts of the cave with emphasis on those areas which offer outstanding views in the cave (Graf, 1989). The glossary at the end of this report gives brief descriptions of the speleothem names used.

The sinkhole entrance to Kartchner Caverns is located near the base of an ocotillo-dotted slope of limestone and leads into one of the most beautiful and pristine caves in Arizona. The sinkhole itself drops vertically about 15 feet and measures 25 feet long by 10 feet wide. A few feet above the bottom of the sinkhole, a crevice penetrates the east wall, leading down through several small chambers, a few squeezes and, after about 200 feet of hands and knees crawling, to the "Pop-up" where one can at last stand up. Grand Central Station is located to the left of the "Pop-up". A well-decorated gallery and corridor lead to the right.

From the "Pop-up" and to the right, a 200-foot amble along "Main Corridor" leads to the base of a large breakdown pile at the south end of the Big Room. Here, at the "Y" Junction, the trail divides, one trail continuing along the east side of the Big Room, the left trail climbing up a short ladder onto the breakdown pile and crossing the south end of the Big Room. The first trail continues along the east side of the Big Room and the cave opens into a wide passage to the right - the Mud Flats area. This area has a number of colorful stalagmites and stalactites. The Mud Flats passage continues to the east, gradually rising into a series of collapsed rooms which are within a few feet of the surface.

Continuing straight ahead past the Mud Flats, a second smaller passage takes off to the right - this is the start of the Red River Passage. During very wet years, a small stream emerges from under the breakdown pile in the Big Room and flows into the Red River. The end of the passage is the lowest point in the cave.

A few feet past the start of the Red River is a 15-foot climb up a sloping wall. A rope hand line has been placed here to make the climb easier. At the top of the climb, one has a fine view of the northeast end of the Big Room. To the left, a wall of massive flowstone formations divides the center of the room. Ahead and to the right is a forest of short stalagmites. The trail winds between these formations past an area of shields and bacon draperies to the north end of the Big Room. A passage continues to the left toward the Pool Room while another narrow opening in the flowstone wall directly ahead leads to the Echo Passage.

The Echo Passage is several feet lower than the Big Room, the floor is coated with several inches of mud and the walls are a dark-colored limestone. A few feet into the passage, the trail passes between several formations. Looking back, one can see that this is a spectacular shield formation we have just walked under. The Echo Passage continues for another 70 feet with an outstanding display of helictites and flowstone along the left side of the passage.

Returning to the junction before the Echo Passage, the main trail turns to the left and one must soon crawl between cave formations into the Pool Room. Once again we find that the formations we have passed through are spectacular shields. Beyond the Pool Room, the ceiling rises and the passage can be walked once again. After approximately 70 feet, the trail enters the Strawberry Room. In this room, the right wall

is covered with a profusion of red, pink and white colored flowstone formations. This area has some of the most highly colored shields, flowstone, stalagmites and soda straws in the cave.

The trail divides in the Strawberry Room, with the left branch climbing up a steep breakdown pile to the Big Room Overlook. The Overlook affords the best view of almost the entire Big Room. To the right, the stalagmites at Kartchner Towers are visible; directly in front is the flowstone wall dividing the Big Room; and to the left is a forest of stalagmites.

The other trail in the Strawberry Room descends to a level mud floor at the start of the Cul-de-Sac Passage. Here the mud floor has a thin coating of rock dust that has sifted down over the ages. The Cul-de-Sac soon terminates in a sloping wall of rubble along a prominent fault zone. This is the end of the cave in this direction.

Returning to the "Y" junction at the start of the Big Room, we find the trail to the left climbs a short ladder, meanders between boulders and nearly crosses beneath the summer roosting spot of a maternity colony of about one thousand Cave bats (Myotis velifer). On the far side of the breakdown pile is the first place that one can glimpse a portion of the Big Room from this side. From this point, only the west half of the room is visible. The vaulted expanse of the main part of the chamber and a profusion of stalactites, stalagmites, columns and flowstone lays before the visitor. This area covers nearly an acre of floor space and is one of the highlights of the cave. The trail continues down the other side of the breakdown pile past a group of large stalagmites named Kartchner Towers to a short, tight downclimb that marks the beginning of the River Passage.

The River Passage is a series of rooms originally formed below the water table. They have been modified and integrated by solution and erosion from in-cave stream flows. A somewhat arduous trip leads along this passage through Lovers' Leap, the Bathtub Room, Thunder Room, Shelf Passage and Grand Canyon to the Pyramid Room. Several reaches of stream channel (which have contained flowing water only twice since 1974) emerge into this section of passage, only to disappear into sumps a short distance further. Particularly noteworthy along the River Passage are the helictites, flowstone, cave pearls and other speleothems adorning the Shelf Passage. The remaining rooms along the River Passage are sparsely decorated and several rooms contain little more than piles of breakdown.

Beyond the Pyramid Room, the arduous becomes downright nasty! In order to reach the Rotunda Room-Throne Room and the Subway Tunnel-Pirate's Den, the other two main chambers of the cave in addition to the Big Room, the Triangle Passage must be traversed. The Triangle Passage is a 100-foot-long, low, muddy crawl on belly and hands and knees. Unfortunately, the worst is still ahead: the Mud Trench, a 70-foot-long exhausting struggle through thigh-deep mud. This section became so difficult that a series of bridges constructed from PVC pipe and plastic fencing were built over the sections of deep mud.

Beyond the Mud Trench, the route becomes easier and leads to The Doorway, a vertical slit cutting through a foot-thick wall of quartz. The Quartz Divide, as this feature is called, is the insoluble vestige of siliceous infilling along a fault. Boxwork has formed on the limestone ceiling bordering this quartz dike, one of the few places in the cave where this speleothem is found.

Once through The Doorway, the cave changes in aspect to very wide, often low but walkable, mud-floored passages. The passages are attractive for their sweeping curves, scallop-shaped solution features, and the fossil crinoids and horn corals

etched in relief on the walls. Speleothems, though not abundant, have typically formed at the ends of these passages. The Pirate's Den and Sue's Room both have good displays of speleothems, and an unusually fine example of a shield is found in the Angel's Wing Passage. All of the passages beyond the Doorway have mud floors. In places, the mud becomes quite deep and additional bridges have been installed at these difficult spots.

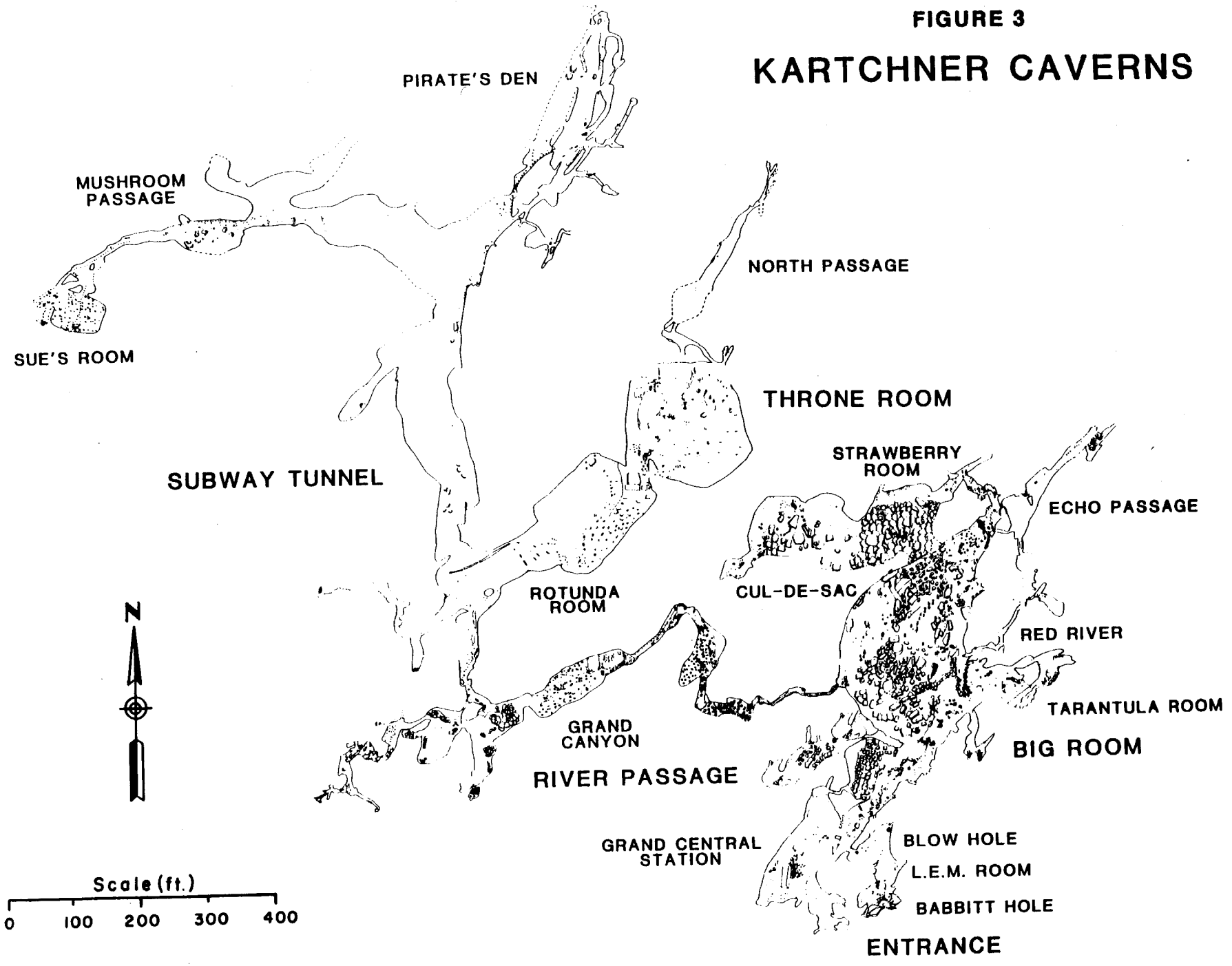
Back outside The Doorway, a trail branches right to the Rotunda Room. The Rotunda Room was named for the limestone beds arching dramatically across the passage. The floor of the room slopes gently to a low point on the opposite wall. This floor is composed of a moist mud that has at some time in the past dried and cracked. Only a narrow trail crosses the right edge of the room. At one point a myriad of beautiful helictites and barb-ended soda straws hang from the roof near the trail. Several of these, the Fallen Straws, now stand upright in the mud floor, apparently once having been attached to the roof overhead.

From the Fallen Straws, the trail ascends a huge breakdown pile to the highest point in the cave, an overlook above the Throne Room. The Throne Room is the most magnificently decorated room of the cave. From the overlook, the whole room is visible. Near the center is the giant column, Kubla Khan, and the towering stalagmite, Nefertiti. Kubla Khan, at 55 feet tall, is the largest known and probably most massive column in an Arizona cave. Surrounding these two giants is a forest of stalactites and stalagmites. The overlook area itself is spectacularly decorated. Helictites the thickness of spaghetti grow from the ceiling and walls, curving delicately through the air in apparent defiance of gravity. A special distinction for the Throne Room is that it houses the longest known soda-straw stalactite (21 feet 2 inches) in the world.

The total length of all horizontal segments of surveyed passage in Kartchner Caverns stands at 12,648 feet (2.40 miles). Surprisingly, the entire cave lies within a rectangular area of 1600 feet by 1100 feet. Of the three main chambers of the cave, the Big Room is the largest, about 350 feet long and 180 feet wide. The vertical extent of the cave is 135 feet and the greatest ceiling heights, about 100 feet, are found in the Throne Room. The terminal sump of Red River Passage, located off the Big Room in the Red River Room, is the deepest point in the cave - 74 feet below the entrance sinkhole. At a few points in the cave, roots are visible where the roof thickness is small. The greatest thickness of limestone overburden, about 260 feet, occurs where the Mushroom Passage crosses under the summit ridge of the limestone hill containing the cave.

FIGURE 3

KARTCHNER CAVERNS



HISTORY

The History of Kartchner Caverns was prepared from three standpoints:

- Journalistic/Historical – a timeline of key events, a document index and a recollective narrative. The timeline identifies key periods and episodes and the narrative elaborates on them, from the period of the earliest discoveries up to the signing of Senate Bill 1188. Covered are: key individuals and organizations in Kartchner Caverns history and a description of their roles; a list of known visitors to the cave and a description of their activities.

- Interpretive – categorized historical data based upon a list of questions commonly asked cave interpreters.

- Cave Management – recording the early observations of the cave and site made by the discoverers and owners plus describing the conservation approaches taken by them and their evolving concept of the developed cave.

Sources included ACPI files and news clips, plus interviews with the key participants.

A more complete History of Kartchner Caverns was prepared and submitted to Arizona State Parks in fulfillment of Task 1.1.1 (Tufts, 1989). The full history will not be included here. The intent here is to summarize the events that led up to the creation of Kartchner Caverns State Park.

It had been known for years that there was a sinkhole on the land at the base of the eastern edge of the Whetstone Mountains. But down on the plains was not as good a cave-hunting ground as up in the hills, so the sinkhole was mostly left alone. John Porter, Charlie and Tom Dean decided to explore the sinkhole in 1967. Tom was small enough to negotiate through the breakdown in the bottom and reported that there was a cave with "all kinds of formations" (the Crinoid Room). In 1967, Randy Tufts, John Powell, Steve Wade and Harry Walker found the sinkhole, explored it but deemed it too dangerous to continue. Then, in 1971, John Porter returned with Lane Larson to enlarge the small crevice at the bottom and entered what are now called the Crinoid and LEM rooms. That's as far as they went.

It wasn't until 1974 that the cave received any serious attention. Tufts and Gary Tenen went to the sinkhole and decided to press further into the cave. They squeezed through the same opening that Porter had enlarged and continued to explore. They found what appeared to be the source of the warm, moist air that they could feel - a fist-sized hole at the end of a small crawl. They came back another day and spent time chipping away at the bedrock to enlarge this opening. Once they were through, they advanced as far as the section now known as Mud Flats and stopped for the day, knowing they had quite a cave left to explore.

In the ensuing years, they recruited trusted cavers and explored "Xanadu Cave". Since secrecy was the best protection for a cave, and Xanadu seemed to warrant the best protection they could give it, they enlisted only those cavers they felt would keep the secret. However, as time went on, the "secret" started leaking out. One trusted caver would tell another "trusted" caver who would tell another and so on. Tenen and Tufts felt they would have to do something more to protect Xanadu and, while

brainstorming ideas, they thought of developing the cave for public viewing. If they could find the right steward for the cave, it could be protected while allowing the public to view this wonder.

They found out, again secretly, that the Kartchner family owned the land and were unwilling to sell it. After much deliberation, they approached the Kartchners about Xanadu. Once members of the Kartchner family were taken into the cave (Figures 4 and 5) and saw what they had, they agreed that it should be protected. They decided, though, that they could not develop it themselves.

Once the decision was made to develop the cave somehow, the discoverers knew they would need a map of Xanadu. Orion and Jan Knox from Natural Bridge Caverns near San Antonio, Texas were recruited to map the cave. The Knoxes started mapping in December 1978 and, by early 1979, had a map ready showing about 9,000 feet of passage. In the next couple of years, Tenen, Tufts, members of the Kartchner family and other cavers, added another 4,000 feet to this map.

The project was then placed on hold until 1984 when Tufts approached Ed McCullough, Dean of the Faculty of Science to see if the University of Arizona would be interested in a research cave. McCullough suggested that Tufts contact Arizona State Parks Department since they were currently looking for new state park sites. Tufts then went to Phoenix to talk with Charles Eatherly, Special Projects Coordinator. Eatherly was interested and he and McCullough met with Tenen, Tufts and Dean Kartchner to discuss the project. Eatherly was unable to enter the cave, but when McCullough was shown the cave, he heartily endorsed its development under the Arizona State Parks system. Eatherly suggested that Xanadu Cave now be referred to as "Secret Cave".

Thus began discussions with officials of the Arizona State Parks Department. Mike Ramnes, Director, Paul Malmberg, Tim Brand, Tanna Thornburg, management personnel, were briefed on Secret Cave. They were enthusiastic about acquiring the cave for State Parks and immediately started thinking about how they could do it without jeopardizing the safety of Secret Cave.

Tenen and Tufts also approached Bob and Debbie Buecher to help. They started a subjective assessment of the cave, comparing it to the "average" Arizona cave, including four significant Arizona caves, and Carlsbad Caverns in New Mexico.

Tenen and Tufts felt that contact with then-Governor Bruce Babbitt would benefit their cause, so Tufts contacted Betsy Bolding whom he had met in the course of his career in grass roots politics. Bolding was now the Southern Arizona coordinator for Governor Babbitt and arranged an appointment for the discoverers to discuss Secret Cave with him.

Babbitt met with the cavers involved, looked at slides and proposals and decided he wanted to see the cave. For this visit, the original Blowhole entrance was deemed too small to take the Governor through, so Tenen, Tufts and Buecher excavated another hole off the LEM Room. The new opening they created is now called the Babbitt Hole. Governor Babbitt toured the Big Room, Echo Passage and Cul-de-Sac and was impressed by all of it. He did not evince support for the project that day, but later indicated that he was interested in the project.

It then seemed as if everything was in place: Arizona State Parks was interested, Governor Babbitt was enthused. Only details needed to be worked out - price, how to pay for the land and then what to do with it.

The next two years, however, proved to be tumultous. There were shifts in State Park management, in government - Ev Mecham was elected governor to replace

Babbitt - and an appraisal process could not be agreed upon by both parties, the Kartchner family and State Parks, much less a price. The Nature Conservancy was approached to act as a temporary owner of the land while State Parks came up with the necessary funding, but were balking because there were no endangered species involved - one of their criteria for acquiring land.

By 1986, the Buechers had completed their assessment of Secret Cave and this was added to the arsenal for convincing public officials of the favorability of developing the cave. Key legislators, BLM officials and Nature Conservancy officials were taken into the cave to try and convince them of the desirability of Secret Cave as a commercial venture.

By early 1987, the Kartchner family was ready to seal the cave and drop the whole project. They were thoroughly discouraged with how slow the process was and felt that sealing the cave would be the best thing to do to protect it. They made a couple of trips to make video tapes of the cave and prepared to seal it. Then, in April 1987, Ken Travous was named Executive Director of State Parks and a month later, Tufts returned from a year-long trip. Travous, Tenen and Tufts met to become acquainted with each other and then the discoverers introduced Travous to the Kartchner family and to Secret Cave. Travous convinced the family to hold off sealing the cave.

Travous also met the State Parks Board and told them that this cave, in his opinion, should be top priority. The Board gave the go-ahead and Travous proceeded to try and put the pieces together to buy the land. Paul Malmberg and Tim Brand visited the site and started to familiarize themselves more with the project.

The method of appraisal was agreed upon and appraisers were selected and hired. Bud Cannon, an appraiser from Dearborn, Michigan had specialized in unusual appraisals for the Nature Conservancy. He had done some early appraisal work in 1985 on Secret Cave, updated his appraisal on the cave and the 159 acres above it that were deemed "adequate land for a park". Sanders Solot of Tucson, Arizona was hired to appraise the remainder of the Kartchner land surrounding the cave. Cannon appraised the cave and the 159 acres at $1.3 million and Solot appraised the surrounding acreage at $500,000. Dan Campbell from the Nature Conservancy, who was working privately to help the project, asked the family to donate $250,000 for a final price of $1,550,000. This would reduce the burden on State Parks and the Kartchners would retain some tax benefit. Representative Larry Hawke had suggested the previous November that the park be named after James and Lois Kartchner and Campbell passed this suggestion on at this time. Campbell sought and was given approval by the Nature Conservancy executive staff to offer the Conservancy's assistance as an intermediate buyer until the State Parks had the necessary funds.

Travous then started contacting key legislators on a one-to-one basis, garnering support for a bill that would authorize funds for purchase of Secret Cave. Senator John Hays, who had visited the cave in 1986, introduced Senate Bill 1188 in January 1988. This bill created an Acquisition and Development Fund, out of which future Arizona state parks would be acquired and developed. The "JAK" property would be the first acquired.

Also in January 1988, Gary Tenen, Randy Tufts and Bob Buecher filed the charter for a new organization called Arizona Conservation Projects, Inc. This non-profit organization was formed to continue as an advocate for the continued protection of the cave and to educate the public about the value of the cave.

After much work, many meetings with legislators to explain and expand on ideas and much more behind-the-scenes arranging, on April 27, 1988, Senate Bill 1188 was

passed by the Senate, the House and taken up to Governor Rose Mofford to sign. It became law immediately and the James and Lois Kartchner Caverns State Park became a reality.

Figure 4. James D. Kartchner and his son Fred in Kartchner Caverns. The elder Mr. Kartchner was in his late 70's at the time.

Figure 5. The Kartchner family after a trip to the back of the cave.

SURFACE CLIMATE STUDY

INTRODUCTION

The goal of climatological monitoring is to provide a record of those external climate variations which affect the microenvironment within the cave and which are frequently the driving force behind such changes. Correlations between surface and subsurface climate data have been sought to identify the major external influences on the cave climate. This study has been divided into two sections: the determination of general surface weather conditions on the park and a detailed assessment of the microclimate within the cave.

RESULTS OF SURFACE CLIMATE MONITORING

The program of surface climate monitoring was initially outlined by Ozark Underground Laboratory (OUL), with instrument installation, maintenance and data collection performed by ACPI. Additional measurements have been incorporated by ACPI as part of the quality control program. Analysis and interpretation of the collected climatological data has been performed by ACPI.

With the approval of the climate monitoring plan, ACPI installed a surface weather station located approximately 550 feet southeast of the natural entrance and 100 feet east of the administrative site at an elevation of 4646 feet (Figure 6). A thermograph, hygrograph and microbarograph were placed in an instrument shelter. A recording rain gauge was also installed near the weather station. Each of these instruments records data on a chart which is changed on a weekly basis. The accuracy levels for these instruments is in accordance with National Weather Service specifications. Surface climate data has been collected continuously from June 1989 to June 1991. A summary of the data collected is presented in Appendix A and Table 1 shows a capsulation of the data. Continued operation of the weather station is now being performed by Arizona State Parks personnel.

Surface Temperatures. Air temperatures have been measured since June 1989 with a recording thermograph. During this period, the highest temperature has been 109.5°F on June 26, 1990. The lowest recorded temperature has been 19°F on February 15, 1990. The daily mean temperature fluctuates from a high of 95.5°F to a low of 27.4°F, which is a range of 68°F. The mean surface temperature measured over the 24-month study period is 62.4°F. Figure 7 shows a graphical representation of the daily high, low and mean temperatures.

Precipitation. In one form or another, precipitation is the source of all of the water which appears in the cave. This water may enter the cave by direct percolation from the surface or by infiltration from adjacent washes. A knowledge of the precipitation received at the park is essential to understanding the cave moisture balance. Daily precipitation has been measured at the park since August 1988 by State Parks. In May 1989, a weighing rain gauge with a chart recorder was installed by ACPI. Figure 8 shows a graphical representation of the monthly precipitation.

Relative Humidity. In June 1989, a recording hygrothermograph was installed by ACPI at the park. Due to difficulties during installation, the hygrothermograph was not operational until July 1989. The monthly average relative humidity fluctuates between a low of 28% and a high of 63%. The mean relative humidity for the 23 months of record is 45.9%. Figure 9 shows the daily mean relative humidity for the park. The amount of moisture contained in the surface air can be determined from the relative humidity and temperature. The difference between the moisture content of surface

and cave air is a measure of the potential for drying out the cave by enhanced airflow. Figure 10 is a plot of the surface daily air moisture content determined from the relative humidity and temperature. As can be seen on this graph, the mean daily moisture content of the surface air was always less than that of the cave.

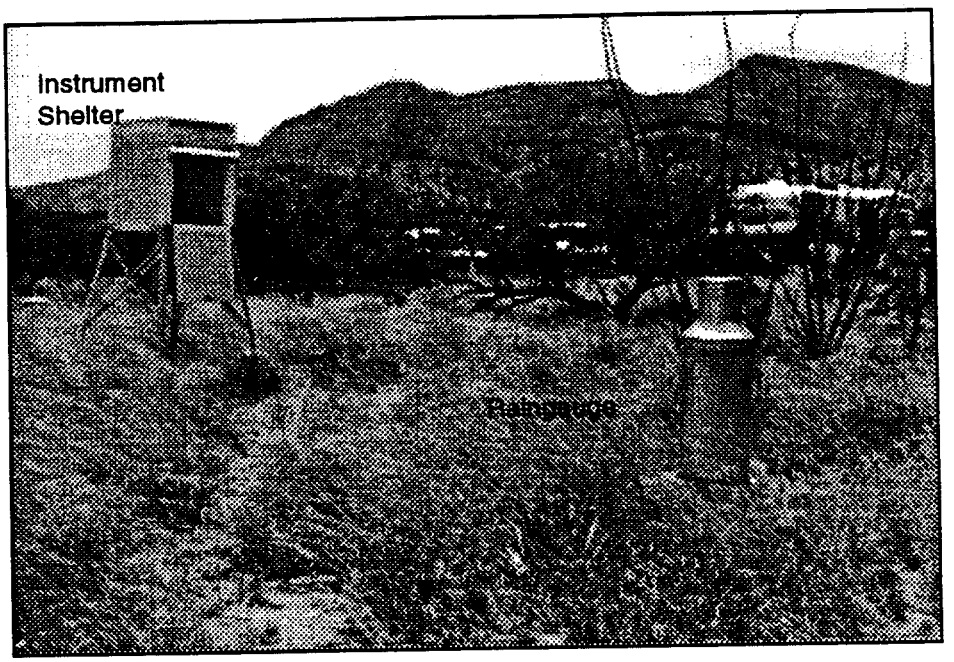


Figure 6. Surface weather station: recording rain gauge, hygrothermograph and microbarograph.

FIGURE 7

Kartchner Caverns State Park

Surface Daily Maximum, Minimum and Mean Temperatures

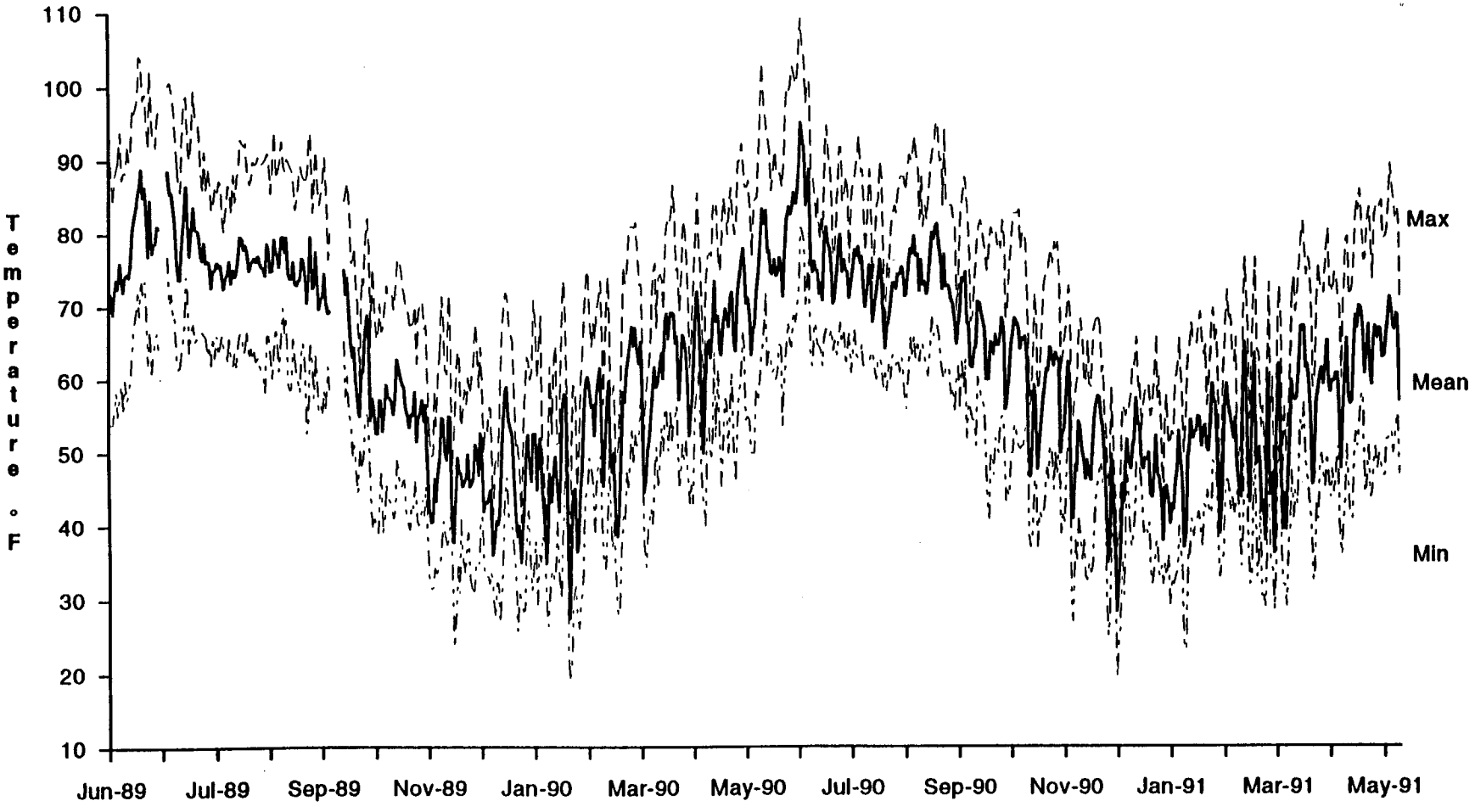


FIGURE 8

Kartchner Caverns State Park
Monthly Precipitation

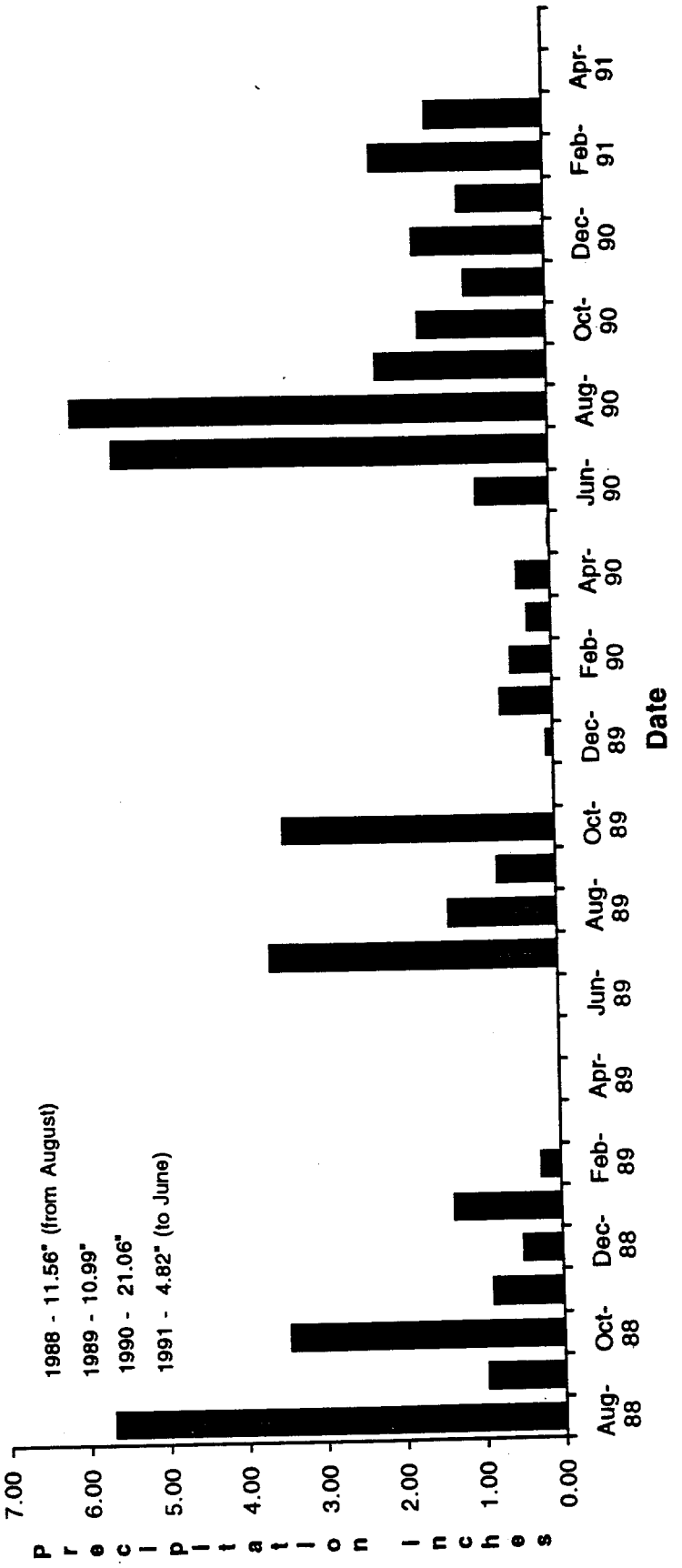


FIGURE 9
Kartchner Caverns State Park
Surface Daily Mean Relative Humidity

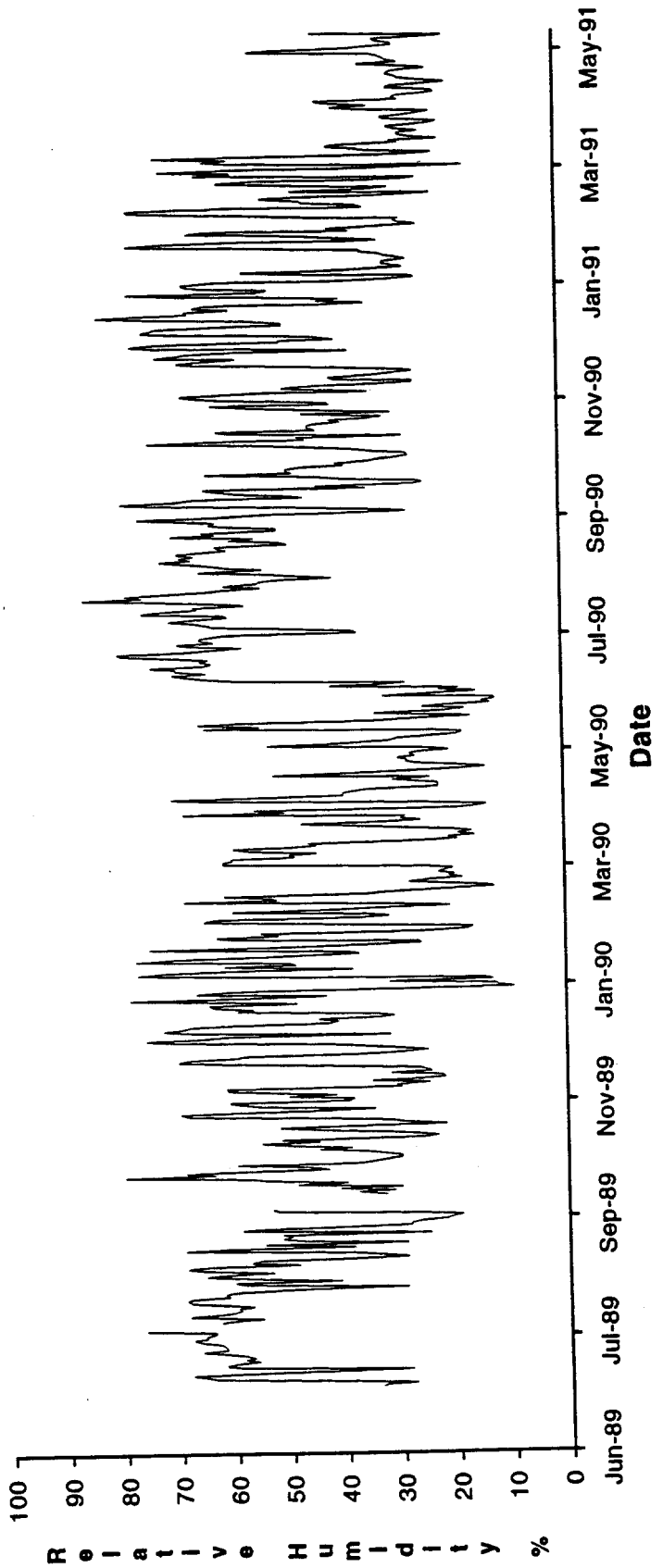


FIGURE 10
Kartchner Caverns State Park
Surface Daily Air Moisture Content

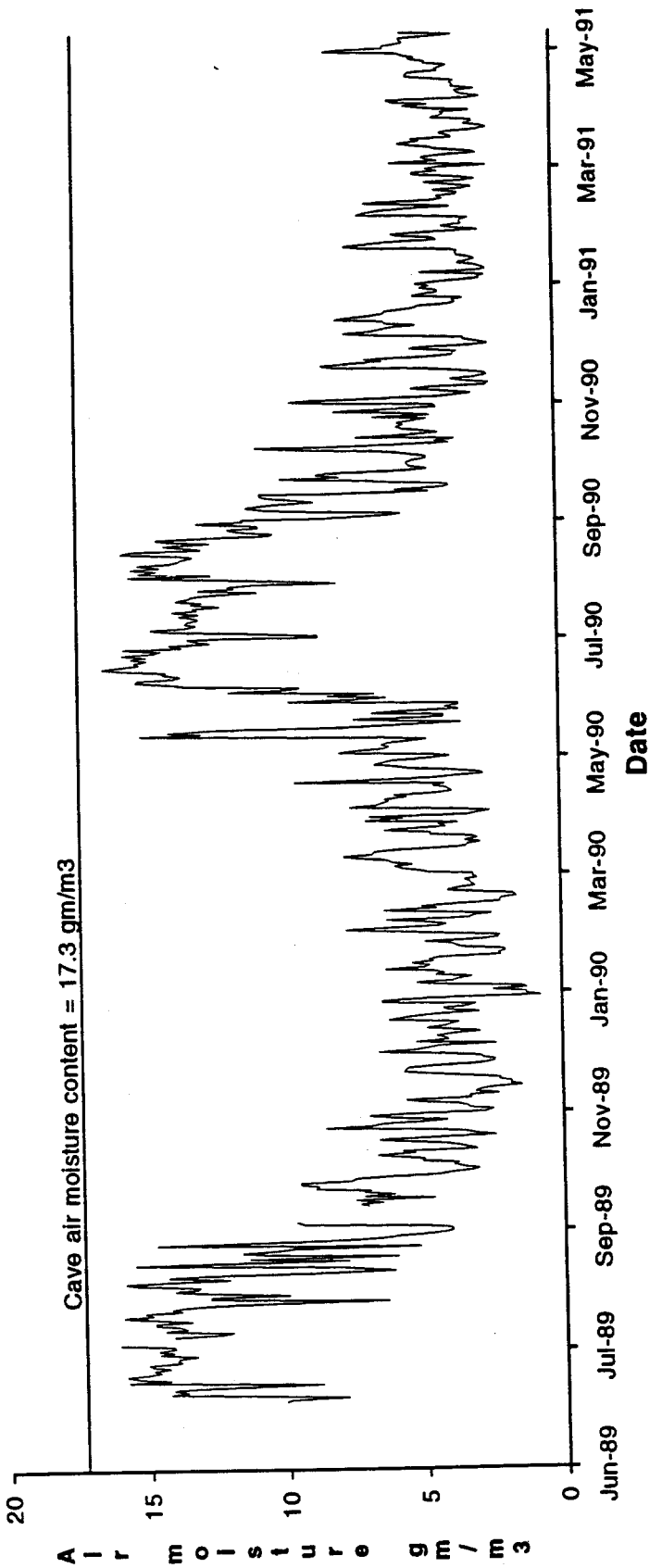


TABLE 1
Surface Temperature and Relative Humidity

MONTH	Mean Temp. (°F)	Mean RH (%)	Air Moisture (gm/m^3)	Precip. (inches)	Barometric Pressure (Mb)
Jun-89	78.3	-	-	0.00	858.0
Jul-89	79.3	56	13.2	3.65	859.9
Aug-89	76.0	60	13.4	1.38	858.7
Sep-89	75.1	44	9.8	0.75	859.0
Oct-89	63.3	45	6.7	3.46	860.5
Nov-89	55.0	43	4.8	0.02	859.9
Dec-89	47.6	43	3.7	0.10	859.2
Jan-90	46.7	47	3.8	0.67	858.7
Feb-90	46.9	49	4.1	0.53	858.2
Mar-90	55.1	36	3.8	0.31	857.5
Apr-90	62.8	36	4.9	0.44	856.9
May-90	67.5	33	5.5	0.03	856.5
Jun-90	81.2	28	7.2	0.94	858.1
Jul-90	76.0	63	13.8	5.54	859.7
Aug-90	73.1	63	12.8	6.05	860.7
Sep-90	73.1	59	12.0	2.18	859.8
Oct-90	65.0	45	7.0	1.64	861.0
Nov-90	55.5	48	5.6	1.04	860.6
Dec-90	46.9	53	4.5	1.69	860.1
Jan-91	46.9	54	4.6	1.11	860.5
Feb-91	52.7	43	4.4	2.21	860.7
Mar-91	49.8	46	4.1	1.50	857.3
Apr-91	59.1	30	3.9	0.00	857.3
May-91	65.3	30	4.8	0.00	856.9

Atmospheric Pressure Changes. In all large caves, changes in barometric pressure influence the rates of air exchange with the surface. During periods of rapid atmospheric pressure change, air will be either expelled or drawn into the cave. The amount of air exchange will be determined by the size of the pressure change, the volume of the cave and itsentrance geometry. Changes in barometric pressure have been shown to produce substantial air exchange in some caves. This is usually the case for very large caves which have a single small entrance. In these cases, the cave acts as a closed container with a small opening to the general atmosphere. When the outside pressure is falling, then air pressure inside the cave will be slightly higher and force air out of the cave. When the atmospheric pressure is rising, outside pressure is higher than in the cave and air blows into the cave. Theoretically, the amount of air exchanged is only enough to balance the pressure difference between the cave and the surface air.

There is a natural daily cycle of barometric pressure change. Barometric pressure is usually higher in the morning and lower at night. The daily cycle is superimposed on the pattern of air exchange from the cave.

There is also a general correlation between barometric changes and moisture content of the air exchanged. High barometric pressure is usually associated with cool, dry air. Low barometric pressure is associated with storms where the moisture content can be quite high. Because of these weather patterns the cave is more likely to draw in cool, dry air and to exhale when outside moisture content is highest.

The mean barometric pressure at the weather station is 859.0 Millibars (Mb), with a high of 870.7 Mb on 11/29/90 and a low of 846.1 Mb on 2/14/90. This is a range of 24.6 Mb (2.9%) over the 24-month study period. The measured mean barometric pressure (859.0 Mb) agrees well with the anticipated barometric pressure of 854.3 Mb based on the elevation of the weather station.

In order to determine the relative contribution of the barometric changes to the air exchange of Kartchner Caverns, a series of the microbarograph charts were analyzed in detail. For each chart, the pressure trace was digitized and the total rise and total fall in atmospheric pressure were determined for each chart. A total of 183.5 days of data were examined in this way. The average daily total rise and fall in pressure is 4.9 Mb.

The average atmospheric pressure at the cave is 856 Mb. A daily change of 4.9 Mb would exchange 4.9/856 = 0.0057 of the cave's total air volume or approximately 31,500 cubic feet per day. If the exchanged air was completely mixed with the air in the cave, it would take 175 days to completely change the air in the cave by barometric pressure fluctuations alone. The observed barometric pressure fluctuations are capable of producing no more than 2 complete air exchanges in a year.

Comparison With Other Surface Weather Stations

The climatological study at Kartchner Caverns State Park is primarily based on the 24 months of data collected at the park. In order to insure that the collected data is truly representative of the long-term conditions and does not reflect a local bias, a comparison has been made with two adjacent surface weather stations (Table 2) (Sellers and Hill, 1974).

Based on a comparison with Tombstone and Sierra Vista surface weather stations, the long-term mean surface temperature is estimated to be 62.7°F at the park. This agrees well with the mean temperature measured at the park of 62.4°F.

The precipitation record for this period was also compared with the Tombstone and Sierra Vista weather stations to determine the probable long-term average precipitation. It is estimated that the average precipitation at the park would be approximately 16.5" per year. This compares well with the average of 15" per year for the 24 months of study.

Surface Climate Monitoring Recommendations

This study has shown that surface climate exerts a strong influence over the microclimate of the cave. The surface monitoring of temperature, relative humidity, barometric pressure and precipitation should continue. It may be worthwhile to replace the existing instruments, which are all chart operated, with a computerized weather station. Such a station should also include wind direction and speed.

TABLE 2
Kartchner Caverns State Park Climate
Estimate from Adjacent Weather Stations

Month	Nearby Weather Stations				Mean Temperature (°F) Kartchner SP Estimated From		Measured Kartchner SP 24 mo. Avg.	Average Precipitation Kartchner SP Estimated From		Measured Kartchner SP 34 mo. Avg.
	Sierra Vista		Tombstone							
	Mean	Precip	Mean	Precip	Sierra Vista	Tombstone		Sierra Vista	Tombstone	
Jan	46.3	1.10	47.3	0.84	47.3	47.4	46.8	1.02	1.06	1.05
Feb	48.8	0.96	50.0	0.77	49.7	49.9	49.8	0.86	0.98	1.00
Mar	53.8	0.66	54.4	0.66	54.5	54.2	52.9	0.53	0.85	0.60
Apr	60.3	0.28	61.5	0.24	60.6	61.0	60.9	0.12	0.36	0.15
May	67.5	0.24	69.2	0.20	67.4	68.3	66.4	0.07	0.31	0.01
Jun	76.8	0.52	78.2	0.47	76.3	76.9	79.7	0.38	0.63	0.47
Jly	77.3	3.86	79.3	3.62	76.7	77.9	77.7	4.04	4.32	4.60
Aug	75.3	3.47	77.1	3.38	74.9	75.8	74.5	3.62	4.04	4.38
Sep	72.2	1.73	74.1	1.48	71.9	72.9	74.1	1.71	1.81	1.30
Oct	64.1	0.87	65.4	0.73	64.2	64.7	64.1	0.76	0.93	2.86
Nov	53.6	0.62	55.0	0.61	54.2	54.7	55.3	0.49	0.79	0.65
Dec	47.1	1.08	47.8	0.86	48.1	47.9	47.3	0.99	1.09	0.77
Ave.	**61.9**	**15.39**	**63.2**	**13.86**	**62.2**	**62.6**	**62.5**	**14.59**	**17.18**	**17.84**

CAVE ENVIRONMENTAL MONITORING PROGRAM

GOALS AND APPROACH OF MICROCLIMATE STUDIES

In order to anticipate the likely impacts of developing the cave on the microclimate of the cave, we must first understand the basic processes which influence the microclimate. The cave environmental monitoring system is designed to provide data necessary for determining the nature and magnitude of microclimate changes which will likely result from the development of the cave and the construction of one or more man-made entrances. Understanding how the cave microclimate currently operates will aid in the selection of sites for the man-made entrance(s) so as to minimize the impact on the cave features.

The cave as a whole can be considered to be an essentially closed system. In this study we will consider the whole cave as a single unit that can be adequately described by the volume, surface area, average moisture flux, etc. If we look at what moves in and out of the cave; i.e.,moisture, air and heat, these quantities must be in balance in order for the cave to be in equilibrium with its surroundings. The amount of heat, moisture and air entering the cave must equal the amount leaving. Furthermore, these numbers must be mutually consistent. The amount of heat and moisture carried by the air must be consistent with the observed quantity of airflow. This consistency provides a powerful cross check on the estimated values for these quantities. Also it must be remembered that these values can be only approximately estimated. By considering several dependent parameters, it is possible to obtain several independent estimates. For instance, the concentrations of water vapor as measured by relative humidity, carbon dioxide gas and radon gas are all dependent upon the rate of ventilation. By studying each of these, we can determine independently what the ventilation rate for the cave is. A comparison of the various estimates provides an additional degree of confidence in the results obtained.

From the data collected, an approximate moisture balance, air exchange rate and overall heat balance of the cave will be determined. With this information, it will be possible to make intelligent inferences about the effect that development will have on the cave microclimate.

The program of environmental monitoring was initially outlined by the Ozark Underground Laboratory (OUL) with instrument installation, maintenance and data collection performed by ACPI. Approaches suggested by OUL have been modified by ACPI as necessary in order to obtain more reliable data The design of the study was based on several generalizations about the cave microclimate based on studies of other caves and a few basic observations made in Kartchner Caverns (Moore and Sullivan, 1978; Tuttle and Stevenson, 1977; Geiger, 1957).

- The temperature is relatively constant, with an annual variation of only a few degrees at most. Temperature should be close to the mean surface temperature.
- The relative humidity is very high, approaching 100% in all parts of the cave.
- Air flow is observed in the entrance passages and River Passage, occasionally in other areas.
- The cave is moist but not wet. Except for areas adjacent to the entrance, all areas are moist but there are no permanent pools of water.
- Carbon dioxide levels are 5 to 30 times higher than in surface air.
- Radon and radon daughters are likely to be present in relatively high concentrations compared to surface air.

The microclimate studies at Kartchner Caverns are designed to measure the following parameters:

- Air Temperature
- Soil Temperature
- Relative Humidity
- Evaporation Rates
- Air Trace Gases
- Airflow

ACPI installed a total of 22 environmental monitoring stations (EMS) distributed throughout the cave. The locations were selected after consultation with Tom Aley of OUL. The majority of these stations are placed in pairs. One is located as close as is practically possible to the location of a potential entrance study site. The second station is located approximately one hundred or more feet deeper into the cave and acts as a reference station. The distribution of the monitoring stations is not uniform nor was the original intent of the system to provide uniform coverage of the interior portions of the cave. These stations have been placed so that the existing and future impact of an entrance or proposed entrance on the microclimate of the cave could be assessed. The location of each monitoring station is shown in Figure 11.

The equipment placed at each EMS included: a 9" diameter water evaporation pan (surface area 382 cm^2) with a drip shield, a PVC pipe stand to hold thermometers, an air temperature sensor and a soil temperature sensor. In the back portions of the cave, temperatures are also measured with a digital thermometer which stores the high and low temperatures. In the front of the cave, each EMS is wired into a computer datalogger which records a wet bulb, dry bulb and soil temperature each hour.

Approximately once a month, each station is visited and additional independent air, soil and water temperatures are taken with a portable thermometer. The volume of water lost by evaporation is also measured at this time. Other measurements of relative humidity, alpha radiation levels and carbon dioxide are usually taken at the same time. A summary of the measurements is given in Table 3 and more complete summaries may be found in Appendix D.

AUTOMATED DATA COLLECTION SYSTEMS

In addition to the monthly manual temperature measurements taken at each monitoring station, two computer systems collect and record temperatures on an hourly basis. Gathering temperature data by computerized dataloggers has the following advantages:

- More measurements can be taken.
- Simultaneous measurements can be taken at different locations.
- Probes have come to equilibrium.
- There is no interference from the presence of the observer.
- Readings can be taken without disturbing bats.

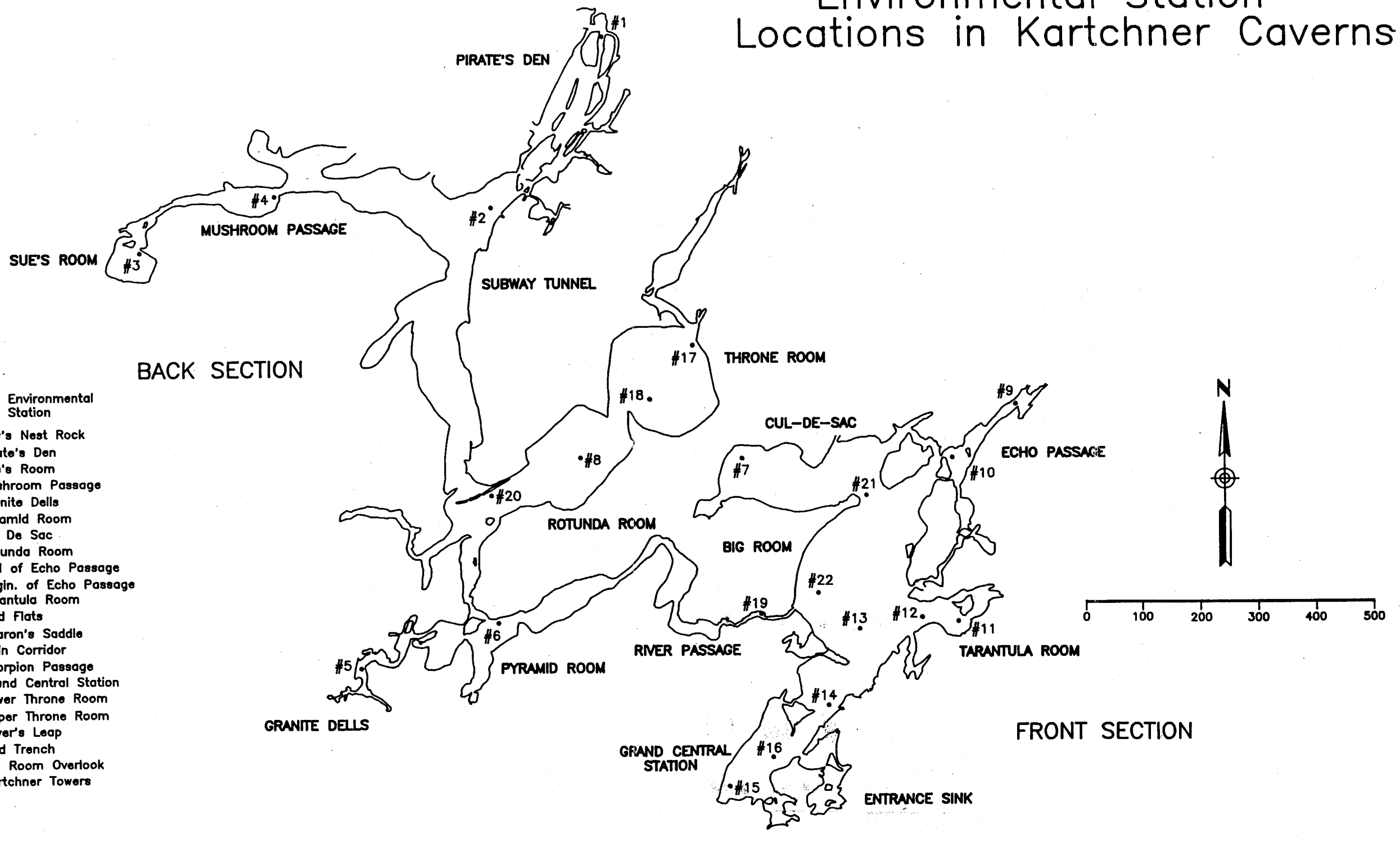
Two separate computer systems have been installed in Kartchner Caverns. Selection of equipment, identification of sites, installation, data collection and maintenance was performed by ACPI. In March 1989, a datalogger and seven temperature probes were installed in the entrance passages. Two of the probes measure unventilated wet bulb temperatures. These allow an estimate of relative humidity to be made. Figure 12 shows the location of the datalogger and associated temperature probes. Figures 13 and 14 display the average daily temperature and relative humidity at the T1 and T2 probes in the LEM Room. These probes are located

approximately 100 feet into the cave. As can be seen from the graph, the annual temperature varies by only 8°F at this location. The relative humidity shows the influence of dry air entering the cave during winter months.

A second, more elaborate computer datalogger system was installed in the Big Room in May 1989. Initially, this system had 30 temperature probes. Figure 15 shows the system layout. Three temperature probes were connected to each of the ten environmental monitoring stations around the Big Room. At each station, these probes measure air temperature, wet bulb temperature and soil temperature . The initial system measured temperatures with a resolution of 0.5°F. In October and December 1989, the system was expanded to 40 probes and the temperature resolution increased to 0.1°F. In June 1990, two additional probes were added to measure temperatures at bat roosts. Figures 16 and 17 illustrate the average daily temperatures measured at two stations. Annual temperatures vary by approximately 1°F per year at these stations, which are located approximately 500 feet from the entrance. It is interesting to note that these stations indicate that the Big Room is coldest in May and June and warmest in November and December.

FIGURE 11

Environmental Station Locations in Kartchner Caverns



• #3 Environmental Station

1 Crow's Nest Rock
2 Pirate's Den
3 Sue's Room
4 Mushroom Passage
5 Granite Dells
6 Pyramid Room
7 Cul De Sac
8 Rotunda Room
9 End of Echo Passage
10 Begin. of Echo Passage
11 Tarantula Room
12 Mud Flats
13 Sharon's Saddle
14 Main Corridor
15 Scorpion Passage
16 Grand Central Station
17 Lower Throne Room
18 Upper Throne Room
19 Lover's Leap
20 Mud Trench
21 Big Room Overlook
22 Kartchner Towers

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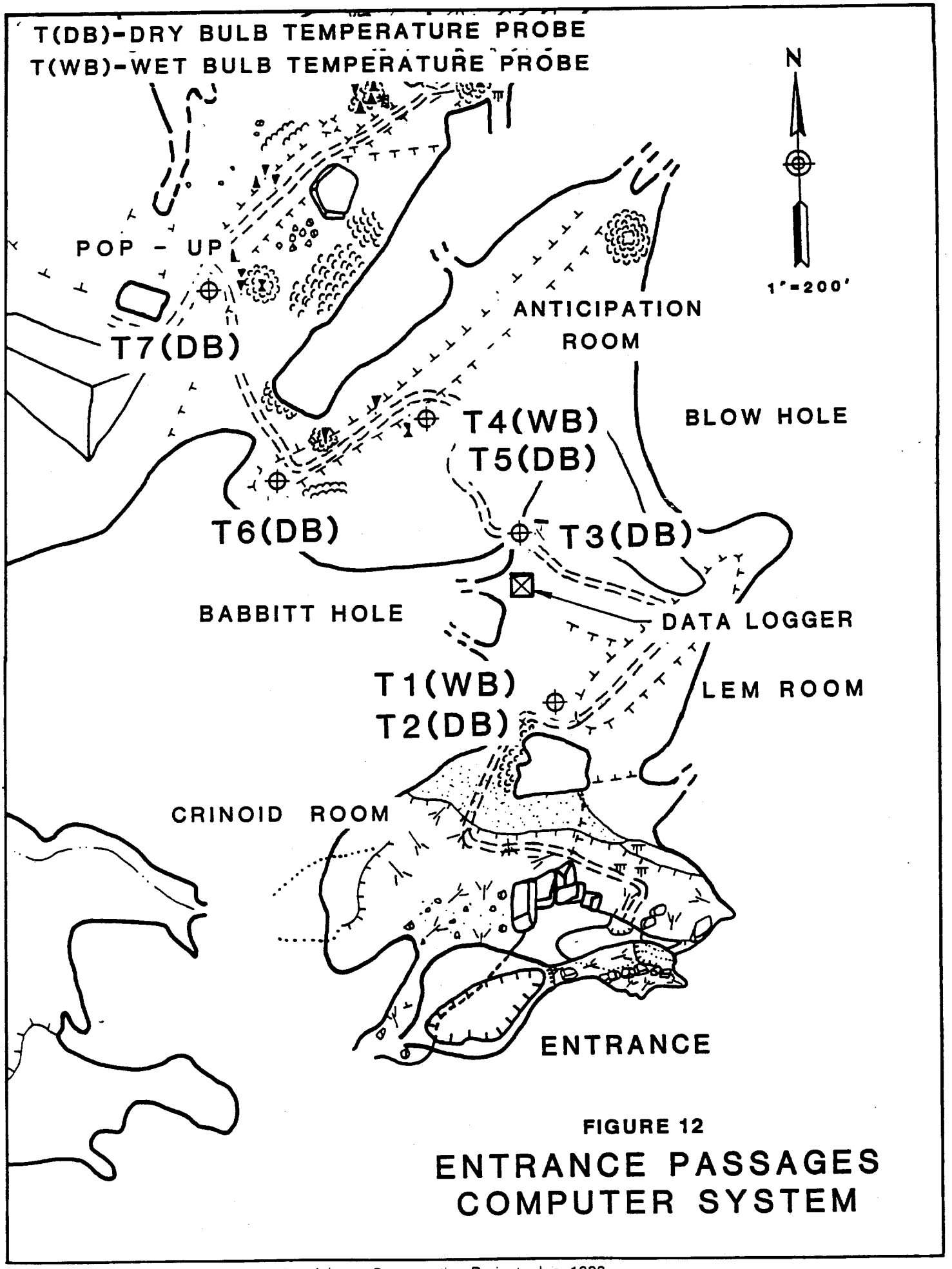


FIGURE 12

ENTRANCE PASSAGES COMPUTER SYSTEM

FIGURE 13

LEM Room Daily Temperatures Probe T2

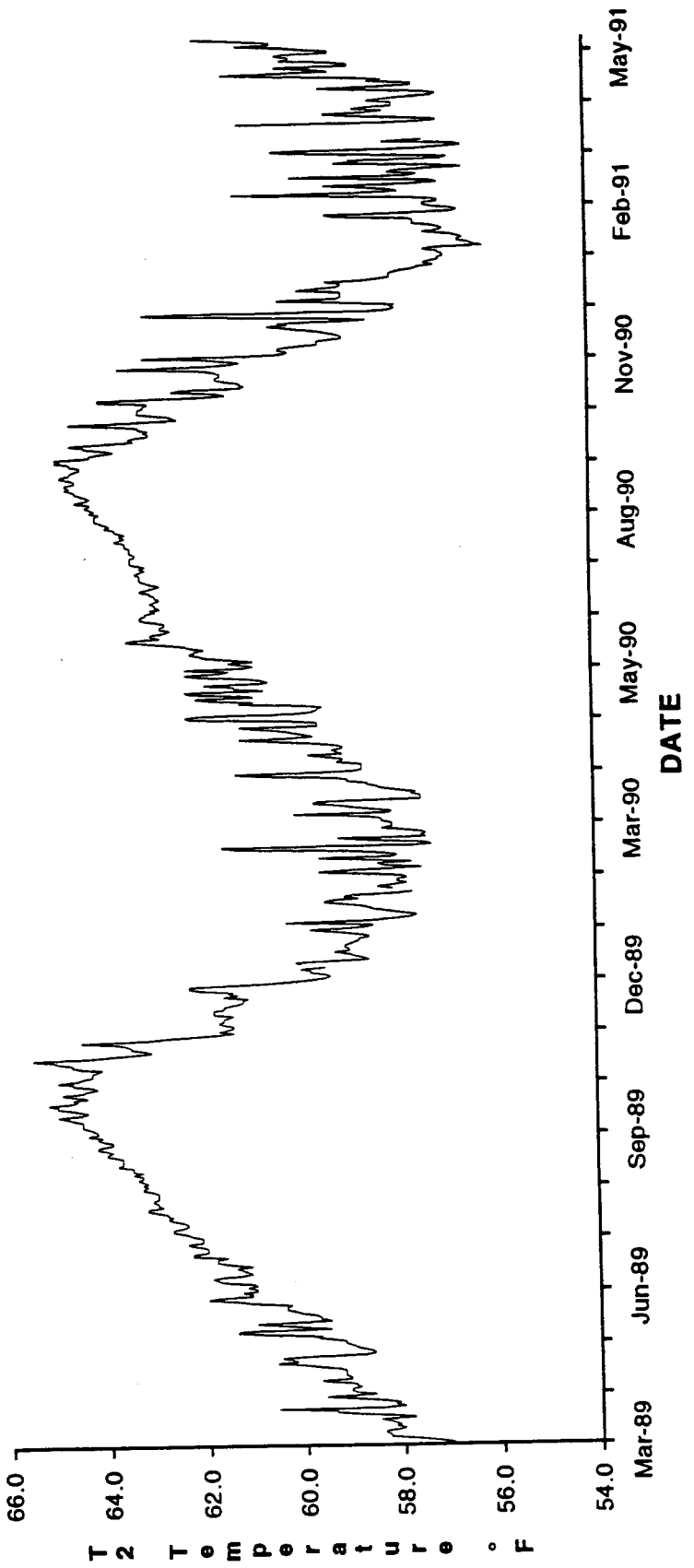
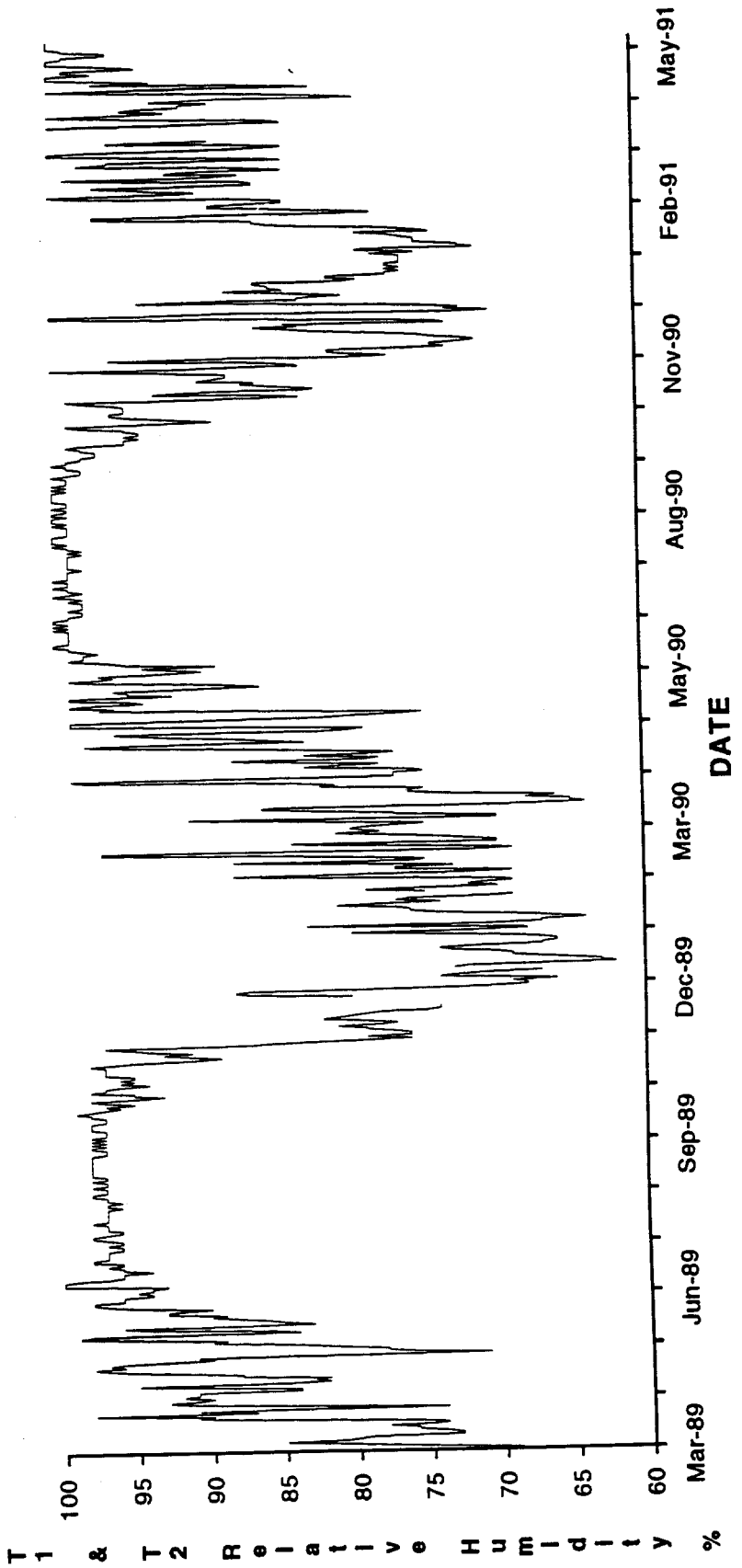
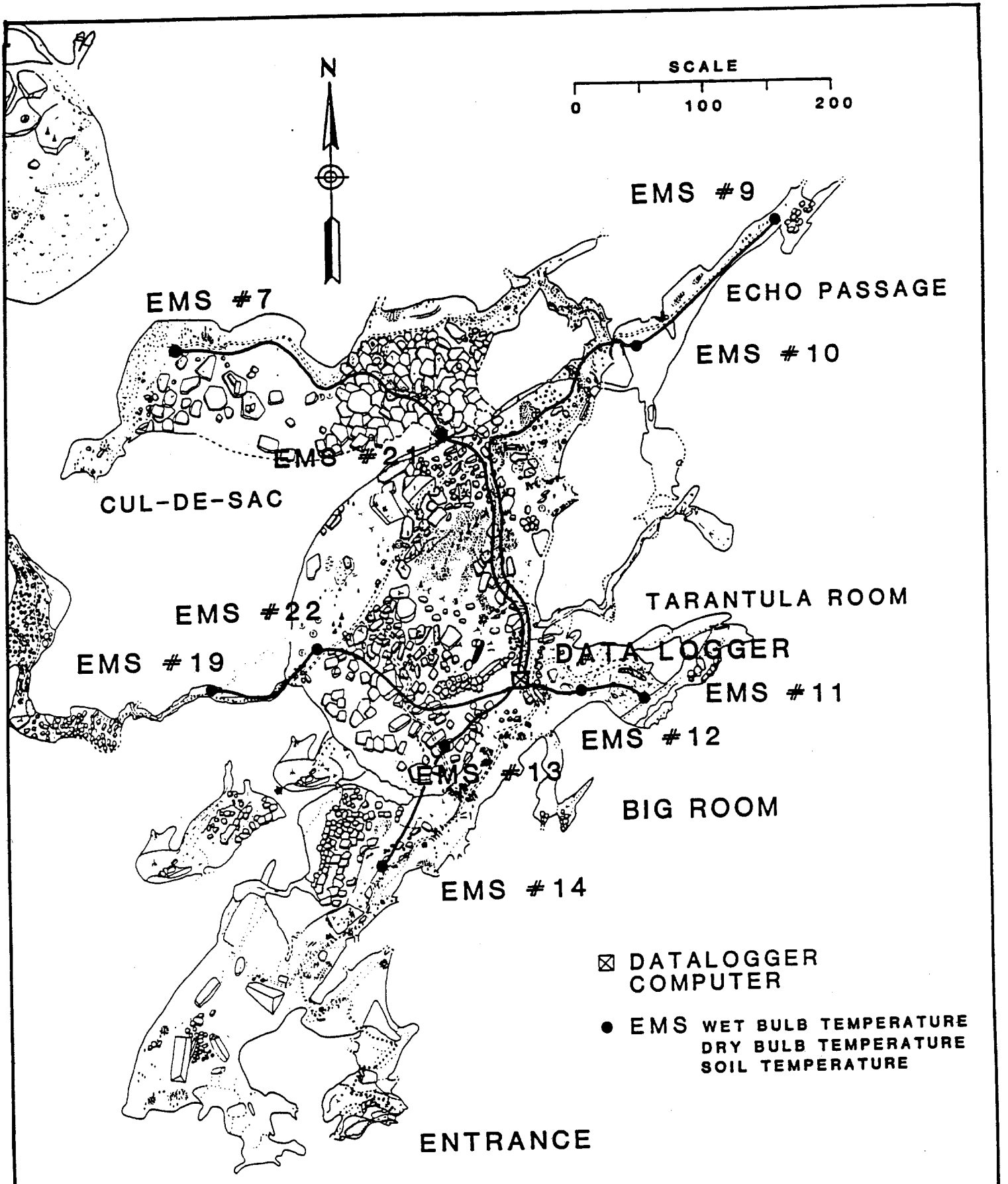


FIGURE 14

LEM Room Daily Relative Humidity Probes T1 & T2





BIG ROOM COMPUTER SYSTEM

FIGURE 15

FIGURE 16
Sharon's Saddle - EMS #13
Daily Air Temperature and Pan Evaporation Rate

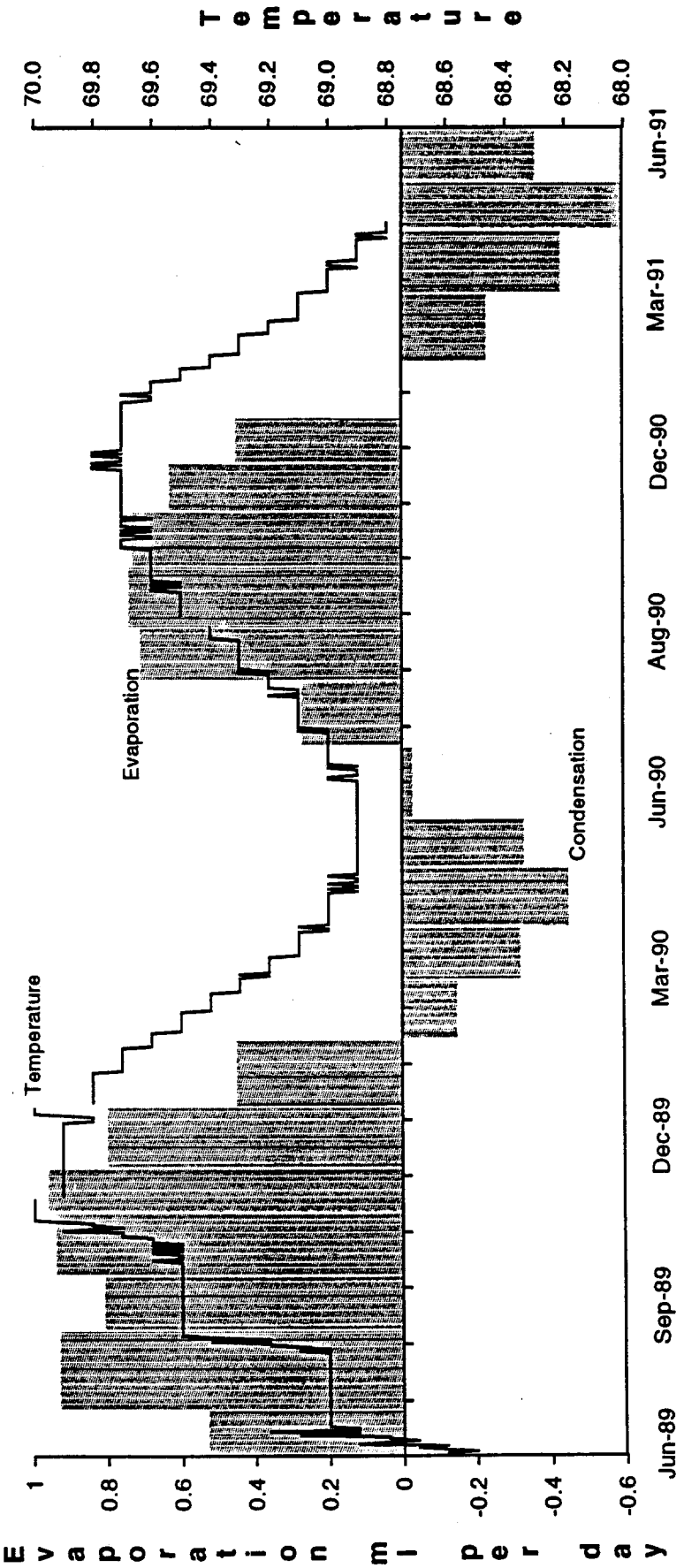


FIGURE 17

Tarantula Room - EMS #11
Daily Air Temperature and Pan Evaporation Rate

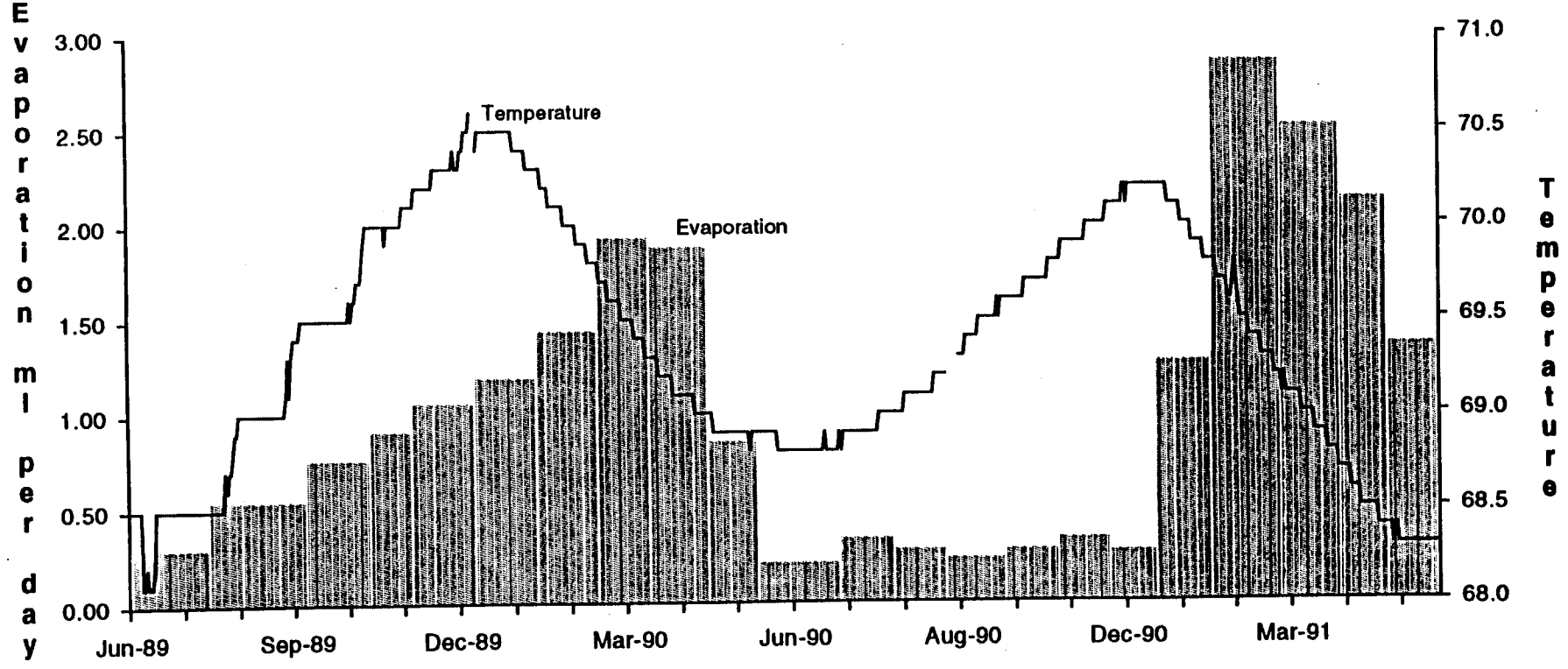


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TABLE 3
KARTCHNER CAVERNS STATE PARK
Environmental Station Data June 1989-May 1991
(For Stations 1,2,3,4,6 and 20, June 1989-Aug 1990)

STATION		EVAPORATION (ml/day)	TEMPERATURES WATER	AIR	SOIL	RH (%)
1-Crow's Nest Rock	Averages	0.23	65.4	65.7	65.8	99.07
	Standard Deviations	0.15	0.43	0.39	0.48	0.76
2-Pirate's Den	Averages	0.27	65.3	65.6	65.5	99.19
	Standard Deviations	0.19	0.16	0.23	0.30	0.71
3-Sue's Room	Averages	0.08	68.2	68.4	68.4	99.38
	Standard Deviations	0.03	0.20	0.26	0.32	0.57
4-Mushroom Passage	Averages	0.64	66.7	67.3	67.2	99.38
	Standard Deviations	0.28	0.25	0.42	0.57	0.64
5-Granite Dells	Averages	0.17	65.6	66.0	65.9	99.28
	Standard Deviations	0.12	0.32	0.46	0.64	0.51
6-Pyramid Room	Averages	0.22	67.0	67.2	67.1	99.27
	Standard Deviations	0.08	0.52	0.48	0.38	0.80
7-Cul-de-Sac	Averages	0.08	69.0	69.2	69.2	99.52
	Standard Deviations	0.06	0.13	0.22	0.30	0.45
8-Rotunda Room	Averages	0.22	67.6	67.6	67.8	99.48
	Standard Deviations	0.08	0.18	0.24	0.32	0.52
9-End Echo Passage	Averages	0.07	68.8	69.1	68.9	99.30
	Standard Deviations	0.04	0.13	0.21	0.12	0.56
10-Begin Echo Passage	Averages	0.12	68.8	69.0	68.9	99.38
	Standard Deviations	0.11	0.27	0.27	0.30	0.52
11-Tarantula Room	Averages	1.04	68.8	69.2	69.2	98.43
	Standard Deviations	0.80	0.68	0.65	0.63	0.91
12-Mud Flats	Averages	0.36	68.4	68.4	68.5	99.15
	Standard Deviations	0.38	0.39	0.48	0.35	0.58
13-Sharon's Saddle	Averages	0.26	68.8	69.0	68.9	99.3
	Standard Deviations	0.53	0.52	0.48	0.50	0.68
14-Main Corridor	Averages	0.68	67.8	67.9	67.8	98.8
	Standard Deviations	0.76	0.52	0.57	0.55	1.67
15-Scorpion Passages	Averages	0.58	65.9	66.1	66.2	98.8
	Standard Deviations	0.51	0.44	0.44	0.38	1.18
16-Grand Central Station	Averages	1.81	65.4	65.8	65.6	97.0
	Standard Deviations	1.65	0.86	0.64	0.81	3.80
17-Lower Throne Room	Averages	0.34	67.3	67.4	67.4	99.4
	Standard Deviations	0.07	0.22	0.22	0.23	0.51
18-Throne Rm. Overlook	Averages	0.09	67.5	67.7	67.8	99.55
	Standard Deviations	0.04	0.15	0.23	0.28	0.40
19-Lover's Leap	Averages	0.05	68.3	68.7	68.6	99.50
	Standard Deviations	0.21	0.27	0.40	0.36	0.50
20-Mud Trench	Averages	0.14	66.9	67.3	67.1	99.33
	Standard Deviations	0.06	0.25	0.30	0.22	0.69
21-Big Room Overlook	Averages	0.18	69.3	69.6	69.7	99.39
	Standard Deviations	0.11	0.29	0.37	0.41	0.69
22-Kartchner Towers	Averages	0.35	68.9	69.1	69.0	99.30
	Standard Deviations	0.13	0.39	0.45	0.43	0.67
Whole Cave Average		0.36	67.53	67.79	67.75	99.15
Average without Stations	5,14,15,16	0.22	67.86	68.08	68.05	99.30

IMPORTANCE OF MONITORING RELATIVE HUMIDITY

The moisture content of the air within the cave can become a critical management issue. At the present time, evaporation from cave surfaces is the major source of moisture in the air. The rate of evaporation within the cave is largely determined by the relative humidity of the air. It is important to understand that it is the difference in relative humidity from 100% which determines the amount of evaporation. If the relative humidity changes from 99.5% to 99.0%, the evaporation rate will double! This means that very small changes in the relative humidity could have major impacts on the moist conditions in the cave.

RELATIVE HUMIDITY

Relative humidity (RH) is a measure of the amount of moisture contained in the air compared to the maximum amount of moisture that the air could hold at a given temperature. Most caves have high relative humidities, often approaching 100%. At 100% relative humidity, the air contains the maximum amount of moisture and is said to be saturated. Any change in temperature will also change the amount of moisture which can be contained in the air. The amount of moisture contained in a volume of air can be computed from the relative humidity and temperature (Zimmerman and Lavine, 1964; List, 1951; Linsley, et al, 1982).

The method proposed by OUL for the collection of relative humidity measurements with hand-held thermometers has a maximum accuracy of ±0.7% RH at the high humidity levels typically found in the cave. Our experience has shown that this method is not accurate enough to determine the variations in relative humidity throughout the cave, the relative humidities almost invariably turn out to be 100%. Without better accuracy the relative humidity measurements merely confirm a very high relative humidity without giving sufficient accuracy to allow correlations to be made with other measurements. In order to obtain meaningful results, ACPI researched equipment capable of measuring high relative humidity with the required precision.

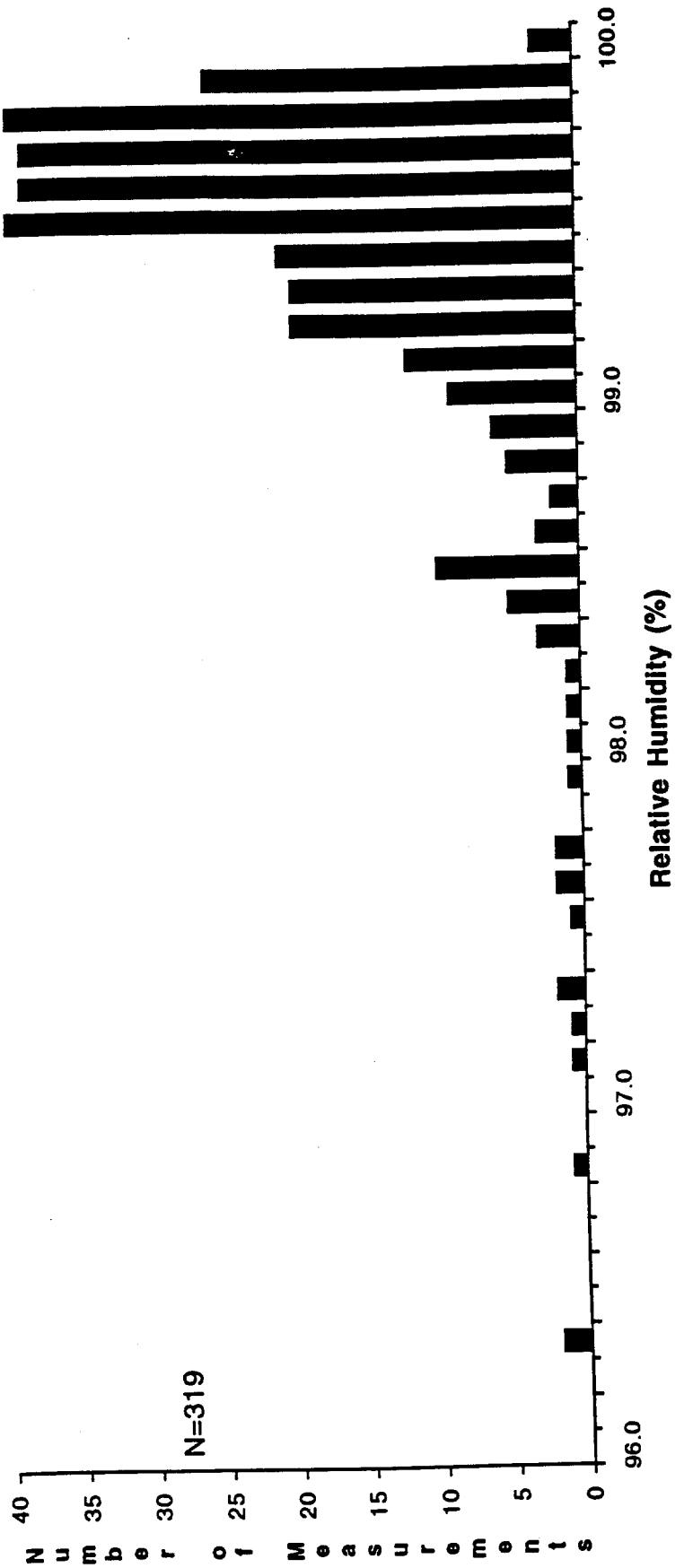
Precise relative humidity has been measured with a dewpoint microvoltmeter at each of the monitoring locations. This instrument is capable of measuring the relative humidity and dewpoint temperature with great precision. The dewpoint microvoltmeter purchased by ACPI has a typical accuracy of 0.05%. A total of 318 measurements were taken throughout the cave with the dewpoint meter. The relative humidity of these measurements range from 96.32% to 100.00% RH. Figure 18 illustrates the distribution of measured precise relative humidities throughout the cave. The average relative humidity for all measurements is 99.42% but is highly skewed toward the higher values.

Measurement of relative humidity is also an indication of the rate of evaporation. Evaporation rates within the cave should be inversely proportional to the relative humidity; i.e. the higher the relative humidity, the less evaporation. At a uniform 100% relative humidity, there would be no evaporation. Because the measured relative humidity levels are quite close to 100%, the evaporation rate is expected to be quite small.

High relative humidity also means that only a very small drop in air temperature is needed to condense water out of the air. For the majority of conditions observed within the cave, a temperature drop of 0.05°F would bring the air to saturation and any additional cooling of the air would cause condensation to occur. A rise in air temperature would have the opposite effect, that of lowering the relative humidity and increasing the evaporation rate. A rise in air temperature of 1°F with no addition of

FIGURE 18

Distribution of Precise Relative Humidity Measurements



moisture would lower the relative humidity from 100% to 96.6%. In a cave with little ventilation, the lower humidity would increase evaporation which would quickly bring the relative humidity back to 100%. However, if the temperature rise were due to a steady supply of warm outside air entering the cave, the evaporation would increase by a factor of 7 over the existing conditions.

EVAPORATION

A significant amount of moisture is lost from the cave by evaporation and subsequent air exchange with the surface (McLean, 1971, 1976). Outside air which enters the cave always contains less moisture than air in the cave. As a result, outside air entering the cave will evaporate moisture off cave surfaces, thus drying out the cave. Moisture lost from the cave by evaporation and air exchange is a significant portion of the overall water balance of the cave. It is also the only mechanism over which we have much direct management control.

Evaporation rates have been measured at each of the 22 environmental monitoring stations on a monthly basis and at a number of other locations adjacent to the natural entrance. At each location, a 9" diameter aluminum pan was filled with a volume of exactly 750 ml of distilled water. The volume of water was carefully measured each month and the evaporation rate in ml/day was determined from the volume lost divided by the number of days between measurements. The distribution of measured evaporation rates is shown in Figure 19. Experience indicates that the evaporation rate can be determined with an accuracy of 0.05 ml/day with the methods used.

The rate at which water evaporates within the cave is expected to be very low because of the high humidity. On the surface, the energy required to evaporate water comes from the sun, differences in air and soil temperatures, and the relative humidity of the air. The annual evaporation on the surface is approximately 65 inches. Inside the cave however, evaporation is much less because temperatures are relatively constant, there is little or no wind and the relative humidity is almost 100%.

The amount of moisture loss that can be expected within the cave can be estimated from the physical process of evaporation. In general, equations for predicting evaporation are based on the difference between the water vapor pressures at the water surface and at a fixed height above the water. Historically, several empirical equations have been derived for estimating evaporation from surface experiments (Linsley, et al, 1982). A representative equation is:

$$\text{Evaporation (inches/day)} = 0.35(e_0 - e_a)$$

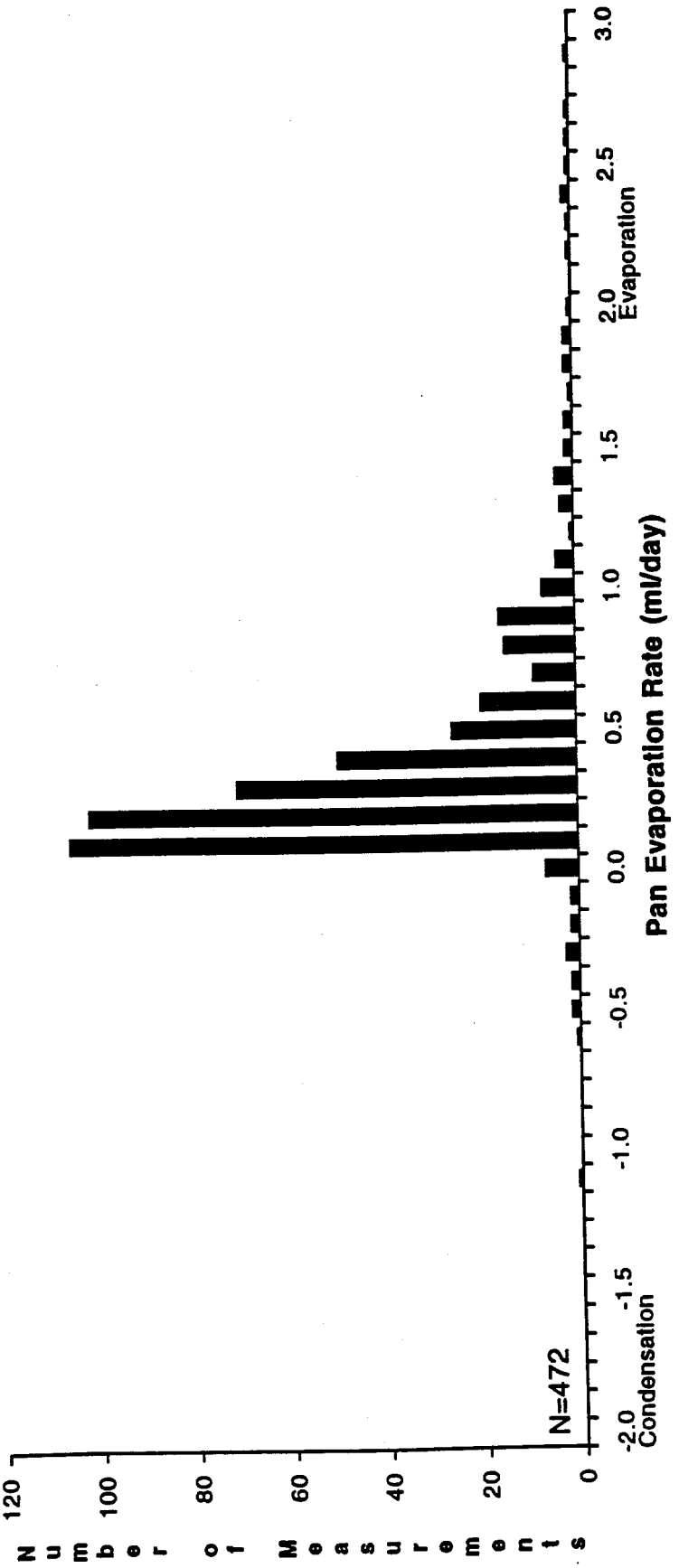
Where: e_0 is the vapor pressure of the water in inches of mercury.
e_a is the water vapor pressure in the surrounding air in inches of mercury.

From this equation, we can estimate the expected evaporation rate inside the cave. Assuming a temperature of 68°F and 99% relative humidity, the vapor pressure of the water is 0.690 inches of mercury. Vapor pressure in the air at 99% relative humidity is 0.683 inches of mercury. The estimated evaporation per day is 0.0025 inches. For the type of evaporation pans used in the cave, the surface area is 59.2 square inches (382 cm^2). The expected evaporation is 2.4 milliliters per day (ml/day) at 99% relative humidity.

A second approach to estimating the amount of water lost by evaporation is based on the diffusion of water molecules from the surface of the pan. The diffusion occurs through a thin layer of stagnant air below the rim of the evaporation pan. The rate of

FIGURE 19

Distribution of Measured Pan Evaporation Rates



water loss by diffusion is computed with the integrated form of Stefan's law (Holman, 1976). The evaporation rate is computed to be 0.54 ml per day at 99% relative humidty for the type of pans being used in this study. Water loss by diffusion represents a lower limit on the expected rates of evaporation. Diffusion will occur in totally still air with no temperature gradients. The presence of moving air, convective currents and temperature fluctuations will all increase the rate of evaporation.

The relative humidity within the cave has been found to average 99.4% based on precise measurements made with a dewpoint meter. This would yield a predicted average evaporation rate of 1.4 ml/day based on the surface equations. However, the average of all evaporation pans measured throughout the cave is 0.36 ml/day and only 0.22 ml/day for stations deep within the cave. The difference between the predicted evaporation and measured pan evaporation rates is much larger than expected. There are several possible reasons for the discrepancy. First, the coefficient for the predictive equation is empirically derived from measurements performed on the surface and may not be valid at the high relative humidities encountered in the cave. Second, the precise relative humidities have been measured at an elevation approximately three feet above the evaporation pan. Relative humidities may be higher closer to the floor of the cave. Third, the "precise" dewpoint relative humidities may not be accurate enough. The accuracy of the dewpoint meter decreases at relative humidities above 99.7%. The true average relative humidity of the cave may in fact be higher than 99.47%.

The expected evaporation rate within the cave due to molecular diffusion at 99.4% relative humidity is 0.32 ml per day. This is very close to the 0.36 ml/day average for all monitoring stations and somewhat greater than the 0.22 ml/day average for stations removed from the natural entrance. This indicates that, for a majority of the cave, molecular diffusion is the predominant mechanism for evaporation. This also implies that air movement is very slight and temperatures are very stable.

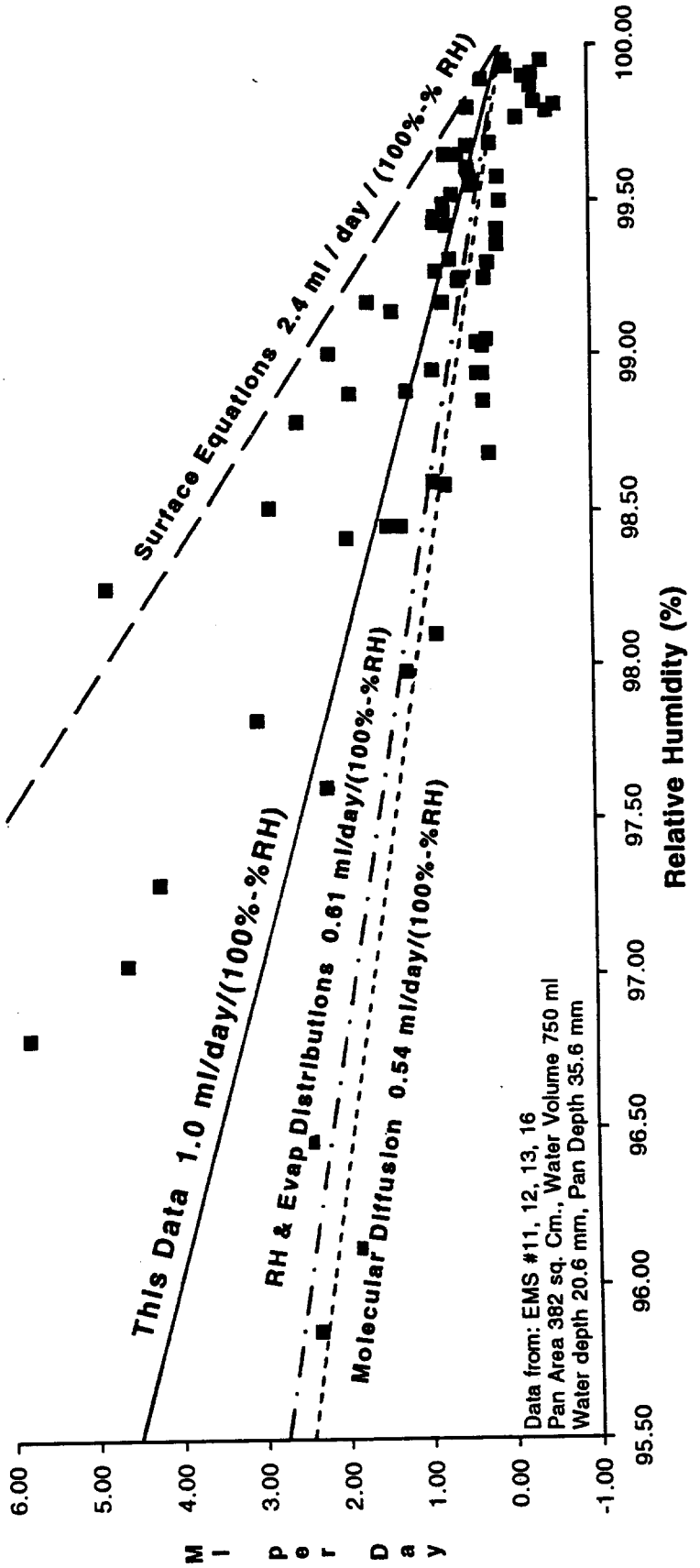
Both the empirical surface equation and molecular diffusion predict that the rate of evaporation will be proportional to the difference in relative humidity below 100%. The relationship is linear only for the range of relative humidities above 90%. Based on the measurements of pan evaporation rates and relative humidity, a linear relationship was sought. Two approaches were used to determine the actual relationship between relative humidity and evaporation rates.

The first approach examines the relationship for those stations for which we have the greatest amount of data. A group of five stations in the Big Room, for which we had the greatest number of relative humidity readings, was selected. More frequent relative humidity measurements allow us to approximate more accurately the true average relative humidity. Measurements are usually taken at the environmental monitoring stations. While the soil psychrometer is capable of great accuracy, the measurements are only spot readings of the relative humidity which is constantly changing. For each of the monthly evaporation rates, the average relative humidity was determined from time-weighted averages of the precise relative humidity measurements. This data is tabulated in Appendix G. A plot of the data (Figure 20) confirms that pan evaporation rates decrease with increasing relative humidity. There is still a considerable amount of scatter to the data. A straight-line fit to the data yields a slope of 1.0 ml/day of evaporation for each 1% of relative humidity below 100%. A line drawn, using the equation developed from surface data, has a slope of 2.4 ml/day per 1% RH below 100%. This line can be seen as being the approximate upper bound for the plotted data.

FIGURE 20

Kartchner Caverns

Pan Evaporation Rate vs. Average Precise Relative Humidity



The five stations on which this relationship is based are also those stations which are located closest to the entrance. Since the stations are close to the entrance, the evaporation rate may be influenced by other conditions such as airflow, stratified air or temperature fluctuations. Indeed, if the average evaporation rate is plotted against the amplitude of the annual temperature fluctuation, we can see that evaporation is also proportional to temperature fluctuations (Figure 21). This indicates that the relationship determined may still be an overestimation of the correct evaporation rate and is likely to be influenced by the nearby entrance.

The second approach considers all of the evaporation pan measurements and all of the precise relative humidities. A plot of the distribution of the measured pan evaporation rates shows that the evaporation rate is skewed toward very low evaporation rates (Figure 19). The number of measurements increase as zero evaporation is approached. The largest number of measurements are in the interval from 0.1 to 0.2 ml per day. At lower evaporation rates, the number declines markedly. This is apparently due to inherent limitations in the methods used to measure evaporation rather than an actual decline. Due to the methods used, 0.05 ml/day is probably the best accuracy possible.

A plot of the distribution of precise relative humidities shows a complementary distribution (Figure 18). This data is also similarly skewed toward very high relative humidities. The number of measurements increases up to 99.5% RH. The fact that it does not continue to increase all the way up to 100% is probably due to increasing difficulties in measuring relative humidities near 100%.

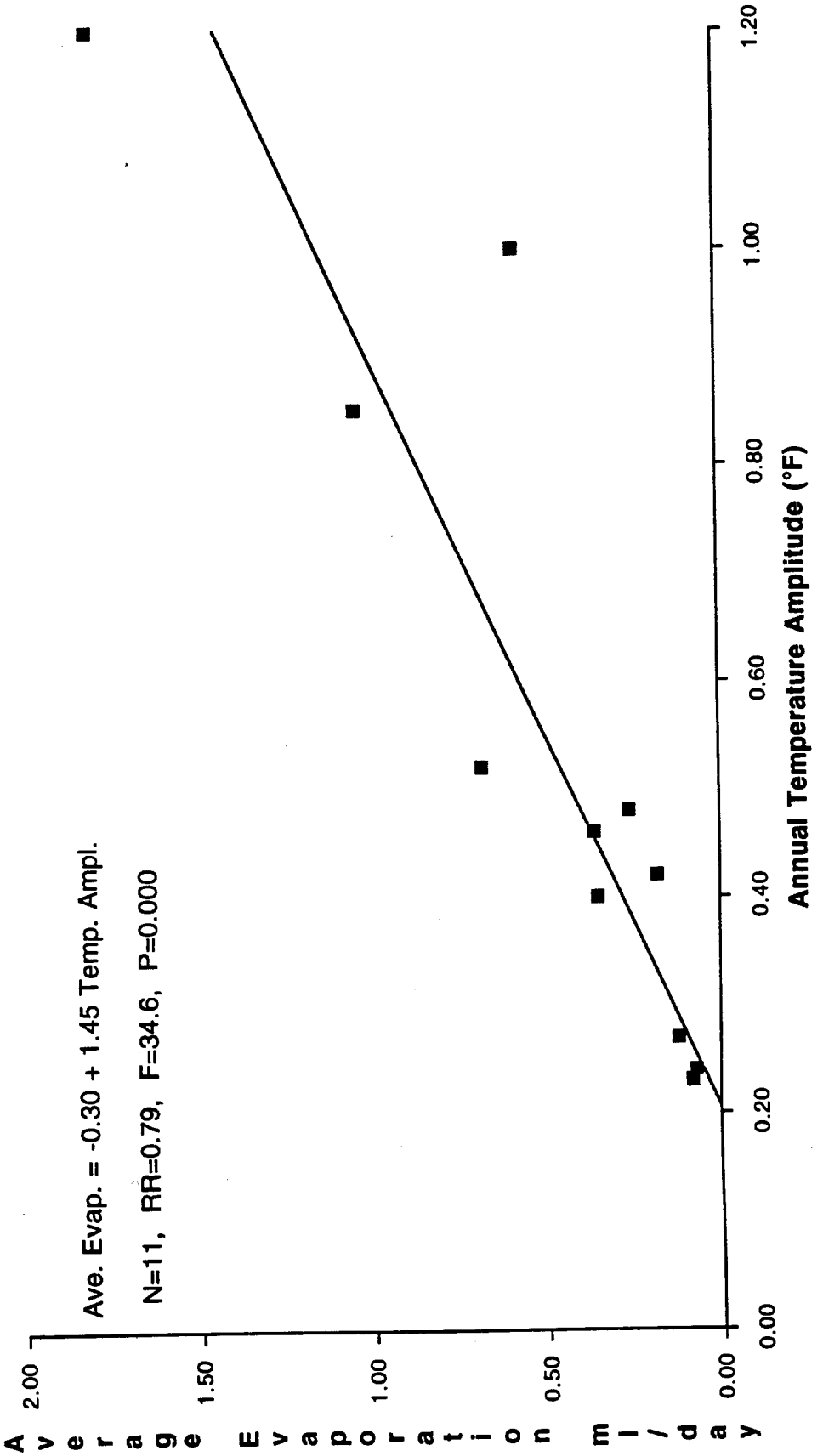
If we make the assumption that both the pan evaporation rates and precise relative humidities are random samples of the true distribution within the cave, we can determine the relationship of the distributions rather than the individual measurements. The two distributions are assumed to coincide. That is, the value of evaporation at the 10% level is equated to the relative humidity at the 10% level. A plot of the corresponding points yields a remarkably straight line with a slope of 0.61 ml/day per % RH below 100%. This is quite close to the rate of evaporation expected from molecular diffusion (0.54 ml/day). Appendix G contains a tabulation of the data and graphical plots of the relationship.

The relationship between evaporation rates and relative humidity has been approached in four different ways. Based on surface studies by others, the evaporation rate within the cave was anticipated to be 2.4 ml/day per %RH below 100%. Measured rates within the cave are much lower than this. Correlating precise relative humidities with pan evaporation for those stations with the most data gives the relationship of 1.0 ml/day per %RH below 100%. This is still several times greater than the observed pan evaporation rates. A separate analysis of these stations indicates that annual temperature fluctuations may be responsible for the increased evaporation observed. A larger sample of evaporation and relative humidity measurements was evaluated by a purely distributional comparison. This yields an estimate of evaporation to be 0.61 ml/day per %RH below 100%. This agrees quite well with the rate of evaporation expected from molecular diffusion alone. The four equations are shown in Figure 20. The lines of slope 2.4 and 0.54 ml/day are seen to form an envelope around the data points. For the remainder of this study, a value of 0.61 ml/day per % RH below 100% will be used for locations removed from the influence of the entrance.

Based on this relationship, we can estimate the average relative humidity from the observed evaporation rates. The average evaporation for all stations removed from

FIGURE 21

Evaporation vs. Annual Temperature Amplitude



the natural entrance is 0.22 ml/day. This corresponds to a relative humidity of 99.64%. This is equivalent to an evaporation rate of 0.00023 in/day (0.0058 mm/day). For a majority of the cave, the evaporation pans would require almost 10 years to completely dry out. As the observed rate of evaporation is quite close to that predicted by molecular diffusion we can also assume that air motion and temperature fluctuations are quite small for much of the cave.

Estimated Annual Evaporation Within the Cave

The total amount of evaporation from all surfaces within the cave can now be estimated based on the measured values from the environmental stations and the derived relationship between relative humidity and evaporation. In order to do this, the cave will be divided into two areas: those near the entrance where evaporation is high and remote areas of the cave where evaporation is quite low.

The zone of influence of the natural entrance has been shown to extend for at least 400 feet into the cave. The near-entrance areas are therefore considered to include the entrance passages, Grand Central Station, Main Corridor, Mud Flats and the Tarantula Room. The floor area of these passages totals 39,889.5 square feet. The evaporation rate in this area is 0.89 ml/day which is equivalent to 0.21 gallons per square foot per year. The floor area of the remaining areas of the cave beyond the range of influence of the entrance is 269,863.4 square feet. The evaporation in this area is estimated to be 0.22 ml/day which is equivalent to 0.05 gallons per square foot per year.

The total area of all surfaces can be estimated to be approximately 3 times the floor area. Not all of this area may be effective, however in evaporating water. We know that water percolates down into the cave from the surface and drips from the ceiling of the cave. This would appear to indicate that the ceiling has more moisture than other surfaces and so may also be more humid. Additionally, air which contains more moisture is lighter than drier air, so we would expect that air near the ceiling would be more humid and have less evaporation potential. Rates of evaporation have been determined to be proportional to the difference between the relative humidity at the water surface (100%) and the cave air. A small number of measurements of the relative humidity of cave surfaces indicates that they are at a higher humidity than the cave air. This would also reduce the amount of evaporation which would actually take place since the difference in relative humidities between cave surfaces and cave air is less than the difference between the evaporation pans and cave air. For these reasons, the area of effective evaporation is assumed to be only twice the area of the floor. Evaporation from the ceiling is assumed to be zero.

Entrance Areas	0.21 gal/yr/ft^2 X 39,889.5 ft^2 X 2 = 16,754 gallons/year
Deep Cave	0.05 gal/yr/ft^2 X 269,863.4 ft^2 X 2 = 26,986 gallons/year

The amount of evaporation estimated for the entrance areas is 16,754 gallons per year. However, this is a theoretical amount which assumes that there is sufficient moisture available for this to occur. The amount of moisture reaching the cave has been estimated to be 0.3" per year. Over the area of the entrance passages (39,889.5 ft^2), this amounts to 7,500 gallons of available water, less than the potential evaporation of 16,754 gallons. The evaporation cannot exceed the available moisture supply, so evaporation in the entrance passages will be limited to the available

moisture supply of 7,500 gallons per year. Total evaporation from the entire cave based on evaporation pan measurements is estimated to be:

Entrance Areas	7,500 gallons/year
Deep Cave	27,000 gallons/year
Total	34,500 gallons/year

Several assumptions have been made in determining the total evaporation. In order to assess the impact that these assumptions might have, a high and low estimate has also been calculated. For the low estimate, the evaporation rate deep within the cave is estimated to be 0.13 ml/day. This lower rate may more accurately reflect the correct evaporation rate considering the limitations of the measuring techniques used and accuracy of the dewpoint meter. The evaporation rate for entrance areas and the effective evaporation surface remains the same as above. Total evaporation for the low estimate is 23,500 gallons/year.

The high evaporation estimate is made by assuming that all surfaces, including the ceiling, are effective for evaporation deep within the cave. No change is made in the entrance passage evaporation as the amount being evaporated already equals the moisture supply. The high evaporation estimate is 48,000 gallons per year.

These estimates of total evaporation will be used in determining the overall water balance for the cave and assessing the impact that development and variations in precipitation will have on the cave.

CAVE TEMPERATURE

The temperatures of large caves are generally considered to be at the same temperature as the mean surface temperature. A comparison with the temperatures measured in 54 other Arizona caves (Buecher, 1977; Moore and Sullivan, 1978) indicates that the temperature of a cave at Kartchner's elevation should be about 59.7°F. The temperatures in Arizona caves are generally about 2.4°F above the mean surface temperature (Figure 22).

At Kartchner Caverns State Park, the surface weather station has a mean surface temperature of 62.5°F based on 24 months of record. This agrees well with temperatures based on correlations of the Kartchner mean surface temperatures with weather station records for Tombstone and Sierra Vista. The predicted mean temperature for Kartchner Caverns State Park is 62.6°F from the Tombstone record and 62.2°F from the Sierra Vista record. These agree very well with the mean determined from 24 months of measurements at Kartchner Caverns.

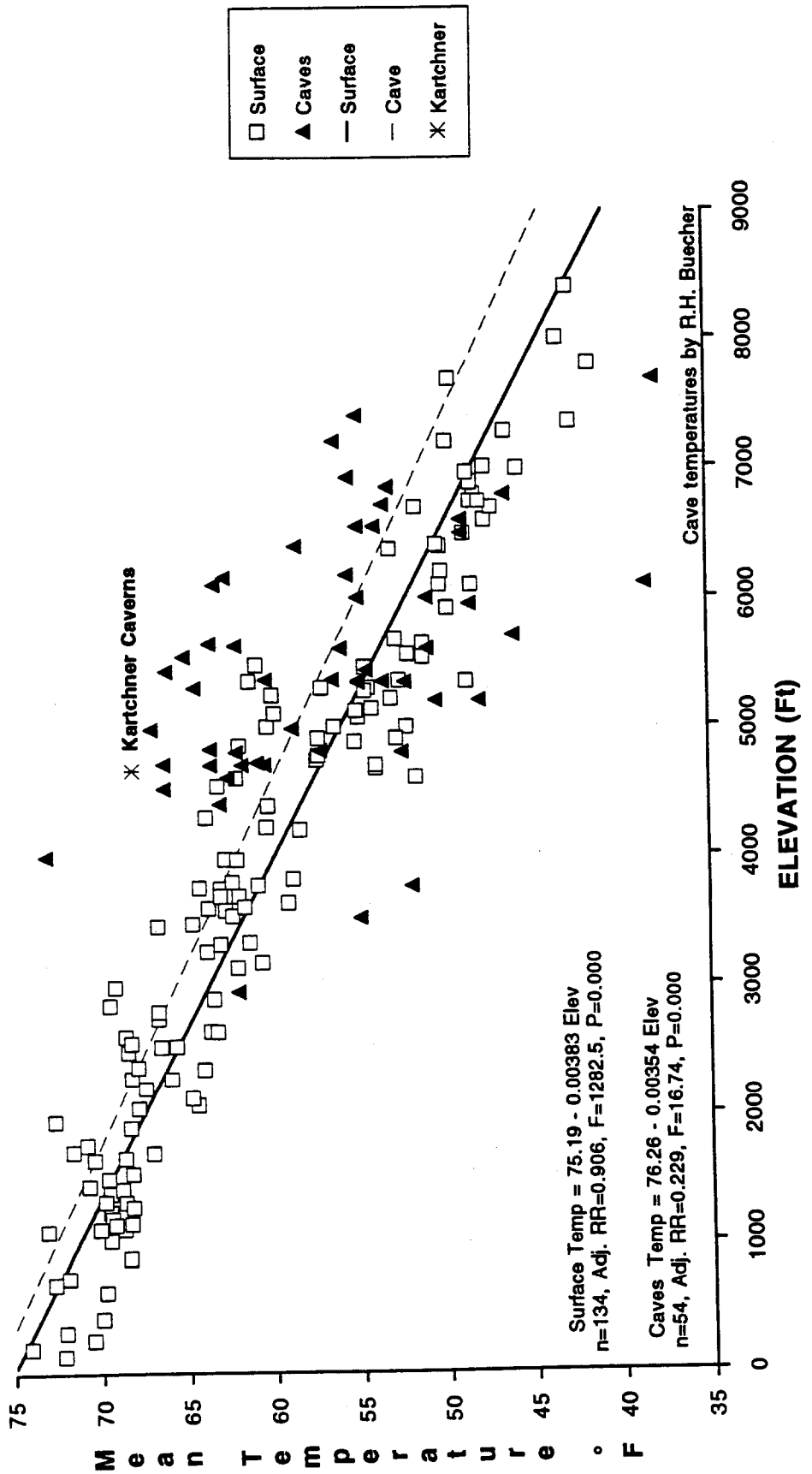
There is a serious discrepancy between the mean surface temperature and temperatures measured within the cave. Inside the cave, temperatures vary from 69.7°F to 65.5°F with a mean temperature of 67.7°F for the whole cave. Temperatures inside the cave are always higher than the mean surface temperature. The cave is 3.0°F to 7.2°F warmer than the mean surface temperature.

There are several possibile explanations for the discrepancy.

1. The Kartchner surface weather station may be underestimating the true mean temperature. This may be caused by incorrectly calibrated instruments or by the proximity to Guindani Wash which would channel cold air near the station. It is unlikely, however, that the source of the difference is any of the above reasons. The calibration of the instruments has been periodically checked and no substantial discrepancies noted. The mean temperature at Tombstone (elevation 4610') is 63.7°F. The mean temperature for Sierra Vista/Ft. Huachuca (elevation 4664') is

FIGURE 22

Arizona Cave and Surface Temperatures vs. Elevation



62.2°F (Sellers and Hill, 1974). Both agree quite closely with the observed mean surface temperature of 62.5°F at Kartchner. The measured mean temperature on the surface at Kartchner Caverns appears to be correct.

2. The hill in which the cave is found slopes generally to the southwest. The majority of the cave is found under the south side of the hill. This hill and the bare limestone surface may receive more solar heating. This is in agreement with the fact that the warmest areas of the cave are in the Big Room, which is closest to the surface, and also under a southwest-facing slope. Other areas of the cave are located at greater distances from the surface and do not experience as great a warming.

3. There may be microclimate processes operating in the cave which selectively trap warmer air. This could be driven by cool dense air flowing along the floor of the cave and would create an interface several feet above the floor with the warmer cave air. Fog and condensation has been observed at this interface. The creation of fog and condensation will release heat which rises and warms the air in the upper areas of the room. Condensation droplets fall into the cooler air near the floor. Here they evaporate in the drier air, further cooling the air.

4. The increased temperature may be the result of geothermal heating. The 1982 Geothermal Resources Map of Arizona indicates that the San Pedro valley east of the cave is an area of low temperature geothermal water (Witcher, et al, 1982). A geothermal well is located on the west side of the Whetstone mountains (T18,R18,S34bb). The temperature of this well is 42°C (107.6°F). Near Tombstone, the heatflow from the earth has been measured to be in the range of 74 to 85 mW/M^2 (1.9 Heat Flow Units). Bill Russell has developed an empirical relationship between the heat flow and increased cave temperatures (Russell, 1979). The expected increase (°F) is Heat Flow - 1.2 Heat Flow Units X 8.1°F. Russell also gives a map of heat flow in the western United States which indicates that much of Arizona has a heat flow of 2 heat flow units. Geothermal heat flow of 1.9 to 2.0 heat flow units would increase the cave temperature by 5.7°F to 6.5°F. The predicted temperature of Kartchner Caverns would be 68.2°F to 69.0°F. This agrees with the warmest areas of the cave. This is also in agreement with the observation that Arizona caves are generally about 2.4°F warmer than the mean surface temperature.

The fact that geothermal heating may be the cause of the warmer than expected temperature of the cave has been independently confirmed. There are several water wells located on the park. Measurements of the temperature profile of the Kartchner Well in July and November 1991 show that the asymptotic temperature of 67.3°F is reached at about 50 feet below the surface. Figures 23 and 24 show the measured temperature profiles and the expected profile based on the mean surface temperature (Whitaker, 1977; Lee, 1965 and Cropley, 1965). The shape of the two profiles is similar and indicates that we are indeed measuring the annual temperature cycle. In each case, the measured profile approaches a temperature which is 4.9°F warmer than predicted from the mean surface temperature alone. The measured temperature of 67.3°F is in extremely good agreement with the mean temperature of the cave.

Temperatures in Kartchner Caverns are elevated primarily because of regional geothermal heat flow. The above-average heat flow over much of Arizona is responsible for an increase in cave temperatures of 2.4°F to 6.5°F above the mean surface temperature. This indicates that the temperature of Kartchner Caverns should be in the range of 64.9°F to 69.0°F. The mean of these estimates is a temperature of 67.0°F. This is in good agreement with the deep well temperature (67.3°F) measured on the park.

FIGURE 23

Kartchner Well Summer Temperature Profile

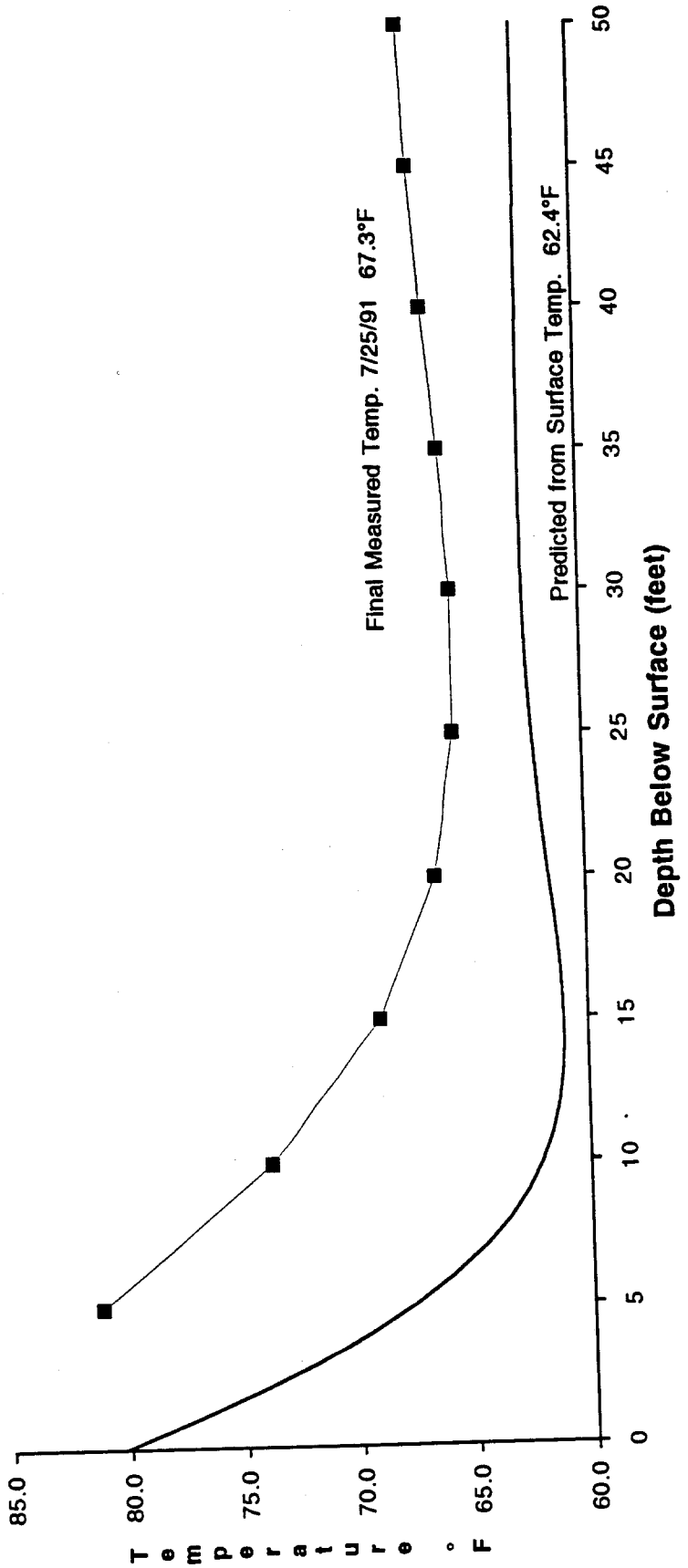
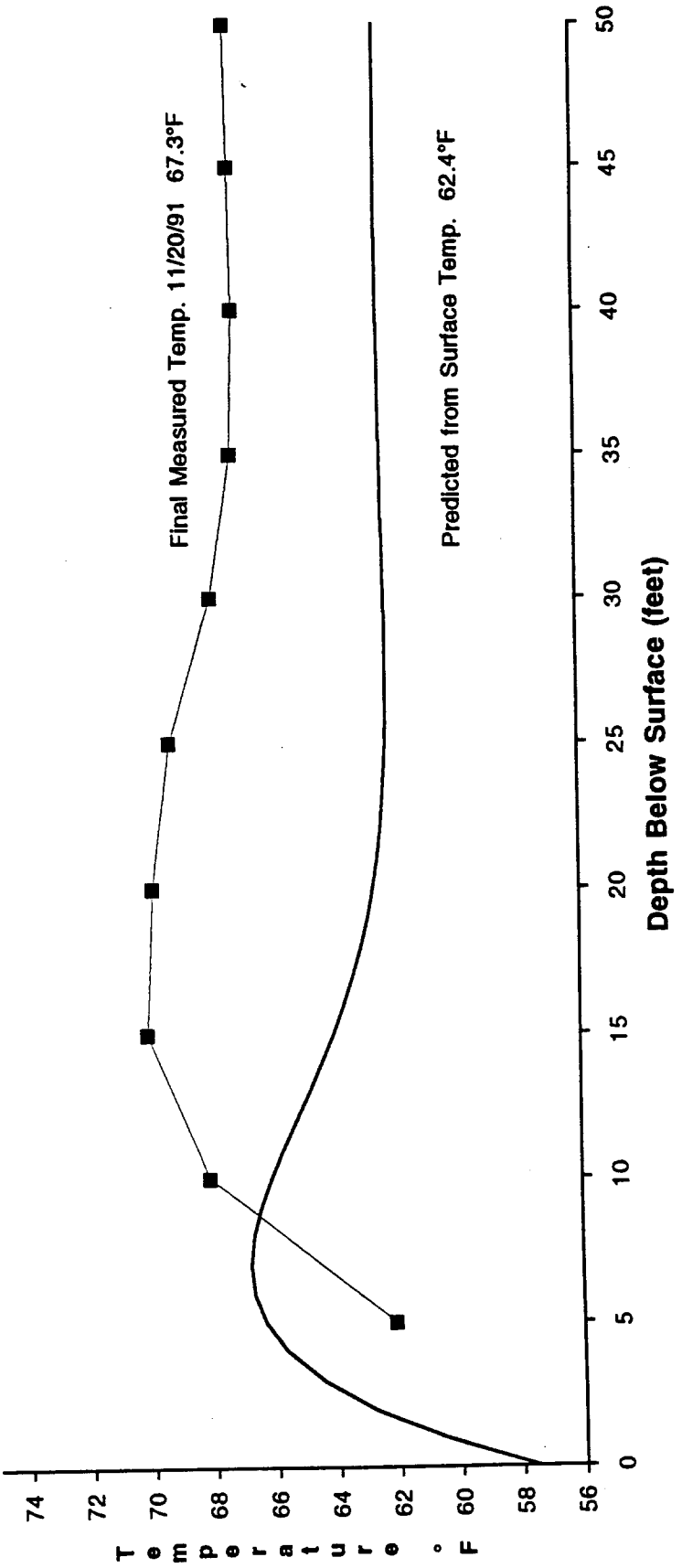


FIGURE 24

Kartchner Well Winter Temperature Profile



While geothermal heating explains the slightly elevated temperature of the cave, it does not explain the large variations found between different sections of the cave. The warmest parts of the cave are in the Big Room at 69.7°F. The coldest parts of the cave are in the Back Sections with a temperature of 65.5°F and the entrance passages which average about 64°F. Temperatures of the entrance passages can be explained as being due to the influence of the entrance and selective trapping of cold air. The average temperature is also quite close to the surface mean temperature. It is more difficult to understand why the other two areas of the cave have such different temperatures. The most likely reason for the cold temperatures in the Back Section is the frequent flooding of the cave during the winter months. While flooding does not occur every year, there is insufficient time for the Back Sections to completely return to equilibrium. It is also possible that cold surface waters are descending below the cave even during years when no floodwaters actually reach the cave. The pattern of cold soil temperatures appears to match the probable direction of floodwater movement through the cave. The area near the Quartz Divide and Mud Trench appears to be somewhat warmer than would be expected if the whole area has been cooled by flood waters. The reasons for this anomalous area is further considered in the discussion of airflow.

Warmer temperatures in the Big Room are thought to be due to stratified air. Cool dry surface air remains near the floor of the cave and does not mix with the warmer air in the Big Room. At the interface between the two masses of air, a thin layer of condensation fog forms. This fog is frequently seen along the Main Corridor passage during winter months. Condensation releases heat which warms the overlying air mass (the upper areas of the Big Room). Condensation droplets fall into the cooler, dryer air near the floor. Here they evaporate and further cool the incoming air while raising the relative humidity of that air.

SOIL TEMPERATURES

ACPI conducted a comprehensive survey of the soil temperatures throughout Kartchner Caverns during April 1990. Temperatures were measured approximately every 50 to 100 feet along the trails throughout the cave. The results of the survey are shown in Figure 25. The survey shows a surprisingly large variation in soil temperature throughout the cave.

The purpose of the survey was two-fold. The first goal was to determine the temperatures of those areas which are poorly represented by the environmental monitoring stations. Several large segments of the cave have no permanent monitoring stations; most notably, the Subway Passage and River Passages. The second objective was to determine if there were areas of anomalous temperatures in the cave. Areas of unusually high or low temperatures can be indications of outside air entering or leaving the cave.

A total of 119 individual measurements were taken. The average of all readings is 66.7°F. Figure 26 illustrates the distribution in soil temperatures throughout the cave. The areas near the natural entrance are unusually cool and bias the average. A better representation of the true interior temperature of the cave is obtained by averaging all areas of the cave exclusive of the entrance passages. The overall average is then 67.3°F.

FIGURE 25

Soil Temperatures in Kartchner Caverns April, 1990

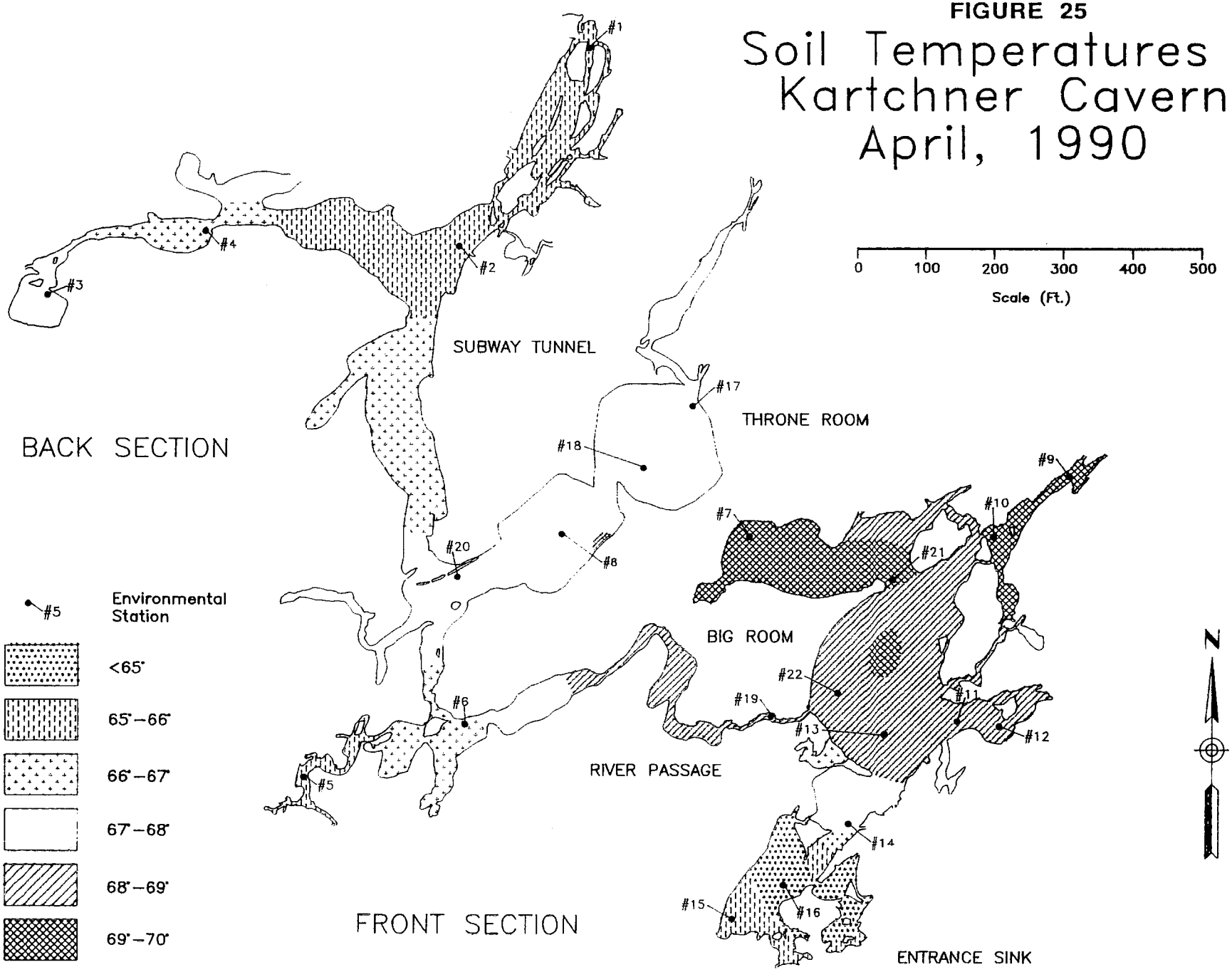


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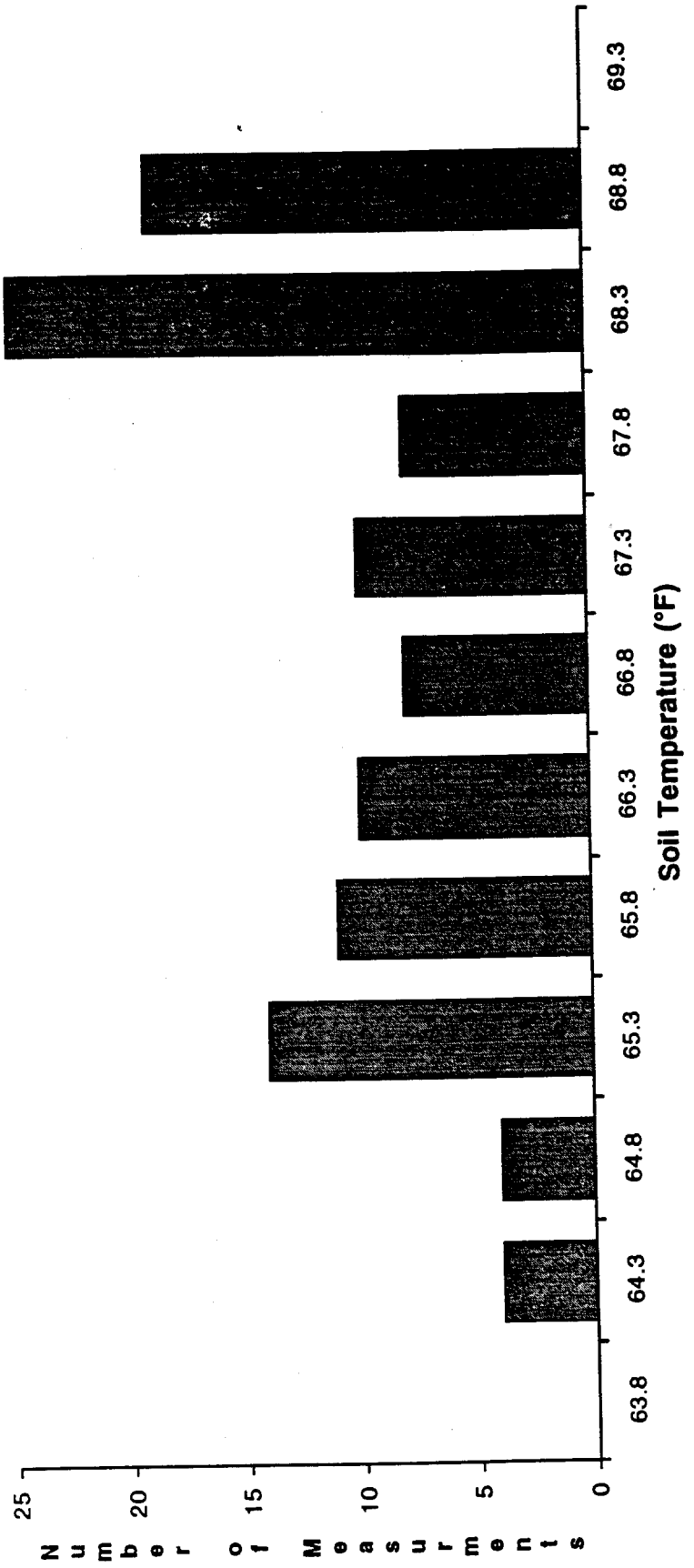
FIGURE 26

Distribution of Soil Temperatures April, 1990



The measured soil temperatures have been broken into six groups corresponding to the major areas of the cave.

	Average	Low	High	Range
Entrance Passages (Natural Entrance to the Ladder up to Sharon's Saddle)	63.6°F	56.4°F	68.0°F	11.6°F
Big Room (Australia, Echo Passage, Cul-de-Sac).	68.3°F	66.4°F	69.0°F	2.6°F
River Passage (Big Room to end of Grand Canyon)	68.0°F	67.5°F	68.2°F	0.7°F
Subway Passage (Granite Dells, Water Room, Pyramid Room to end of Pirate's Den).	65.9°F	64.9°F	66.9°F	2.0°F
Pirate's Den Junction, Hill Room, Mushroom Passage and Sue's Room.	66.4°F	65.5°F	68.0°F	2.5°F
Rotunda and Throne Rooms	67.4°F	67.4°F	67.7°F	0.3°F

A comprehensive mathematical model of the temperature and relative humidity profiles at the entrances of caves was developed by Wigley and Brown (1971). An important aspect of the model is the concept of the relaxation length X_0 as applied to the temperature and relative humidity profiles.

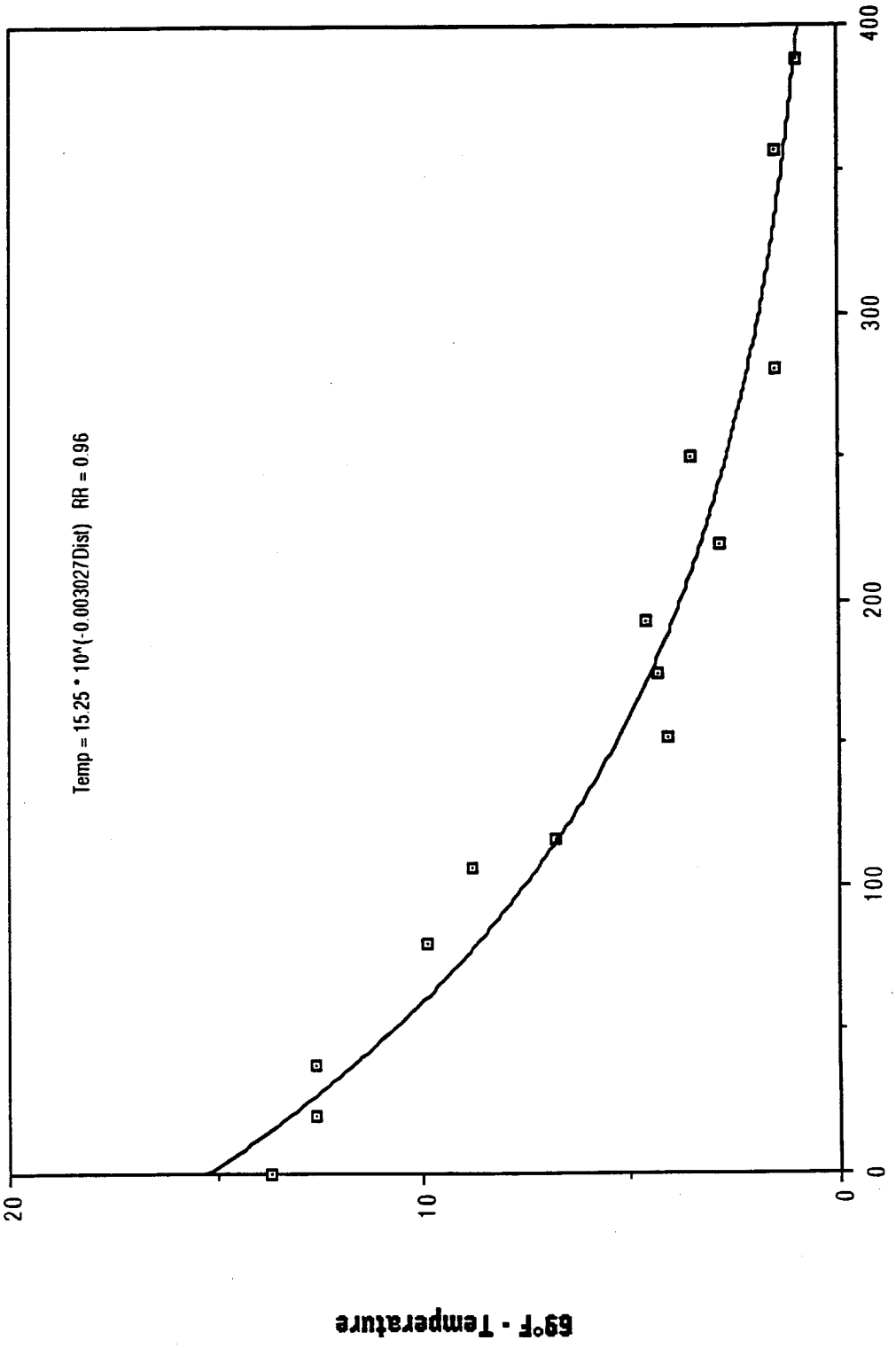
Relaxation length (feet) $X_0 = 63r^{1.2}V^{0.2}$
where r = passage radius in feet and V = air velocity in feet per minute.

The relaxation length is a measure of the rate of exponential damping of temperature differences as one proceeds deeper into the cave. At a distance into the cave of 4 to 5 times the relaxation length, temperatures remain constant year-round. The model predicts the relaxation length based on air velocity and passage geometry. Passages are considered to be essentially circular pipes with moist walls. Air entering the passage gradually comes to thermal equilibrium with the walls through conduction with the walls and the gain or loss of water by evaporation or condensation.

Based on the known entrance passage geometry and measured airflow rates at Kartchner Caverns, the anticipated relaxation length was calculated for an airflow of 30 feet per minute and passage areas of 3.24 and 9.72 square feet. The anticipated relaxation length is 125 feet to 250 feet depending on the passage geometry and airflow rate used. Based on the soil temperatures measured in April 1990, a relaxation length of 100 feet is found. The relaxation length for December 1989 relative humidity measurements in the entrance passages is found to be 50 feet (Figure 27). The observed relaxation lengths are considerably less than what was anticipated based on theory.

This difference may be due to incorrect values for the airflow or passage geometry used in determining the relaxation length. The Wigley-Brown theory is very insensitive

FIGURE 27
Entrance Passages Temperature Profile
April, 1990



to changes in airflow. Airflow would need to be only 10 % to 1% of the measured airflow to obtain the observed relaxation length. The relaxation length is, however, approximately proportional to the passage radius. The observed relaxation length can be obtained by using a passage radius of about half of what was initially used. This, however, results in a passage diameter of only 1.5 feet, much smaller than what is generally found in the entrance to Kartchner. It is also possible that the passages which determine the temperature profile are not the relatively large passages traversed by humans. The entrance passages are quite varied and can be thought of more as a series of small rooms linked by very small openings. The temperature profile may be determined by the sizes of these small openings. Typically, the openings have areas of 2 to 3 square feet and the rooms have cross-sectional areas of 40 to 100 square feet. Such passageways do not match the underlying assumption of uniform circular passages used in the model. The observed relaxation lengths are most consistent with passages which are very small, less than 6" high with a total cross-sectional area of approximately 10 square feet. This is somewhat consistent with what is known about the entrance passages. The largest free path for air movement into the cave passes through the Bat Window and the Blow Hole. Each of these constrictions has a cross-sectional area of approximately one square foot. The remaining pathways for air to enter the cave are through small openings in the loose fill of the entrance sink and Blockade Room and small openings between the LEM Room and Anticipation Room. Because the areas of these openings is quite small, the relaxation lengths will also be small.

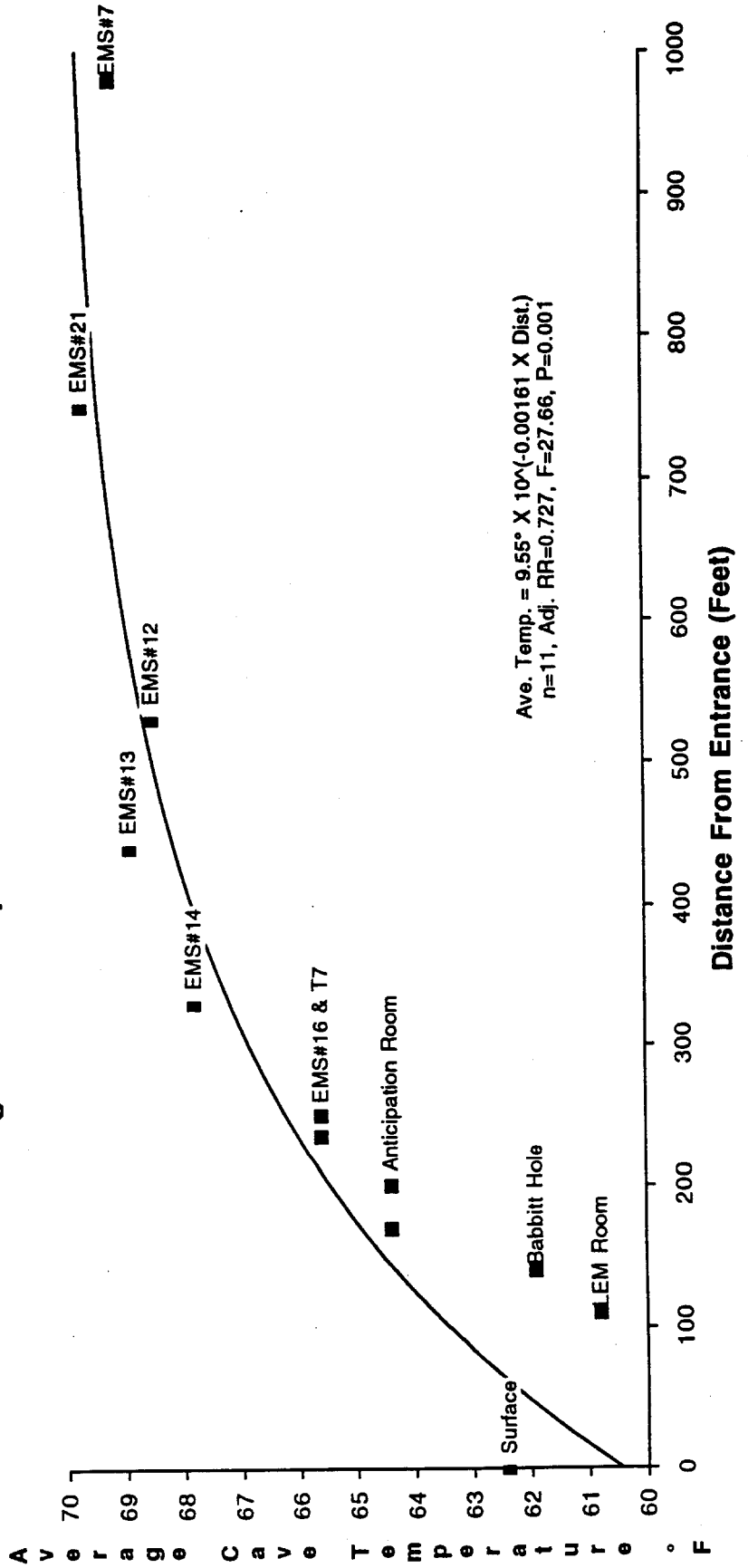
The profile of soil temperatures in the entrance passages shows an exponential decay towards the mean cave temperature. The rate of decay is faster than what is predicted by the Wigley-Brown theory. This is most likely the result of the numerous small constrictions and sudden changes in passage size. The effect of the natural entrance on temperatures within the cave can be traced for at least 400 feet into the cave (Figure 28).

The soil temperature survey shows that the largest horizontal temperature gradient exists at the natural entrance. Here the gradient is 6°F per 100 feet. Large horizontal thermal gradients can be used as an indication of the proximity of an unknown entrance. A temperature gradient of 1°F per 100 feet would indicate a distance of approximately 300 feet from an entrance similar in size to the natural entrance. A smaller entrance would have to be much closer to produce the same gradient. Outside of the entrance passages, only the Pyramid Room/Granite Dells area has temperature gradients in excess of 1°F/100 ft. The steep gradient in this area is more likely to be the result of cooling by floodwater than from airflow from an entrance. However, this method only indicates that it is unlikely that there are additional entrances which draw appreciable outside air into the cave. An entrance which predominantly exhausted cave air would not have an appreciable horizontal temperature gradient. At the natural entrance, the temperature gradient is subdued during the summer months. The fact that no other areas of the cave have large horizontal temperature gradients indicates that there is no other large opening into the cave. In this context a large opening would be one of less than 10 square feet.

The annual temperature variations observed in the cave can be due to two effects, conduction of surface temperature through the overlying bedrock or from airflow entering the cave from the surface. The effect of the surface temperature variations die out very quickly in the limestone bedrock. The expected temperature can be calculated from heat transfer equations for a solid block which experiences a

FIGURE 28

Average Cave Temperature vs. Distance From Entrance



sinusoidal temperature on one surface (Cropley, 1965; Whitaker, 1977 and Lee, 1965). The equation derived for the typical properties of limestone and the observed surface temperature ranges is:

Temperature = 67°F - 16.2°F e(-0.153 Depth) COS (0.0172(Day # - 18) - 0.153 Depth)

Where Depth is measured in feet of bedrock, and Day # is the day of the year. The assumed properties of the limestone are: Thermal conductivity, 0.54 BTU/SF -Hr-°F/Ft; Density, 165 Lbs/CuFt; Heat Capacity, 0.217 BTU/Lb-°F.

This equation shows that the annual temperature fluctuation damps out quite quickly. A graph of the temperature variation is shown in Figure 29. This indicates that, at a depth of 25 feet below the surface, the annual temperature variation is 1°F and lags behind the surface temperature by 220 days. At a depth of 38 feet, the annual variation is only 0.1°F and lags the surface temperature by 340 days. The annual range of temperatures and lag times have been computed for a number of stations in the front section of the cave. The predicted values are compared to the measured values in Table 4.

TABLE 4
Predicted and Observed Annual Temperature Fluctuations and Lag Times

Location	Rock Overburden	Predicted Annual Temperature	Lag Time	Observed Annual Temperature	Lag Time
LEM Room	42'	0.05°F	374 days	8.4°F	60 to 100 days
Grand Central	52'	0.01°F	463 days	2.6°F	30 to 70 days
Sharon's Saddle	22'	1.13°F	196 days	1.0°F	105 to 160 days
Mud Flats	50'	0.02°F	445 days	0.9°F	125 to 145 days
Big Room Overlook	66'	0.00°F	587 days	0.8°F	165 to 200 days
Cul-de-Sac	140'	0.00°F	1246 days	0.4°F	175 to 210 days

Except for the station at Sharon's Saddle, there is no correspondence between the predicted and observed annual temperature fluctuations and lag times. This indicates that conduction of surface temperatures is not a major control of the temperatures in the front section of the cave.

The second possibility that temperatures were being influenced by the entrance was also investigated. Data for a number of stations in the front section of the cave was compiled and tabulated (Table 5) in order of increasing distance from the natural entrance.

TABLE 5
Front Section of Kartchner Caverns
Temperature Characteristics

Station	Annual Temperature Range (°F)	Distance From Entrance	Max. Temperature Lags by(days)	Min. Temperature Lags by (days)
Surface	53.0	0	0	0
T2	8.4	110	100	60
T3	8.8	140	70	60
T5	2.5	170	100	75
T6	2.5	200	70	60
T7	2.6	235	100	30
EMS16	2.6	250	70	30
EMS14	1.1	330	130	105
EMS13	1.0	440	160	105
EMS12	0.9	530	145	125
EMS21	0.8	750	200	165
EMS7	0.4	980	210	175

This data is also shown graphically in Figures 30, 31 and 32. These show quite clearly that temperatures and lag times are strongly dependent on the distance from the natural entrance. These plots show that temperature decays exponentially with increasing distance. The lag time appears to be a linear function of distance from the natural entrance. This relationship is the same as what would be expected if the effect were due to pure conduction. From the lag times and exponential decay constants the values for the conduction equation were determined. The observed temperature fluctuations and lag times might be due to conduction through the bedrock or air from the entrance. However the observed decay exponents and lag times are not consistent with each other. The best fit for both the decay and lag results in conductions that are 25 times faster than in solid rock and 4 times faster that would occur in still air. This indicates that the process while similar to pure conduction is in fact more complicated. The most likely mechanism is for the movement of air in the first 200 to 300 feet of passage being the primary cause. Deeper into the cave, pure thermal conduction between stratified masses of air may dominate.

FIGURE 29

Decay of Annual Temperature Variation With Depth

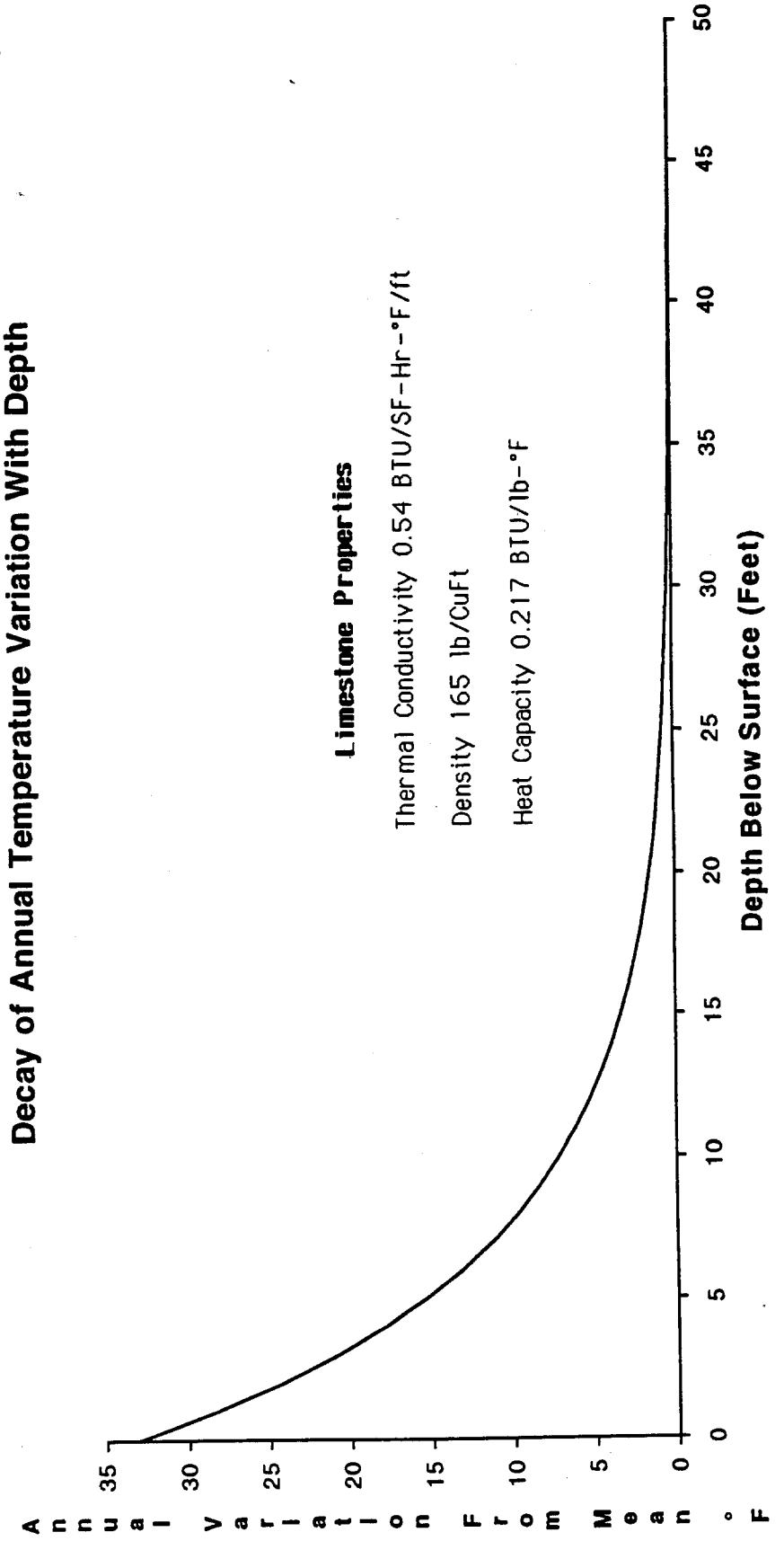


FIGURE 30

Decay of Annual Temperature Fluctuation With Distance Into Cave

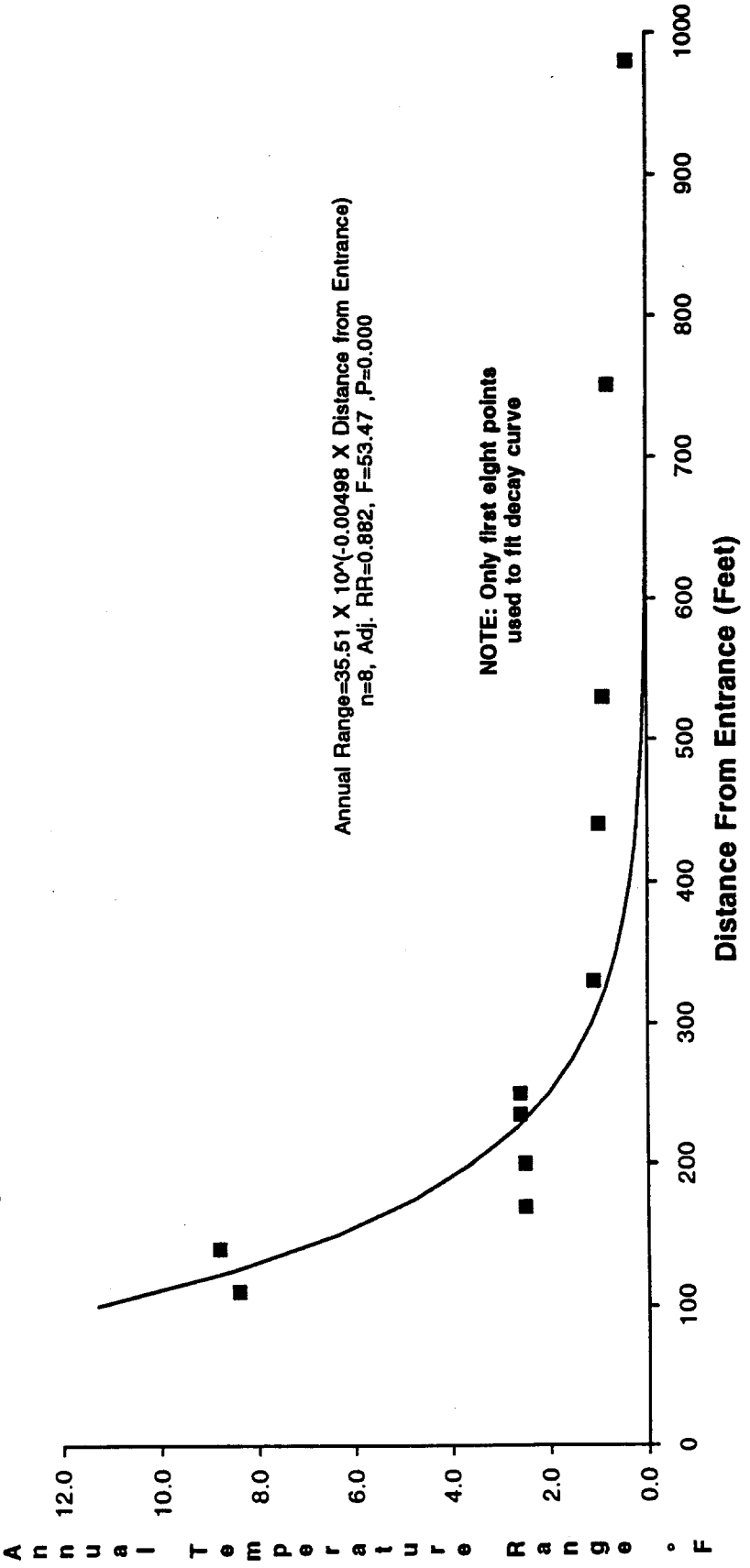


FIGURE 31

Lag of Time of Maximum Temperature With Distance Into Cave

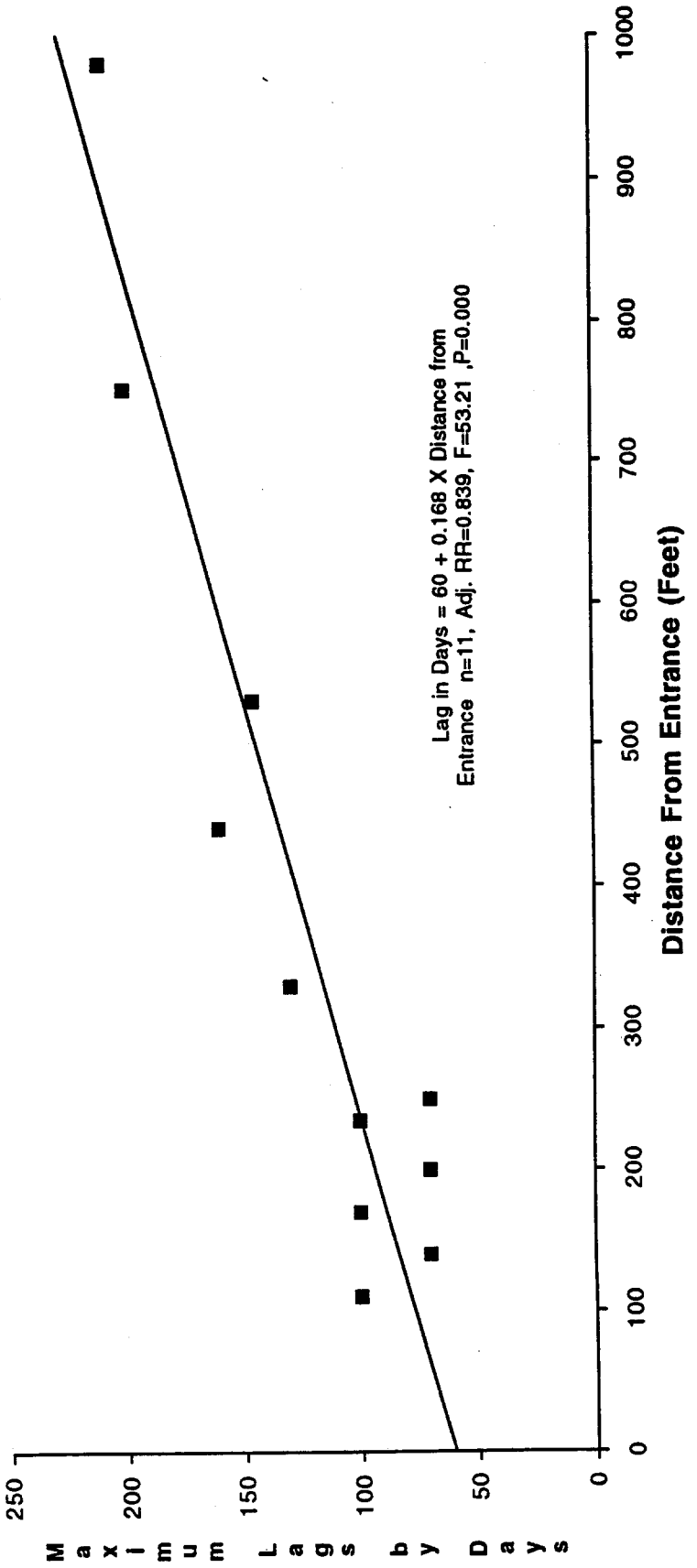
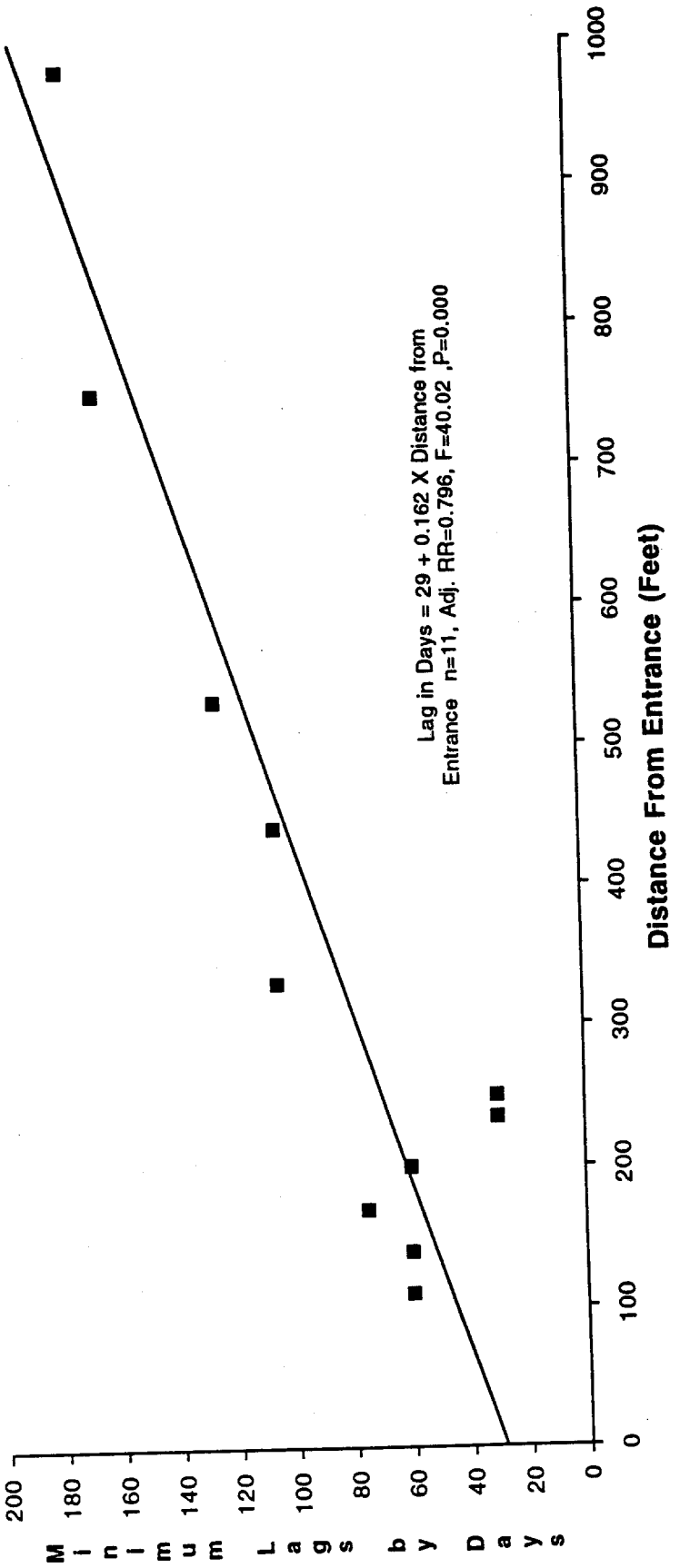


FIGURE 32

Lag of Time of Minimum Temperature With Distance Into Cave



ENTRANCE PASSAGE TEMPERATURES

The existing natural entrance to Kartchner Caverns is the only known connection to the surface. The majority of these studies indicate that it has a profound influence on the conditions throughout the cave.

Three types of surface temperature variations can affect the conditions within the cave; 1) the annual change in surface temperature, 2) diurnal temperature changes, 3) weather disturbances such as warm or cold fronts. Based on the data gathered, the major controlling factors influencing temperature variations in the entrance passages will be identified.

A short distance into the cave, a system of seven dry and wet bulb temperature probes has been connected to a computer data logging system. Temperatures have been recorded each hour since March 1989. Based on temperatures from the wet bulb and dry bulb probes, we can determine the approximate relative humidity. Figures 13 and 14 graphically portray the temperatures and relative humidities recorded in the LEM Room.

It is clear from these plots that temperatures and relative humidity follow an annual cycle. However, the temperatures at even this short distance into the cave do not mimic those on the surface. The peak temperature in the LEM Room is during late September and early October, indicating a lag of 3 months or more behind the surface. The lowest temperatures are in December, January and February and occur at approximately the same time as low temperatures on the surface. The annual cycle is markedly asymmetric; temperatures rise from March to September (7 months) and fall from October to January (4 months). The rise in temperature is much slower than the decline. An additional curiosity is the uniform rise in temperature from mid-June to mid-September. During this period the rise in temperature is remarkably uniform with only small fluctuations.

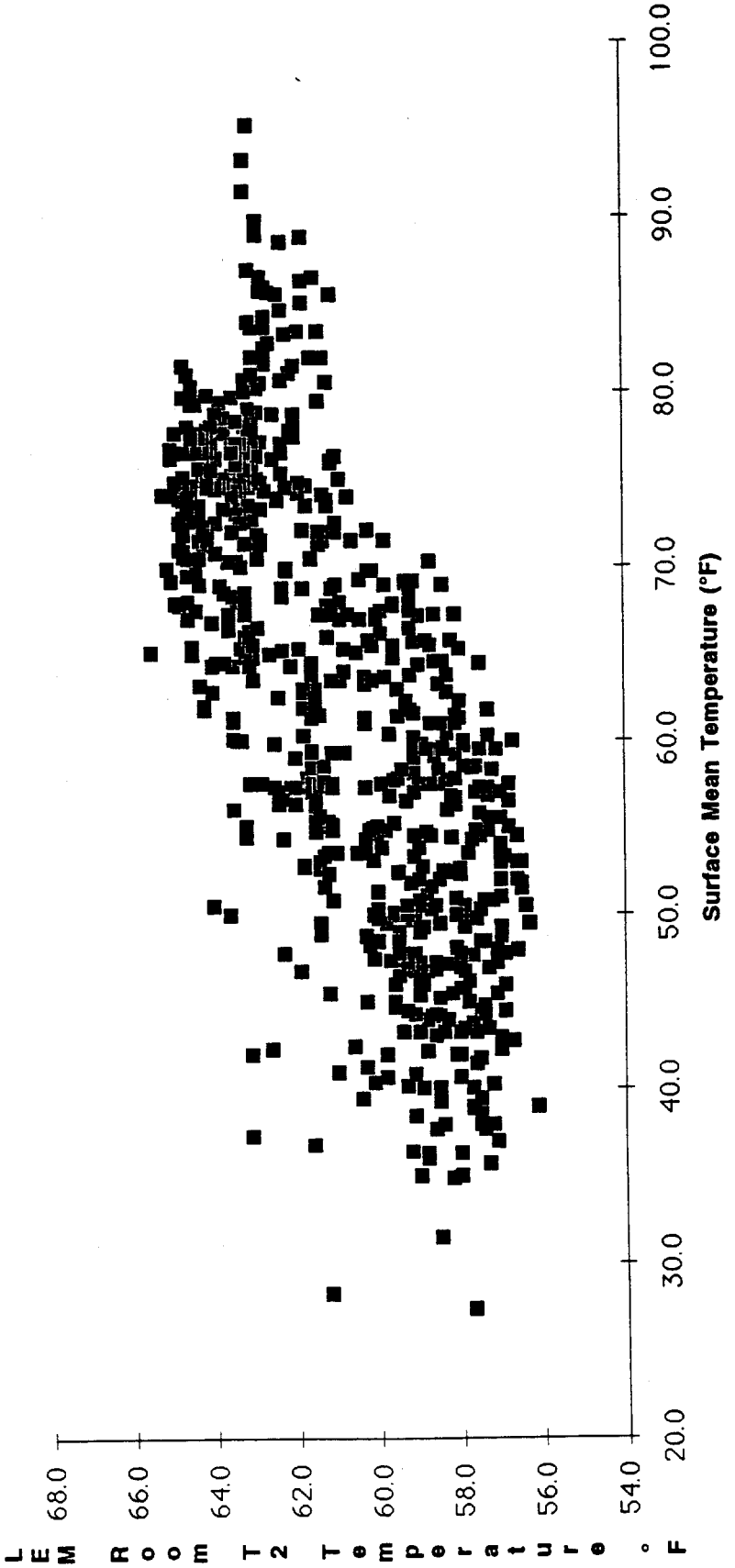
Examination of the annual cycles of relative humidity in the LEM Room reveals a similar pattern. Relative humidity is highest from mid-June to mid-September, when it is typically at or near 100%. During this time period, the relative humidity stays at a remarkably uniform level. The remaining months of the year show numerous short period fluctuations in relative humidity. The lowest relative humidity occurs during December, January and February.

The annual patterns of temperature and relative humidity can be explained partially by the predominent direction of airflow observed in the entrance passages. During the "winter" months cold, dry air flows into the cave. This quickly lowers the temperature in the entrance passages. Large fluctuations occur because of storms and short-term changes in the surface weather. During the "summer" from mid-June to mid-September, the airflow reverses and warm, moist air is blowing out of the natural entrance. As the interior temperature is at a near constant temperature, it maintains the temperature rise in the entrance passages at a uniform rate. The uniform rate of temperature rise and constant high relative humidity is caused by steady airflow out of the natural entrance during the summer months.

Additional insight into the operation of the natural entrance can be obtained by plotting the surface temperature against the LEM Room temperature as in Figure 33. Here we can see that the annual temperature cycle follows a closed loop. There are two possible explanations for this. The first is that the rock in the entrance passages is storing heat and the area of the interior of the annual loop is a measure of the heat storage. During the spring, temperatures rise slowly because the amount of heat stored is low and the surface temperature is also slowly rising. During the autumn,

FIGURE 33

LEM Room T2 Temperature vs. Surface Mean Daily Temperature



temperatures in the LEM Room fall rapidly because there is a larger differential between the now warm LEM Room and the rapidly falling surface temperatures. The second possibility is that the amount of moisture in the surface air is producing the effect. Winter and spring are times when the surface air is very dry, containing little moisture. This dry air will evaporate more water from the cave surfaces and tend to cool them more by evaporative cooling. This may explain why spring temperatures in the LEM Room are 3°F cooler than fall temperatures at the same surface temperature.

One way to decide which of these is the mechanism which controls the entrance passage temperatures is by performing a regression analysis on surface temperatures and LEM Room temperatures. A series of three regressions was done for each of the 23 months of complete records correlating surface conditions to LEM Room temperature (Table 6). The results of these regressions are summarized in Tables 7 and 8. Strong correlations (those with probabilities of being the result of random chance being less than 1%) were found for only 28% of the months. No correlation (probability of occuring by random greater than 20%) were found for 42% of the months. The remaining months, 30%, showed ambiguous correlations. Generally, those models that incorporated both surface temperature and surface air moisture content produced the best correlations. The models which contained only surface temperature produced the least number of correlations. While significant correlations were found, the amount of variance explained by these models was generally disappointing. It appears that surface weather is generally poorly correlated to temperatures in the LEM Room for much of the year. Other important variables must account for the remaining unexplained variation.

A significant pattern emerges when the months which have significant correlations and those with no correlation are plotted on Figure 34. Those months with significant correlations occur almost exclusively from August to February along the upper left half of the loop. Those months with no correlation occur from November to September almost exclusively along the lower right side of the loop. This indicates that significant correlations of surface conditions to LEM Room temperatures are found only when the temperature in the LEM Room is falling. When the temperature in the LEM Room is rising, no significant correlation with surface conditions can be found. These results can be interpreted to mean that the cave has two modes of operation. During the winter, surface air enters the cave and cools the entrance passages. During this time there is significant correlation between the LEM Room and the surface because the surface air is directly entering the LEM Room. During the summer and spring, the cave is blowing out warm air from the interior of the cave. The exhaled air is at a uniform temperature and humidity and is relatively unaffected by surface weather.

A new step-wise regression was done using monthly surface temperatures and surface air moisture content to predict LEM Room temperatures. The asymetric shape of the annual temperature fluctuations and the loops in Figure 34 indicate that the storage of heat in the entrance passages may be an important variable. A third variable was created: "Surface Degree Days". This is the running total of the mean surface temperature above or below the mean annual temperature. The Surface Degree Days is a measure of the potential heat storage. Heat can be added to the rock as long as the temperature is above the mean annual temperature. Heat is lost from the rock when the temperature is below the mean annual temperature. (For this analysis the mean annual temperature was 61.7°F. This differs from the correct mean temperature because only 23 months of the 24 months of data were complete enough to be used.) The data used in the regression is shown in Table 6. The step-wise

TABLE 6
Surface Temperature & LEM Room Temperature

Month	Mean Surface Temperature	Mean Surface Moisture	LEM Room T2 Temperature	Surface Degree Months	Predicted LEM Temperature
Jul-89	78.6	13.4	62.8	16.96	63.0
Aug-89	76.2	13.4	63.7	31.51	63.5
Sep-89	75.1	9.8	64.6	44.97	64.2
Oct-89	63.3	6.7	63.7	46.62	62.6
Nov-89	55.0	4.8	61.4	39.92	61.1
Dec-89	47.2	3.7	59.3	25.48	59.1
Jan-90	46.8	3.9	58.5	10.62	58.2
Feb-90	46.9	4.1	58.4	-4.13	57.4
Mar-90	55.1	3.8	58.7	-10.69	58.1
Apr-90	62.8	4.9	59.8	-9.59	59.2
May-90	68.8	5.5	61.4	-2.49	60.5
Jun-90	80.5	7.2	62.5	16.31	63.2
Jul-90	76.1	13.8	63.1	30.70	63.5
Aug-90	73.1	12.8	63.7	42.12	63.7
Sep-90	73.1	12.0	64.5	53.53	64.4
Oct-90	65.1	7.0	63.4	56.91	63.5
Nov-90	55.5	5.6	61.7	50.73	61.8
Dec-90	47.0	4.5	59.6	36.01	59.7
Jan-91	46.9	4.6	57.9	21.21	58.8
Feb-91	52.7	4.4	57.3	12.24	59.1
Mar-91	49.8	4.1	58.1	0.38	58.0
Apr-91	57.6	3.9	58.1	-3.69	58.9
May-91	65.4	4.8	59.6	0.00	60.2
Average	**61.7**	**6.90**	**61.0**	**22.0**	**60.9**
Std. Dev.	**11.7**	**3.62**	**2.4**	**21.9**	**2.3**

Surface Degree Months =Cumulative Sum(Monthly Temp - 61.7°)
Predicted LEM Temp = 51.08° + 0.139 Surf temp + 0.059 Surf Degree Months

TABLE 7
LEM Room Daily Temperature Predicted From Surface Temperature or Air Moisture Content

	LEM Temperature from Surface Temperature					LEM Temperature from Surface Air Moisture				
Month	Constant	Surf. Temp. Coefficient	Adjusted R squared	F	Probability	Constant	Air moisture Coefficient	Adjusted R squared	F	Probability
Jul-89	64.420	-0.020	0.064	2.578	0.123	62.240	0.043	0.104	3.670	0.068
Aug-89	*61.030*	*0.036*	*0.000*	*0.887*	*0.355*	64.710	-0.073	0.172	6.630	0.016
Sep-89	*64.160*	*0.006*	*0.000*	*0.105*	*0.749*	*64.600*	*-0.002*	*0.000*	*0.025*	*0.876*
Oct-89	**54.830**	**0.140**	**0.715**	**58.750**	**0.000**	61.850	0.280	0.224	7.640	0.011
Nov-89	**57.130**	**0.078**	**0.655**	**55.970**	**0.000**	**60.630**	**0.166**	**0.204**	**8.420**	**0.007**
Dec-89	**56.280**	**0.065**	**0.446**	**17.090**	**0.001**	*59.230*	*0.029*	*0.000*	*0.168*	*0.686*
Jan-90	*58.150*	*0.007*	*0.000*	*0.136*	*0.716*	57.730	0.190	0.176	7.200	0.012
Feb-90	*58.030*	*0.007*	*0.000*	*0.094*	*0.762*	57.430	0.230	0.054	2.530	0.124
Mar-90	*57.430*	*0.024*	*0.016*	*1.476*	*0.234*	57.700	0.276	0.134	5.640	0.024
Apr-90	*57.450*	*0.038*	*0.017*	*1.500*	*0.231*	60.820	-0.200	0.078	3.440	0.074
May-90	*61.390*	*0.001*	*0.000*	*0.001*	*0.980*	*61.110*	*0.062*	*0.000*	*0.747*	*0.397*
Jun-90	59.230	0.041	0.133	5.144	0.032	*62.756*	*-0.029*	*0.000*	*0.555*	*0.463*
Jul-90	*62.530*	*0.007*	*0.000*	*0.592*	*0.448*	*63.375*	*0.022*	*0.023*	*1.691*	*0.204*
Aug-90	**60.250**	**0.048**	**0.287**	**13.094**	**0.001**	*64.242*	*-0.040*	*0.005*	*1.159*	*0.290*
Sep-90	*64.240*	*0.004*	*0.000*	*0.247*	*0.623*	**65.081**	**-0.045**	**0.309**	**13.971**	**0.001**
Oct-90	58.970	0.068	0.144	6.034	0.020	**62.161**	**0.177**	**0.523**	**33.927**	**0.000**
Nov-90	*61.450*	*0.005*	*0.000*	*0.032*	*0.859*	60.235	0.249	0.188	7.701	0.010
Dec-90	*60.120*	*-0.011*	*0.000*	*0.147*	*0.704*	*58.950*	*0.140*	*0.014*	*1.440*	*0.240*
Jan-91	**52.520**	**0.114**	**0.276**	**12.440**	**0.001**	**55.200**	**0.591**	**0.710**	**74.360**	**0.000**
Feb-91	*58.210*	*-0.018*	*0.000*	*0.270*	*0.608*	**55.950**	**0.308**	**0.309**	**13.080**	**0.001**
Mar-91	*59.860*	*-0.035*	*0.023*	*1.719*	*0.200*	**55.260**	**0.688**	**0.334**	**16.080**	**0.000**
Apr-91	*55.170*	*0.050*	*0.029*	*1.621*	*0.218*	*57.840*	*0.059*	*0.000*	*0.089*	*0.770*
May-91	*57.310*	*0.035*	*0.000*	*0.512*	*0.480*	57.790	0.378	0.135	5.690	0.024

Numbers in BOLD indicate Significant Correlations ($p<0.01$)
Numbers in ITALICS indicate no Correlation ($p>0.20$)

Arizona Conservation Projects, Inc. 1992

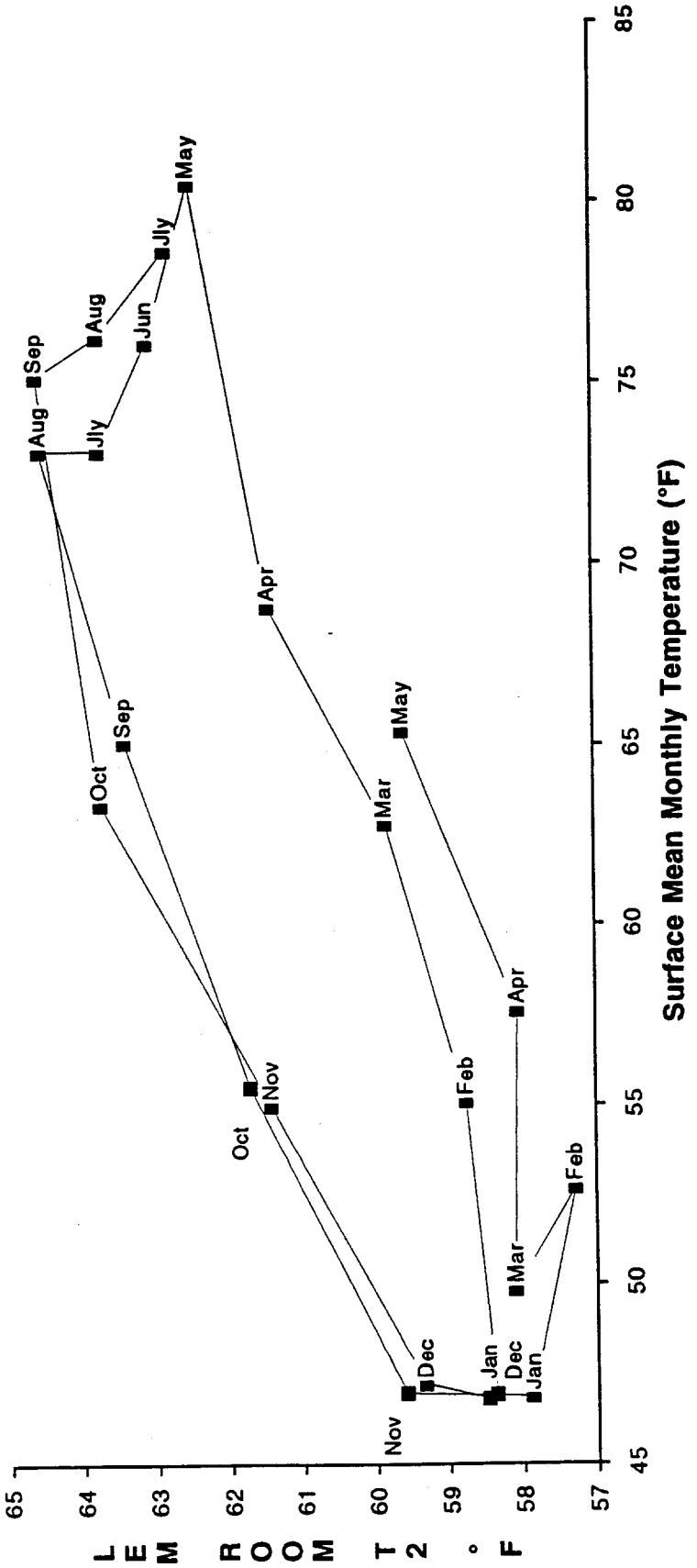
TABLE 8
LEM Room Daily Temperature Predicted .
From Surface Temperature and Air Moisture Content

LEM Temperature From Surface Temperature & Air Moisture						
Month	Constant	Surf. Temp. Coefficient	Air Moisture Coefficient	Adjusted R squared	F	Probability
Jul-89	62.940	-0.007	0.034	0.069	1.852	0.182
Aug-89	61.490	0.043	-0.075	0.191	4.179	0.027
Sep-89	*63.760*	*0.012*	*-0.008*	*0.000*	*0.155*	*0.857*
Oct-89	**54.960**	**0.128**	**0.098**	**0.730**	**32.061**	**0.000**
Nov-89	**57.140**	**0.071**	**0.037**	**0.697**	**34.280**	**0.000**
Dec-89	**56.190**	**0.065**	**0.026**	**0.423**	**8.316**	**0.003**
Jan-90	57.510	0.005	0.189	0.148	3.524	0.044
Feb-90	*57.480*	*-0.001*	*0.232*	*0.016*	*1.217*	*0.313*
Mar-90	55.910	0.031	0.302	0.186	4.420	0.021
Apr-90	*61.190*	*-0.005*	*-0.213*	*0.044*	*1.666*	*0.208*
May-90	*61.020*	*0.001*	*0.062*	*0.000*	*0.358*	*0.703*
Jun-90	59.461	0.040	-0.026	0.116	2.772	0.082
Jul-90	*63.003*	*0.005*	*-0.020*	*0.000*	*0.933*	*0.405*
Aug-90	**60.614**	**0.055**	**-0.072**	**0.390**	**10.582**	**0.000**
Sep-90	**63.668**	**0.023**	**-0.066**	**0.499**	**15.450**	**0.000**
Oct-90	**60.330**	**0.030**	**0.162**	**0.537**	**18.405**	**0.000**
Nov-90	62.229	-0.043	0.336	0.227	5.265	0.012
Dec-90	*60.430*	*-0.039*	*0.222*	*0.028*	*1.426*	*0.257*
Jan-91	**52.560**	**0.063**	**0.522**	**0.786**	**56.124**	**0.000**
Feb-91	**56.610**	**-0.012**	**0.306**	**0.287**	**6.432**	**0.006**
Mar-91	**56.700**	**-0.027**	**0.668**	**0.346**	**8.946**	**0.001**
Apr-91	*54.710*	*0.067*	*-0.135*	*0.000*	*0.937*	*0.409*
May-91	57.120	0.011	0.369	0.106	2.780	0.079

Numbers in BOLD indicate Significant Correlations ($p<0.01$)
Numbers in ITALICS indicate no Correlation ($p>0.20$)

FIGURE 34

Mean Monthly Temperatures - Surface & LEM Room



regression determined that only surface temperature and surface degree days were significant variables. These two variables explained over 90% of the variance. Temperatures in the LEM Room can be accurately predicted on a monthly basis with this simple model (Figure 35). Surface air moisture content did not explain a significant amount of the variance in the data.

The daily temperature in the LEM Room can only partially be explained by the surface temperature and surface air moisture content. Attempts to predict LEM Room temperatures show that the cave operates in two modes. During the fall and winter, cold air is entering the natural entrance and surface conditions influence temperatures in the LEM Room. During the spring and summer, warm air blows out of the natural entrance and surface conditions have little or no effect on temperatures in the LEM Room. Daily temperatures in the LEM Room cannot be adequately predicted solely from the surface temperature and surface air moisture content. The amount of heat stored in the rock surrounding the entrance passages is also a major controlling factor of temperatures in the LEM Room. Monthly LEM Room temperatures can be accurately predicted by including a term for the heat storage.

The diurnal or daily variation in temperature is not as large as the annual surface temperature variation and does not extend as far into the cave. The hourly temperature measurements taken in the entrance passages have been examined to determine how far the diurnal variation extends into the cave. The results are shown in Figure 36. This shows that the T3 probe located in the wood panel covering the Babbitt Hole has the greatest variation followed by the T2 probe in the LEM Room. Probes T5 and T7 in the Anticipation Room and Pop-up exhibit the lowest variation. At the T7 probe, the variation is barely discernible with the half-degree resolution of the datalogger. The graph also shows that the largest variations are during the winter to spring months. The months of lowest variation are July to December.

The same data has been analyzed to look for correlations in temperatures which have been lagged by 24 hours. The results of this correlation are shown in Figure 37. This also shows the highest correlation for probes closest to the entrance and generally decreasing with distance from the entrance. The graph has several peaks and lows. The lows correspond to times in the summer and winter when strong patterns of airflow exist. During these periods the strong directional airflow, out in the summer and in during the winter, overwhelm the daily variations. Broader peaks during the spring to early summer and autumn are times when airflow patterns are weaker. At these times, there is more fluctuation of air movement in the entrance passages.

The diurnal temperature variation is seen to extend at least as far into the cave as the Pop-up, approximately 200 feet from the entrance. At this point, fluctuations are less than 0.25°F. Examination of the temperatures from the Big Room datalogger, which has better temperature resolution, shows that only the Main Corridor station displays any diurnal temperature fluctuations. This station is approximately 350 feet from the entrance. The next two stations in the Big Room, Sharon's Saddle and Mud Flats, do not show any diurnal fluctuations. These stations are located approximately 400 feet and 500 feet from the entrance. Diurnal temperature fluctuations extend approximately 350 feet into the cave during the late winter months when airflow is predominantly into the cave. During the summer, when air is blowing out of the cave, there is little diurnal fluctuation except in the passages closest to the entrance.

FIGURE 35

Predicted LEM Room Temperatures From Surface Temperatures

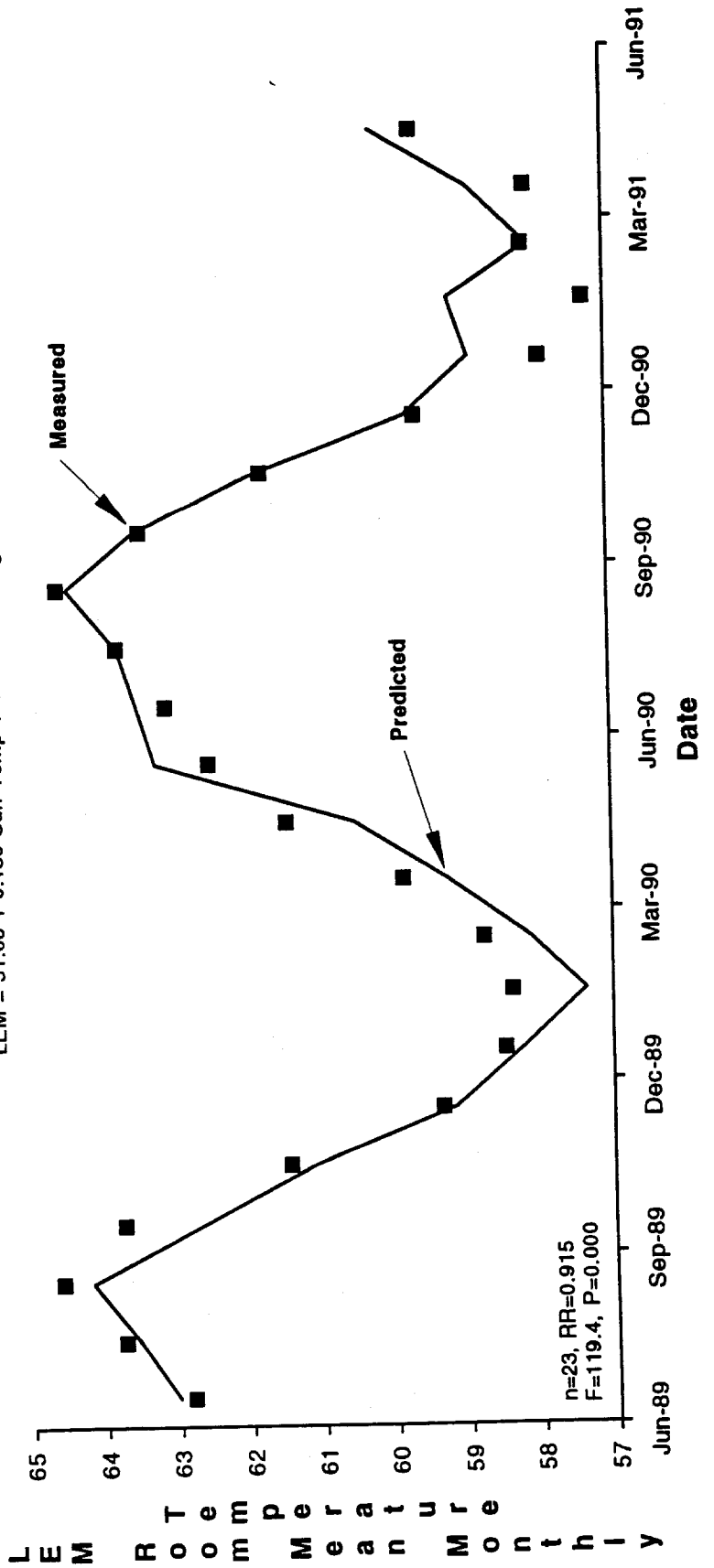


FIGURE 36

Entrance Passages - Hourly Variations by Month of Year

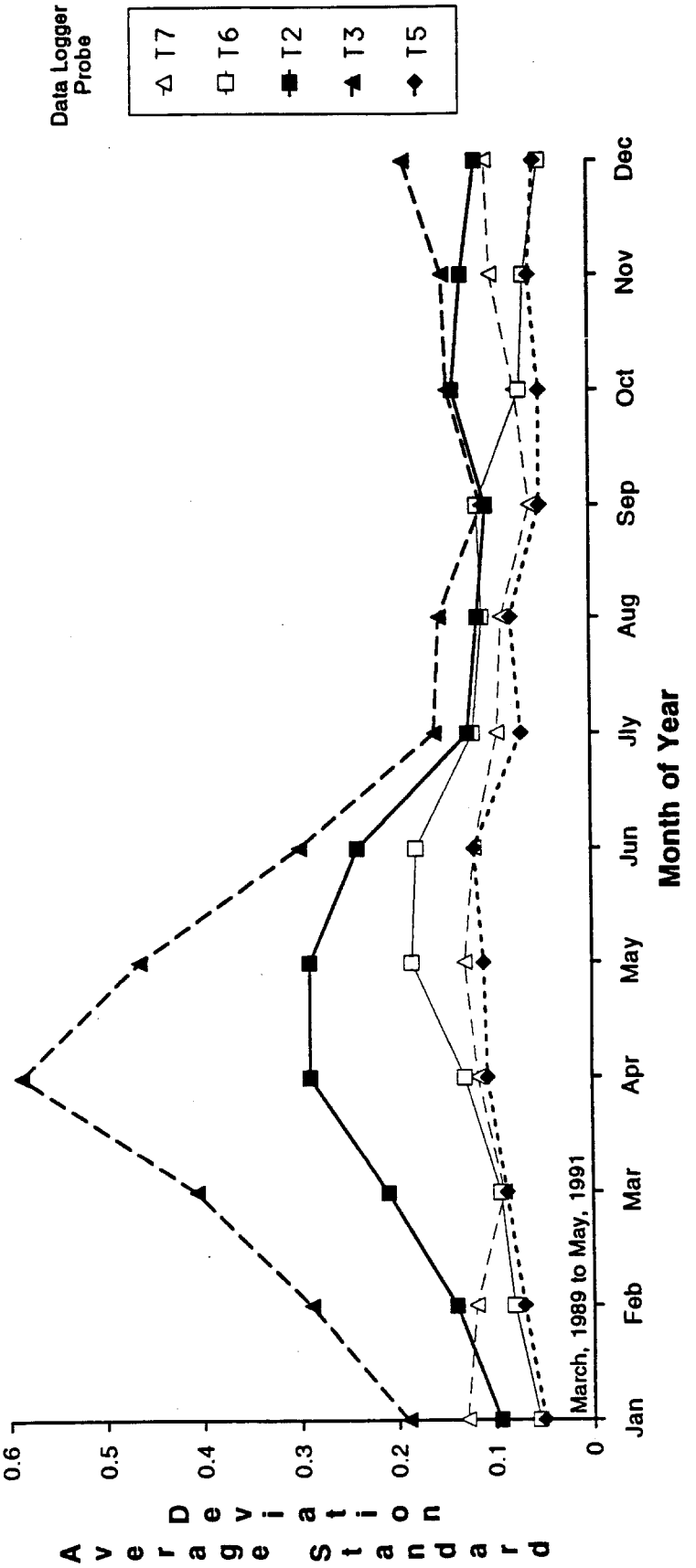
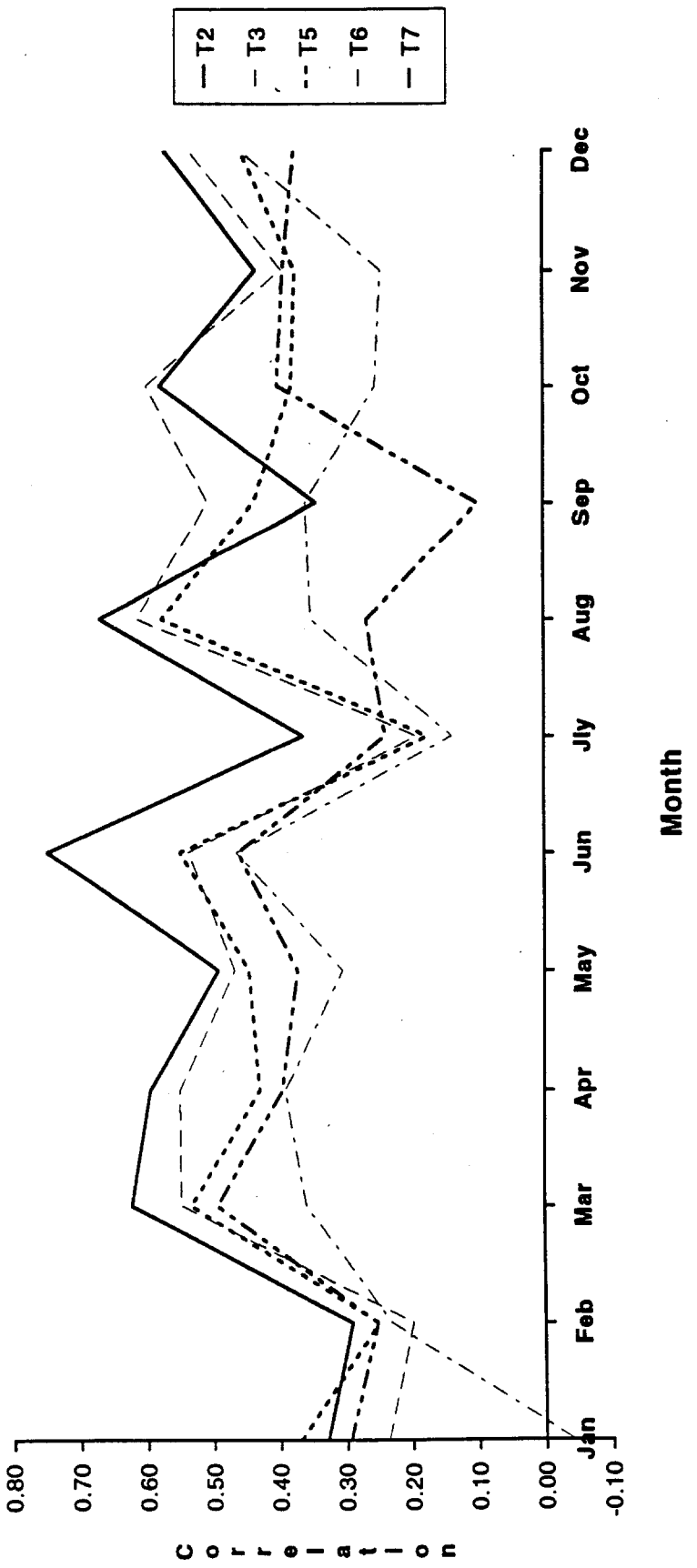


FIGURE 37

Autocorrelation of Entrance Passage Temperatures to 24 Hr. Lag



CAVE TEMPERATURE CONCLUSIONS

1. The cave is warmer than the mean surface temperature by several degrees. The most likely cause is a slight, regional geothermal heating of several degrees. The mean interior cave temperature (67.3°F) is the same as the temperature of Kartchner Well (67.3°F). Because the cave is warmer than the mean surface temperature, there is a greater temperature differential between the cave and surface during the winter than during the summer. This is likely to produce stronger airflows during the winter than during the summer.

2. The Back Section of the cave, including Subway Passage, Pirate's Den and Pyramid Room to Granite Dells, are approximately 2°F colder than the rest of the cave. Temperatures in this area are still warmer than the mean surface temperature. The cooling is apparently due to flooding of the cave. Generally, this occurs during the winter when surface water is much colder than cave temperatures. An alternative explanation is cooling due to the proximity of Granite Dells to Guindani Wash which would act as a channel for cold air. The Pirate's Den may be colder due to lying under a north-facing slope. (Temperatures in the Pirate's Den become colder toward the north end of the passage.)

3. The Big Room is the warmest part of the cave. This is most likely due to stratification of air in the Big Room during the winter. Cool, dry air from the surface flows along the floor through parts of the Big Room and into the River Passage. At the interface between the cool air on the floor and warmer air above, a condensation fog forms. Condensation releases heat which warms the overlying air. A second possible explanation is that the warming of this part of the cave is due to conduction of heat through the overlying rock. This is not as likely because the predicted temperature rise would be smaller than is observed and would occur at different times of the year due to the different thicknesses of overburden.

4. The influence that the natural entrance has on the microclimate of the cave can be observed to extend at least 700 feet into the cave and perhaps as far as 1000 feet. Diurnal fluctuations in temperature extend at least 200 feet into the cave. The zone of influence is smaller than predicted by some theories on the distribution of temperatures in caves. This may be due to the large variations in the size of the entrance passages. This may also indicate that enlargement of the entrance passages could result in substantial temperature changes in the front sections of the cave.

5. Patterns of temperatures in the entrance passage show the influence of cold air entering the cave during the winter months. During this "winter" period, temperatures show large fluctuations. During the summer air blows out of the cave and temperatures are quite stable in the entrance passages.

6. Heat storage in the rock along the entrance passages plays a significant role in controling the temperature of the entrance passages.

CAVE AIRFLOW

Air exchange between the cave and the surface has been identified as one of the major routes by which moisture is lost from the cave. For this reason, controlling the rate of air exchange is one of the most important tasks in developing the cave. Airflow is also strongly related to other processes within the cave, such as the concentration of carbon dioxide and radon gas. Unfortunately the concentration of these trace gases is also an important management issue. Increasing rates of air exchange would lower

the concentrations of these gases but would also result in increased evaporation, drying of the cave and potentially irreparably damaging the beauty of the cave. A knowledge of how these three parameters, evaporation, carbon dioxide and radon, are related to airflow is necessary in order to predict the likely effect of development. The maximum concentrations of both of these gases is determined by the air exchange rate. Estimates of the rate at which air is exchanged have been made by several different approaches. These range from direct measurement of airflow to estimates based on concentrations of trace gases and conservation of mass and energy. No one method has given a clear-cut picture but together they give a consistent overall estimate of the air exchange rate.

In the remainder of this report, it is necessary to understand the different types of airflow. For consistency, 'ventilation' will be used to indicate air exchange between the surface and the cave. Air 'circulation' will be used to refer to internal patterns of air movement within the cave. These are generally not associated with or caused by ventilation. Rather, they are internal circulation cells that distribute moisture and heat throughout the cave. The significant point to remember is that even if all surface air exchange were stopped, there would still be internal air circulation.

AIRFLOW MEASUREMENTS

The most reliable method for determining the rates of air exchange is by direct measurement of the quantity of air entering and leaving the cave. Unfortunately the entrance passages of the cave are complex with many small openings which allow air to move through. Only the largest of these passages are big enough to allow people to traverse. There is no single passage in the front part of the cave for which we can be sure all the airflow must travel through. As a result, airflow measurements can only give us a lower limit on the rates of air exchange.

The equipment used to measure airflow consisted of a sensitive hotwire anemometer, airflow direction indicator, wet bulb and dry bulb temperature sensors and an atmospheric pressure sensor hooked up to a datalogger. Measurements were taken approximately 11 times per minute. The one-minute average of each parameter was then stored in the computer. Data collection runs were limited by battery life and data storage requirements to approximately 40 hours. Data was downloaded from the datalogger to another computer and uploaded for analysis. Airflow was measured at the interior end of the Blow Hole crawlway (Figure 38) and at the entrance to the River Passage. Airflow was measured a total of 22 times and these observations yielded a total of 22.7 days' worth of data. The Blow Hole was measured on 15 occasions with a total of 13.89 days' worth of data collected. Airflow at the start of the River Passage was measured on two occasions and a total of 3.23 days' worth of data was collected. Additional measurements were made in the LEM Room and at Mud Flats in the Big Room. Results of these measurements are contained in Appendix E.

A portion of the data from the Blow Hole has been examined in greater detail in order to understand the airflow near the entrance of the cave. A series of measurements taken during the winter of 1989 and 1990 were selected because they represent a near continuous record of air flow. This data is summarized in Table 9. Figure 39 illustrates a typical graph of data collected. Note that the plotted pressure has not been temperature corrected.

The most surprising finding of the airflow measurements is that, during the winter months, the direction of airflow is overwhelmingly into the cave. The direction of air movement is into the cave for 97% of the measurements. Direct observation of airflow

directions confirm that air is moving almost exclusively into the cave at the Blow Hole during the winter. This is conclusive proof that the cave is functioning as a "chimney" during the winter. Cold dense air enters at the natural entrance, becomes warmer and rises out of openings at a higher elevation. This is the "chimney effect", warm air rises and displaces cold air above (Moore and Sullivan, 1978). A similar effect occurs in caves, where differences in elevation between entrances and differences in temperature in various areas of the cave and on the surface produce air density gradients which cause air to flow through the cave. The naturally induced airflow is usually strongest in the winter, weakest in the summer, and subject to semiannual reversals in the spring and fall.

The airflow measurements show that an opening to the cave must exist at a higher elevation than the natural entrance.

TABLE 9
Airflow Measurements at Blow Hole

Start Date	Sample Time	Air Movement*	Airflow/Day
12/23/89	0.44 days	10,784 feet (IN)	24,509 ft/day
12/27/89	0.26 days	6,787 feet (IN)	26,104 ft/day
12/29/89	0.35 days	11,099 feet (IN)	31,711 ft/day
12/31/89	0.18 days	11,330 feet (IN)	62,944 ft/day
01/12/90	1.74 days	47,743 feet (IN)	27,438 ft/day
01/14/90	1.39 days	30,383 feet (IN)	21,858 ft/day
01/16/90	1.71 days	51,219 feet (IN)	29,953 ft/day
TOTALS	6.07 days	169,345 feet (IN)	27,899 ft/day

* A minor amount of air moved out of the cave during these measurements. The total airflow out was 5,864 feet or 3.4% of the inflow.

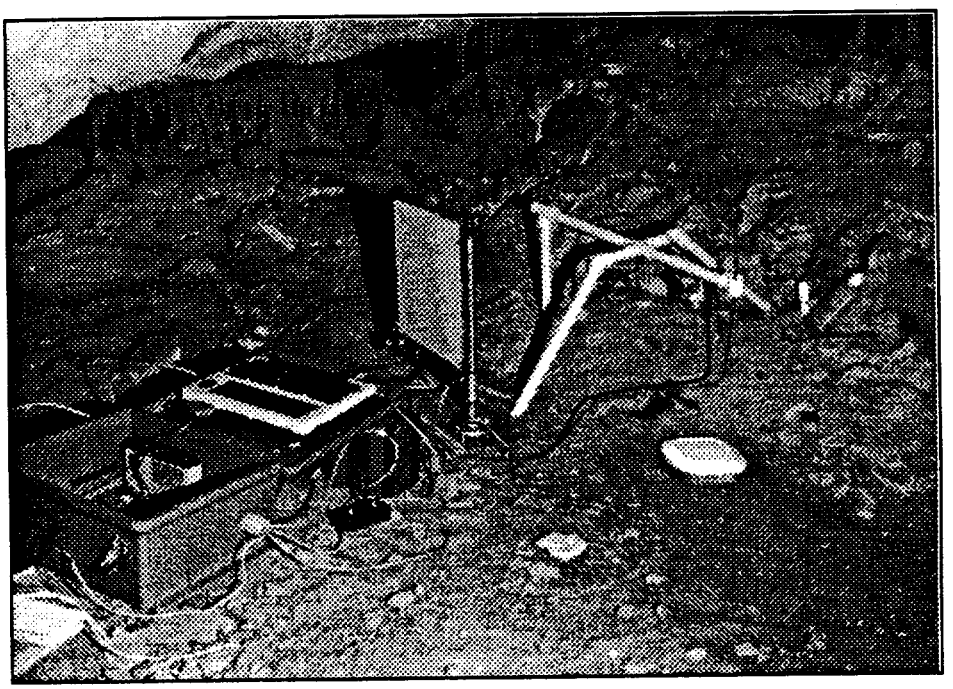
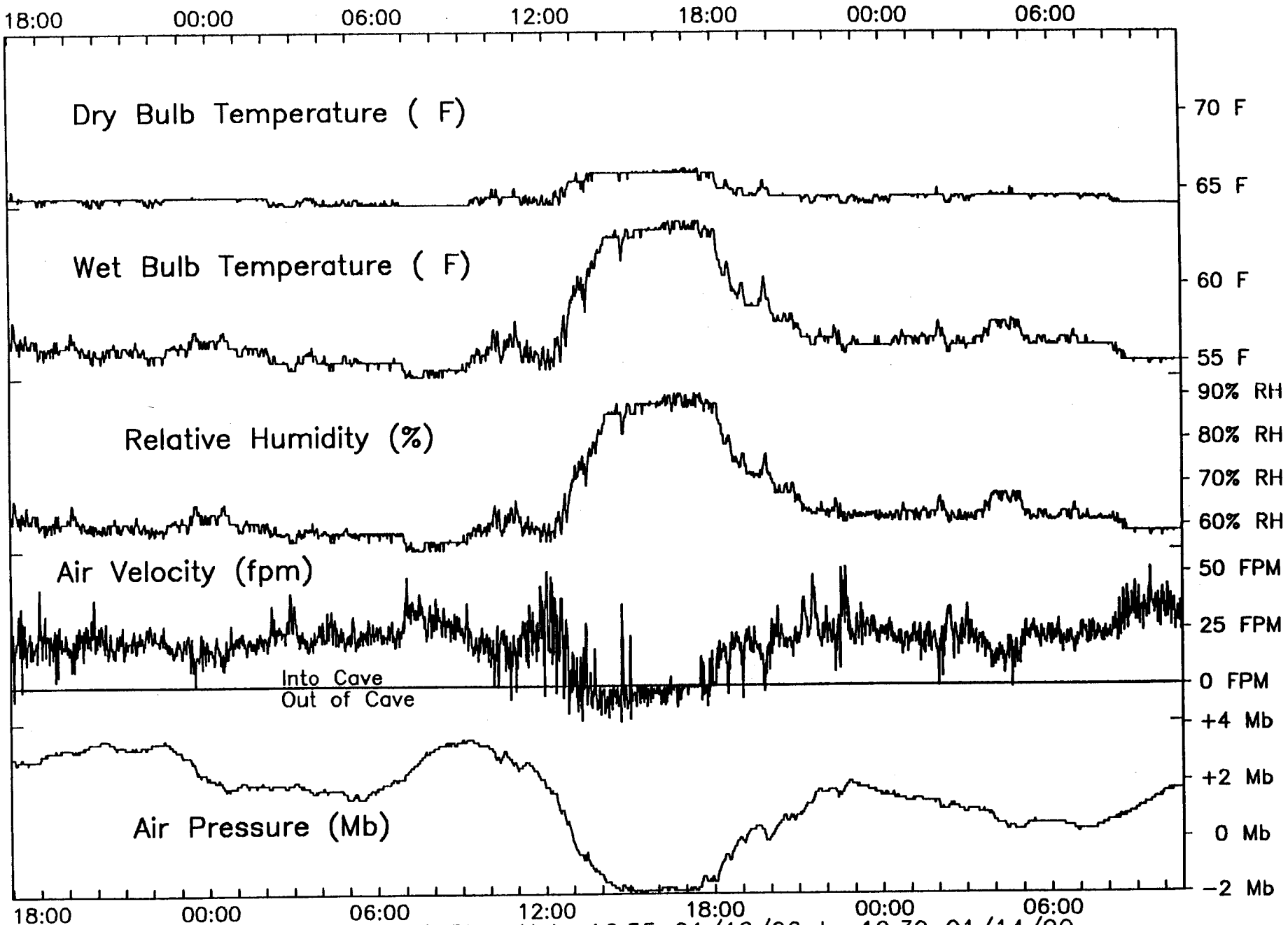


Figure 38. Computer datalogger set up to measure airflow, temperature and humidity at the Blowhole Gate



Airflow Measurements at Blow Hole 16:55 01/12/90 to 10:39 01/14/90
(1 minute averages of 6 second readings) Total Airflow Into Cave = 47,743 feet
Out of Cave = 1,070 feet

FIGURE 39

Arizona Conservation Projects, Inc. 1992

Air flow was measured at the interior end of the Blow Hole crawl, approximately 10 feet past the gated constriction. The area of the passage where airflow was measured is estimated to be 5 sq. ft. The average airflow at this location is 27,899 ft/day X 5 sq.ft. = 139,495 cubic feet day of air entering the cave (3,950 m^3/day).

The Blow Hole is not the only known route for airflow. Air is certainly also entering through the Babbitt Hole and other small openings in the LEM and Crinoid Rooms. Based on the area of these other openings, it is roughly estimated that 1/3 of the airflow is through the Blow Hole. This yields an estimate of 3 X 140,000 ft^3/day = 420,000 ft^3/day for airflow into the front part of the cave. Airflow cannot be appreciably more than this without creating a noticeable airflow in other parts of the Big Room.

Based on environmental station data and soil temperature surveys, the natural entrance appears to be the primary connection to the outside. However, during the winter, airflow measurements show that air flows almost exclusively into the cave. This can only happen if there is another opening at a higher elevation than the natural entrance, thus creating a "chimney effect". No enterable opening has been found during several searches on the surface. The total area of this opening needs to be only a few square feet. It may also be composed of several smaller openings and covered by loose soil materials. Based on the observed airflow patterns in the cave, there appears to be only a single additional opening. There is no evidence to suggest that there are additional openings in the Big Room.

During the winter, there is a steady flow of air from the natural entrance into the River Passage. Approximately $^2/_3$ of the airflow measured at the Blow Hole is also measured entering the River Passage. This indicates that the most likely location for a higher opening is in, or beyond, the River Passage. Likely locations along the River Passage are in the ceiling of the Bath Tub Room or the ceiling of the Grand Canyon. The area around the Bath Tub Room is known to be fairly close to the surface and this area corresponds to a broad low in the Radalert readings. The airflow along the River Passage, however, has been observed to continue past this area. This indicates that very little airflow can be leaving the cave near the Bath Tub Room. During the winter, a steady breeze can be followed through the Thunder Room, Shelf Passage and into the Grand Canyon Passage. The steady airflow which can be followed from the entrance to the start of Grand Canyon becomes lost in the large passageway and cannot be followed further. A continuation of this airflow can seldom be found in the crawlway at the end of Grand Canyon into the Pyramid Room. Condensation fog is also frequently visible in the Grand Canyon.

All of these are indications that the ceiling of the Grand Canyon passage is the location where airflow is leaving the cave. There is a large opening high in the ceiling at the start of the Grand Canyon which may be the exact location. The bedrock in the Grand Canyon passage is quite fractured and it is not difficult to envision small cracks and fissures continuing to the surface. It is also possible that the opening is located in the collapsed breakdown cone off the Onyx and Marble Canyon Passages. This area of the cave, from Granite Dells to Pirate's Den, is unusually cold due to winter flooding. However, the area around these passages is slightly warmer than the adjacent areas. This warming may be due to warm summer air entering the cave. The pattern of airflow in this area is poorly understood. The complexity of the breakdown areas and multiple passages and connections makes it difficult to follow airflow. A final, but less likely, candidate is in the ceiling of the Throne Room. Air has been observed flowing into the Throne Room from the Rotunda Room on several occasions during the spring. The Throne Room is the highest point in the cave and an opening here would induce

the strongest chimney effect. However, the observed airflow is intermittent and does not coincide with the times of strongest airflow at the entrance.

The best candidate areas for the location of the other opening appear to be the ceiling of the Grand Canyon or in the breakdown near the Onyx and Marble Canyon passages.

In the summer, the airflow pattern appears to stagnate or perhaps weakly reverse. Moist air frequently flows out of the natural entrance but not as strongly as dry air which enters in the winter. The fact that the airflow measured entering the cave during the winter does not vary appreciably with outside temperature indicates that the size of the upper opening is controlling the amount of airflow. This pattern of airflow is consistent with a small impassable opening located on the hill somewhere above the natural entrance.

Identification of the location of the opening would be important. The size of the opening appears to be the controlling factor in the quantity of air flowing through the cave during the winter. Any surface construction which modified the size of the opening(s) could change the amount of air entering or leaving the cave. A larger or less restrictive opening would increase the amount of airflow through the cave. Blocking of the opening(s) would result in less air exchange.

While the exact location of the suspected upper opening is not known, we can make a reasonable estimate of the pressure difference between the natural entrance and the upper opening. The natural entrance is at an elevation of 4660 feet, while the highest point on the hill above the Throne/Rotunda Room is at 4880 feet and the maximum difference in elevation is therefore about 200 feet. A rough rule of thumb for estimating the pressure difference is: Pressure head at sea level is 0.03" of water per 10°F difference in average temperature per 100 feet of elevation difference (McElroy, 1966; Hartman, 1982). The anticipated pressure head has been calculated based on an elevation of 4660 feet, a 200 foot elevation difference, an average cave temperature of 67°F, a January mean surface temperature of 47°F and a July mean surface temperature of 80°F. The average winter pressure head is estimated to be 0.26 millibars and the average summer pressure head is 0.16 millibars. The anticipated pressure head on the warmest day (105°F) and the coldest day (20°F) have also been calculated as 0.49 millibars and 0.60 millibars, respectively. The pressure head is quite small, ranging from about 0.2 to 0.6 millibars. This is much smaller than the average daily variation of 4.9 millibars. This indicates that airflow through the cave should still respond to rapid changes in air pressure on the surface such as may be produced by wind blowing across the hillside.

If the cave acts as a chimney, the driving force would most likely be the difference in air density created by air within the cave being warmed or cooled. The strength of the air movement would be dependent upon the difference in temperature between the cave and surface. A portion of the airflow measurements have been examined to determine if there is a strong relationship between surface temperatures and air velocity at the Blow Hole. Data sets for January 12 to 16, and January 16 to 18, 1990 were analyzed. Results of regression analysis for each set of data is included in Appendix E. A small but significant correlation was found for both data sets. Adjusted correlation coefficients were much smaller for these correlations than for correlations involving air pressure. Typically, surface air temperature accounts for only one-third of the variance explained by air pressure. This indicates that while surface temperature variations exert some control on air velocities, the major control is air pressure.

A regression was done to determine if the amount of air stored within the cave was an important component in determining airflow. Air is a compressible fluid and this must be taken into account in determining the quantity that can be stored within the cave. Air which enters the cave can change volume in either of two ways. First, if the air pressure inside the cave is different than on the surface, the incoming air will either expand or contract. Second, if the incoming air is at a different temperature than the cave, it will expand or contract as it reaches the cave temperature. The amount of storage can be calculated from the measurements taken at the Blow Hole. The relationship used to calculate storage is:

$$\text{Storage} = \left(\frac{P_{surface}-P_{cave}}{P_{cave}}\right) \times \text{Vol} + \left(1+\frac{Temp_{Cave}-Temp_{Surface}}{527.67}\right) \times Airflow_{In} - Airflow_{Out}$$

Results of the correlations for two sets of data are given in Appendix E. The regressions indicate that storage of air within the cave is an important part of the airflow mechanism. The coefficients of the equations for both data runs are very similar. The derived equations are:

1/12 to 14/90

Velocity (ft/hr) = 3453 ft + 0.325 $Temp_{Surface}$ - 1162 Pressure + 0.198 Storage

1/16 to 18/90

Velocity (ft/hr) = 3266 ft + 2.020 $Temp_{Surface}$ - 1136 Pressure + 0.191 Storage

For both equations, the most significant variables are Pressure and Storage, with Surface Temperature being the least significant. These correlations should be considered as valid only for the winter months at the Blow Hole.

The results of attempts to correlate air velocity at the Blow Hole with surface barometric pressure and air temperature indicate that barometric pressure and storage are the most significant controls on air velocity at the natural entrance. Surface temperature plays a lesser role. This is consistent with an upper opening which is quite small and which has considerable resistance to increased rates of airflow. The primary control of air velocity on a day to day basis is air pressure and air storage within the cave. While surface air temperature is not the major control of day to day air exchange, the annual pattern of surface air temperature exerts a major influence on the amount of air exchange taking place.

In order to assess the importance of evaporation on the moisture balance of the cave, it is necessary to know the volume of air within the cave. The volume of air in the cave can be determined from the survey data of the cave (Appendix K). At each survey station, the passage dimensions are estimated. This allows the volume between survey stations to be computed. This method works well in small passages, but in the larger rooms, the walls are far away and the survey does not always follow the main trend of the room. For the largest rooms and passages, a series of cross-sections were made. From these cross-sections, the average area of the room can be computed. A series of cross-sections along the length of a room allows the volume to be determined. The total volume of the cave has been determined to be approximately 5,000,000 cubic feet.

The volume can also be determined from the airflow measurements. When the surface air pressure changes, the air inside the cave attempts to maintain equilibrium

with the surface air. By plotting the change in air pressure against the air velocity, we can see that the plot forms several large loops. The area inside of the loop is the volume of air stored in the cave due to the change in air pressure. Figure 40 illustrates one large loop, labeled as area 'a'. The area is 54,216 cubic feet of storage as a result of a 7.1 millibar pressure drop. Knowing the average atmospheric pressure to be 855 millibars, we can estimate the volume of the cave as 855/7.1 X 54,216 cubic feet = 6,500,000 cubic feet total volume. Additional estimates of volume made in this way range from 3,300,000 to 6,750,000 cubic feet (see Appendix E). The average of four determinations is 5,000,000 cubic feet, the same as determined by surveying the passage dimensions.

The good agreement between these two methods indicates that most of the cave is known and that large undiscovered rooms either do not exist or are poorly connected to the rest of the cave. We know from the predominant direction of airflow into the cave during the winter that there must be a higher opening. However, the fact that the cave also stores air indicates that the openings to the surface are not large enough to allow for rapid equalization of cave and surface air pressure. This indicates that the natural entrance is the primary point for air exchange.

The airflow data has also been analyzed to determine if the cave resonates in response to periodic fluctuations in surface air pressure. This type of airflow has been observed in a number of caves (Moore and Sullivan, 1978; Sartor and Lamar, 1962). The direction of airflow will periodically reverse. Depending on the size of the cave chambers and the geometry of the entrance, the period can range from a few minutes to a day or more. The periodic reversals in airflow are apparently driven by fluctuations in winds near the entrance or longer term barometric pressure fluctuations.

The most likely periods for a cave to resonate at can be approximated by considering the cave to act as a simple helmholtz resonator. This is the same type of resonance produced by blowing across the mouth of a bottle to make it hum. A larger bottle has a lower frequency. Caves are so much larger that the resonant frequency is very low, with periods that may be as long as several hours. Based on the known volume of Kartchner Caverns and the passage geometry of the entrance passage and River passage, the most likely range of resonances was identified. The front section of the cave is estimated to have a resonate period of 50 to 150 hours. The back section of the cave should have resonate periods of 80 to 260 hours. These are very long time periods, from 2 days to over 10 days. It is unlikely that periods of this duration can be identified. It is also possible that smaller areas of the cave will resonate. The resonate period associated with the Blow Hole crawl is expected to be 5 hours. To identify a resonant period, we require having a set of measurements at least twice as long as the period. The longest data set is about 40 hours, so this limits us to identifying resonances with periods of less than 20 hours. Therefore we will not be able to confirm the predicted resonances for the front or back sections of the cave.

In order to identify this type of airflow pattern, we need to identify reoccurring periodic airflow patterns. The data from the Blow Hole measurements on 1/16-18/90 were used. Periods in the data were found using a Fourier transform. The resulting plot of all the periods identified in the data is shown in Figure 41. The general flat shape of this plot and a lack of peaks in the data indicate that no resonances with periods less than 16 hours are present in the data. It is unlikely that the longer resonances predicted for the front and back sections exist. The day to day changes in normal barometric pressure are probably random enough to prevent a resonance from developing.

FIGURE 40

Blow Hole Air Movement vs. Air Pressure

1/12/90 17:00 to 1/14/90 10:00

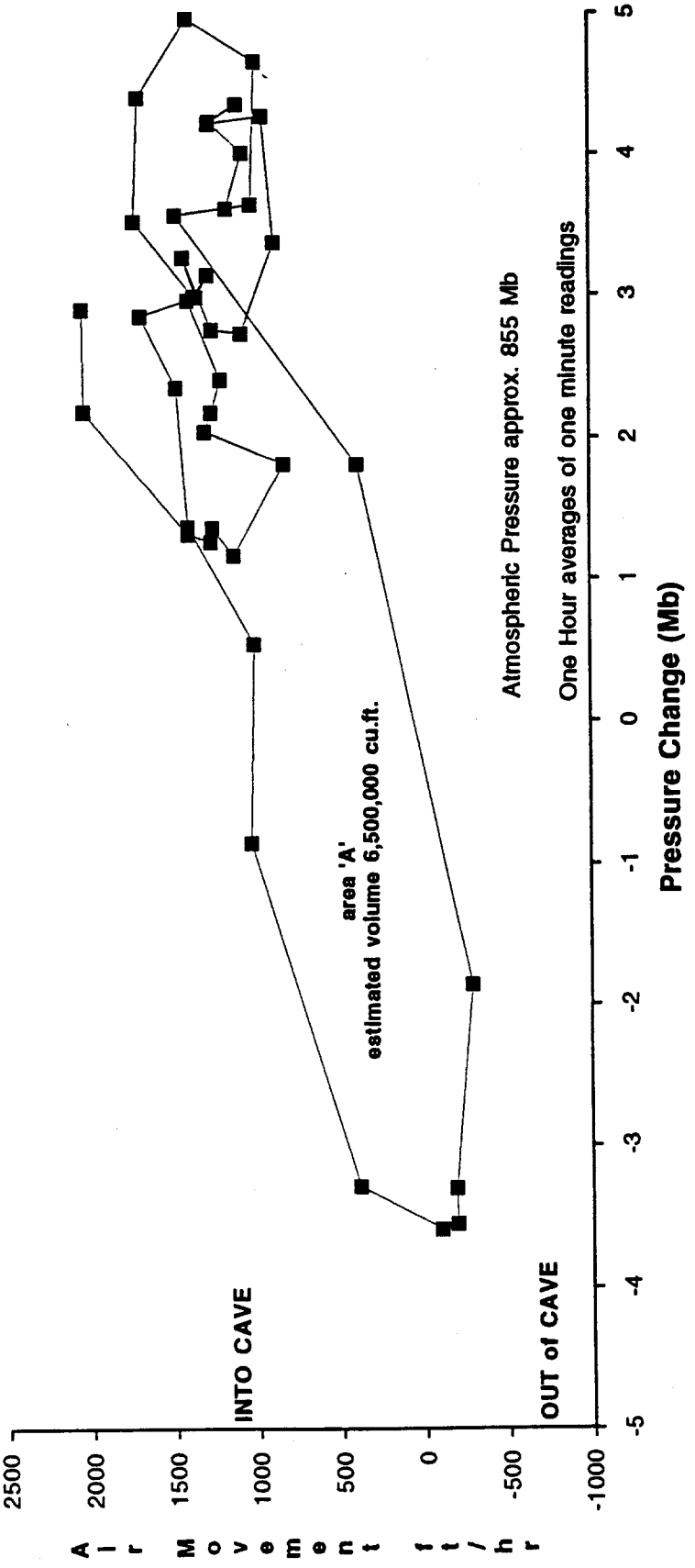
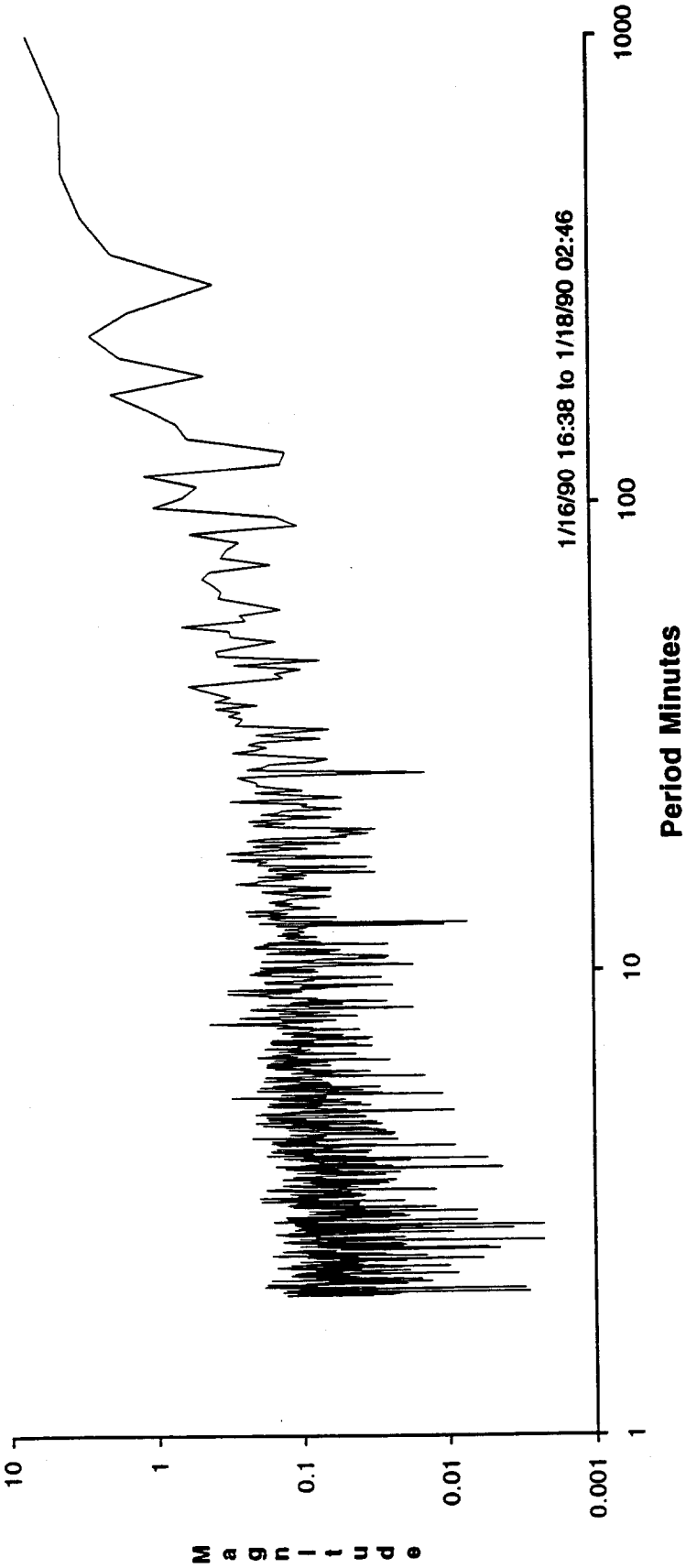


FIGURE 41

Blow Hole Airflow Periodogram



CAVE AIRFLOW PATTERNS

The pattern of airflow through the cave can be deduced by several different methods. First, the airflow direction can be sensed in constricted passages if there is sufficient air movement. In larger passages and rooms, the air velocity is too slow to be observed directly. A second method is to observe the growth patterns of the cave formations. Sustained patterns of airflow for long periods of time can influence the growth, orientation and type of speleothems.

A third method involves the measurement of the properties of the air. The amount of alpha radiation particles, relative humidity and CO_2 in the air are all indications of how long the air has been in the cave and how frequently it is exchanged with outside air. A final method is by examining the rate at which soil temperatures change throughout the cave. Areas near existing connections to the surface will have large horizontal temperature gradients. The size of the area influenced by an entrance is dependent on the size of the opening and predominant direction of air movement.

The volume of air entering the cave has been measured by ACPI at the Blow Hole and start of the River Passage for a total of 6.07 days. The average volume of air measured entering the cave is 140,000 ft^3/day. Airflow is also thought to be entering the cave through other openings in the entrance passages than those measured. Based on the estimated areas of these passages, the total volume of outside air entering the cave is estimated to not exceed three times the observed airflow, or 420,000 ft^3/day.

During all periods of measurement, the direction of airflow was overwhelmingly into the cave (97%). The simplest explanation for this would be the existence of another opening(s) at an elevation above the natural entrance. No evidence of such an opening has been found within the cave. It is thought that the upper opening(s) is either very small or partially blocked by rubble. It appears that the size of this upper opening is what controls the volume of air entering the natural entrance.

Air motion within the cave is generally too slight to be detected. However, in some portions of the cave where the size of the passage suddenly constricts, airflow can sometimes be felt. Based on these observations, a pattern of airflow can be inferred (Figure 42). Additional information on long-term air direction can be gained by studying the growth patterns and orientation of certain cave features (Figure 43). By using both methods, the following pattern of winter airflow is hypothesized.

The natural entrance is the point at which most air enters the cave. In the Anticipation Room, airflow divides, with part going into Main Corridor and the remainder going to Grand Central Station. Surface air is cooler and drier than cave air which also makes it denser and it flows along the floor in a thin layer. Air flows along Main Corridor and under the breakdown of the Big Room. There is no general airflow pattern in the Big Room during the winter. Outside air which enters the cave is denser and flows along the floor. This displaces the warmer, more humid air, in the Big Room and results in a stratification of air. Warm, moist cave air forms a layer starting several feet above the floor. At the interface of these layers, fog and condensation is frequently observed. The air which enters Grand Central Station flows under the breakdown through Australia and exits the breakdown at the start of the River Passage. Air flows along the River Passage and is frequently felt in the Bathtub Room, Thunder Room and Shelf Passage. Noticeable airflow is seldom observed in the crawl into the Pyramid Room from the Grand Canyon. Infrequently, airflow has been observed in the Triangle Passage crawl blowing toward the Subway Passage. Airflow has also been observed entering the Throne Room from the Rotunda Room. This is

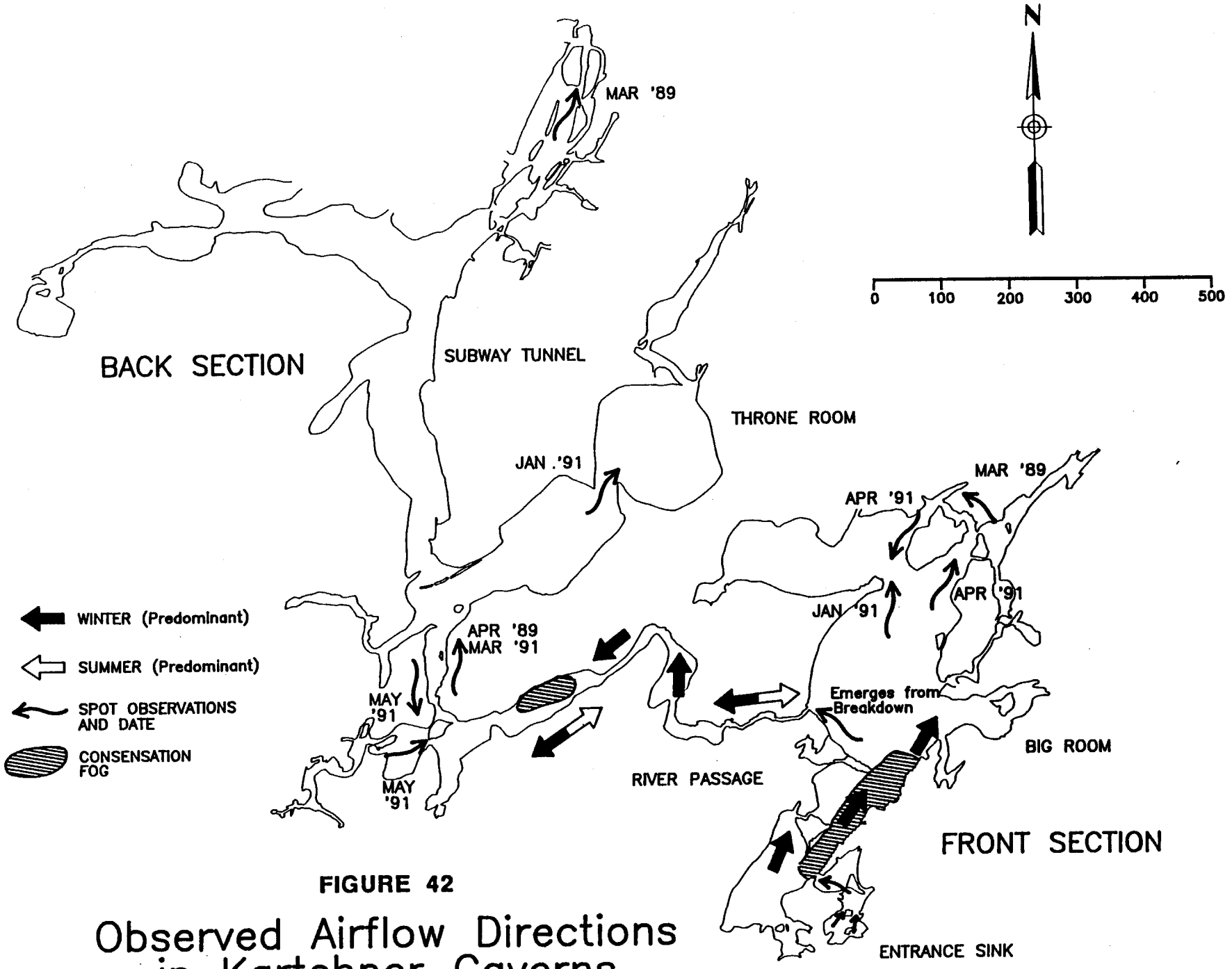


FIGURE 42

Observed Airflow Directions in Kartchner Caverns

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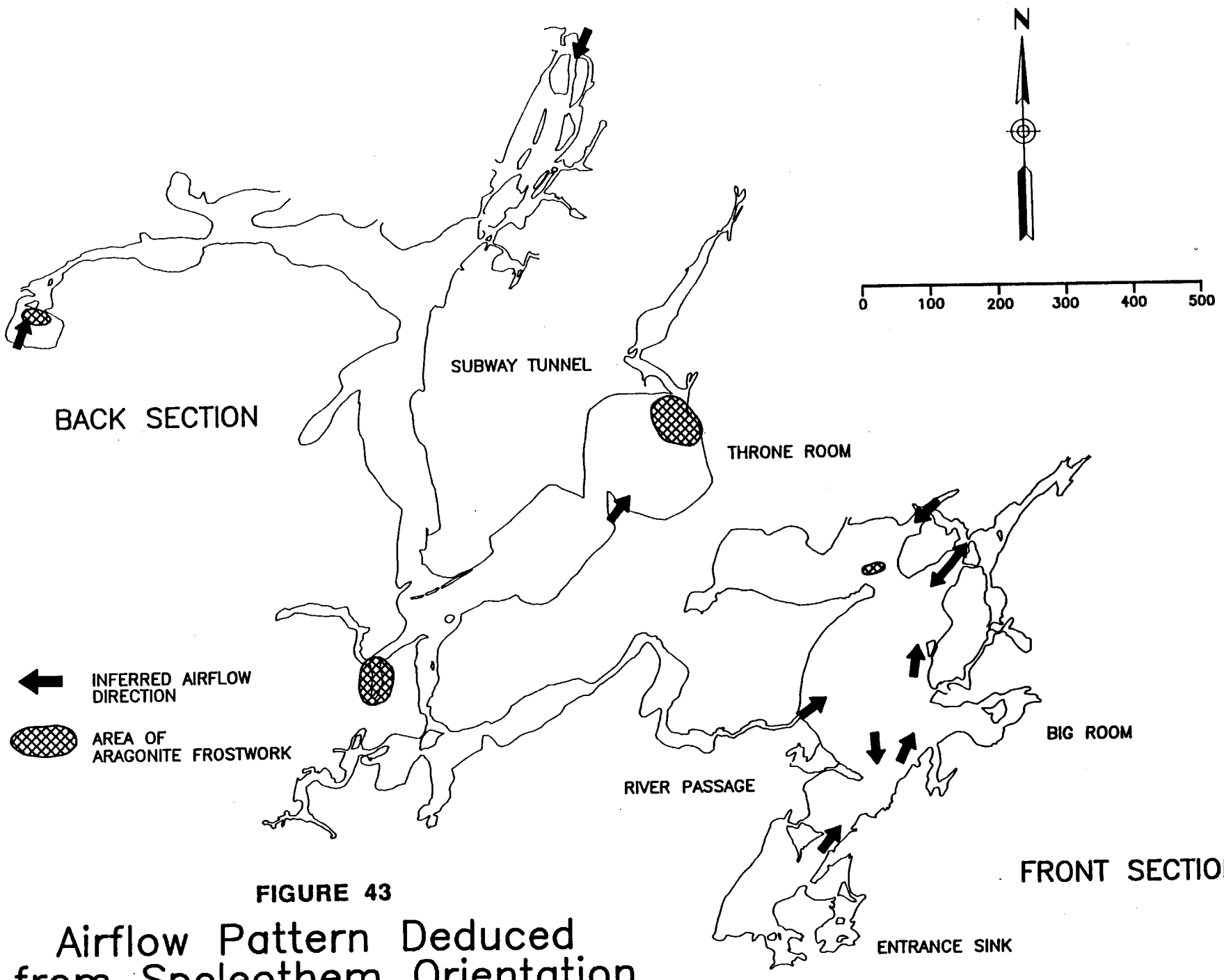

FIGURE 43

Airflow Pattern Deduced from Speleothem Orientation

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also consistent with the observed growth of speleothems. Airflow measurements at the entrance of the cave suggest that one or more openings exist at a higher elevation. Based on the observed airflow, the following are the most likely locations for these higher openings: the ceiling at the start of Grand Canyon, the breakdown cone between the Onyx and Marble Passages and the ceiling of the Throne Room.

Less is known about the pattern of summer airflow. The observed pattern of airflow appears to be much weaker with the direction of airflow at the entrance frequently changing. Airflow appears to flow predominantly out from the back of the cave through the River Passage and into the Big Room.

Air density mechanisms are thought to be responsible for the observed airflow patterns. The relationship of the air density within the cave and on the surface can be determined from the surface climate data, elevations and cave environmental measurements. Table 10 lists the computed air density at each of the environmental monitoring stations ranked by air density. This shows that air density within the cave is almost exclusively a function of temperature. Figure 44 shows the average surface air density for each month of the year as compared to the air density in the entrance passages. As can be seen, surface air generally has a greater density from October to May and would thus tend to flow into the cave. During the summer months, the surface air is generally less dense than air within the cave and cave air would tend to rise out of the cave.

Figure 44 also shows that the surface air has a greater density than cave air for most of the year. Surface air, on the average, always has a greater density than cave air during the night. This means that, during the winter months, the rate of air exchange should increase during the night while, during the summer, it should decrease. The chimney effect is produced by the difference in air density between the cave and surface air. Because the cave is at a temperature that is several degrees above the average surface temperature, the air density difference is greater during the winter. During winter months, the density difference can be 45 gm/m^3 to 70 gm/m^3. During the summer months, the difference is only 25 gm/m^3. We expect that the rate of air exchange will be proportional to the density difference. The summer air exchange rate would therefore be only half to one-third that of the winter months. This may explain why airflow is more frequently observed during the winter than during the summer. The entrance passages, particularly from the Crinoid Room to Grand Central Station, are the cool areas of the cave. The air in these passages is also quite dense. Figure 45 shows a profile of the air density under winter and summer conditions. During the winter, there is a constant decreasing gradient of air density as one proceeds into the cave. This allows surface air to flow continuously into the cave during the winter. During the summer, the air density gradient reverses, air within the cave is less dense and would tend to rise up out of the natural entrance. However, the cool temperatures in the area of the LEM Room create a density hump which partially blocks air from leaving the cave. The net density gradient from the interior of the cave to the surface will still produce an outward flow of air during the summer.

AIRFLOW RECOMMENDATIONS

Maintaining the integrity of the cave microclimate depends on controlling the amount of air exchange with the surface. Temperature, relative humidity, carbon dioxide and alpha radiation levels are all dependent upon the ventilation rate. Unfortunately, from a management point of view, changes in air exchange rates have both positive and negative impacts on the microclimate. Increased air exchange

Table 10
Environmental Stations Ranked by Average Air Density

EMS Sta. #	Location	Elevation	Avg. Air Temp. (°F)	Avg. Air Pressure (Mb)	Air Density gm /meter^3	Air Moisture gm/meter^3
21	Big Room Overlook	4664	69.6	853.73	1000.42	18.20
11	Tarantula Room	4638	69.2	854.56	1002.31	17.97
13	Sharon's Saddle	4640	69.0	854.49	1002.68	17.85
7	Cul-de-Sac	4620	69.2	855.13	1002.99	17.97
22	Kartchner Towers	4625	69.1	854.97	1003.02	17.91
9	End of Echo Passage	4620	69.1	855.13	1003.21	17.91
18	Upper Throne Room	4703	67.7	852.48	1003.24	17.11
10	Start of Echo Passage	4610	69.0	855.45	1003.82	17.85
19	Lover's Leap	4618	68.7	855.19	1004.20	17.68
3	Sue's Room	4635	68.4	854.65	1004.23	17.51
12	Mud Flats	4620	68.4	855.13	1004.80	17.51
8	Rotunda Room	4645	67.6	854.33	1005.67	17.06
14	Main Corridor	4623	67.9	855.03	1005.82	17.23
17	Lower Throne Room	4637	67.4	854.59	1006.42	16.95
4	Mushroom Passage	4632	67.3	854.75	1006.84	16.89
6	Pyramid Room	4633	67.2	854.72	1007.03	16.84
20	Mud Trench	4626	67.3	854.94	1007.07	16.89
5	Granite Dells	4631	66.0	854.78	1009.82	16.19
15	Scorpion Passages	4618	66.1	855.19	1010.09	16.24
1	Crow's Nest Rock	4632	65.7	854.75	1010.46	16.03
16	Grand Central Station	4623	65.8	855.03	1010.58	16.09
2	Start Pirate's Den	4630	65.6	854.81	1010.76	15.98

NOTE: 100% relative humidity used in all air density and moisture calculations

would have a critical impact on the moisture balance of the cave and produce drying of cave features. It would also have the desirable effect of lowering the alpha radiation levels in the cave. The present study has shown how these parameters are interrelated; that it is not possible to change one without making damaging changes to the cave microclimate. The cave is presently in a natural state of equilibrium. The best course of action is to maintain the present conditions to the greatest extent possible. Seemingly minor changes in the interior of the cave can have a significant and detrimental impact on the conditions within the cave. This section presents a compilation of those areas which have been identified as being significant in maintaining the existing microclimate of the cave. Any proposed development of the cave should avoid disturbing these areas.

The natural entrance and passages up to the start of the Big Room are critical areas for maintaining the present pattern of airflow in the cave. During the winter, cold, dry surface air passes through the entrance passages and flows under the breakdown pile below Sharon's Saddle. The airflow emerges from the breakdown near the Kartchner Towers' monitoring station and flows into the River Passage. The winter air entering the cave is cool and dense so that it flows by gravity along the floor. Changes in the passages which would block or divert the airflow can have major consequences for the cave microclimate in the Front Section of the cave. Care must be taken in the design of the trails and other improvements so as to maintain the existing airflow pattern.

The present winter airflow pattern is almost ideal for preserving the moisture balance in the front part of the cave. Because outside air flows through small openings in the

breakdown, it is in greater contact with the rock and the air velocity is reduced. This means that the air will reach equilibrium with the temperature and humidity levels in the cave much quicker than it would in a more direct path. Calculations have shown that the distance into the cave that outside temperatures influence conditions is strongly dependent on the size of the passage openings in the entrance area.

During the summer, the airflow pattern is reversed, with air entering the Big Room from the River Passage and generally leaving the cave at the natural entrance. However this is warm air returning so it rises as it enters the Big Room and does not flow under the breakdown. The summer airflow pattern is less dependent on the nature of the passages than the winter airflow. For this reason most of the recommendations are made to preserve the winter airflow pattern.

Critical areas for airflow are:

1. The entrance sinkhole. Walls around the sinkhole may increase airflow by either trapping more cold air in the sink or acting as a chimney.
2. The bottom of the sinkhole and floor area to the Blockade Room. Air enters the cave through many small openings in the floor. Almost all of these are too small to be seen. The most important areas are the bottom of the sinkhole along the north wall and the opening at the west end.
3. Entrance passages. There are several other openings that the air follows besides the one used by people. These other openings are perhaps the major routes for airflow. Enlargement or blocking of passages can have a significant effect on microclimate conditions in the front portion of the cave.
4. The locations of areas in the Big Room where the floor dries out during the winter should be carefully monitored. The dates and maximum extent of the dry areas should be recorded.
5. The downstream end of Grand Central Station. A major portion of the air which enters the cave leaves Grand Central at this point and flows under the Big Room breakdown pile.
6. The area to the left of the entrance to the River Passage. Air comes out from under the breakdown immediately to the left of the start of the River Passage. This passage is at an elevation several feet lower than the floor of the Big Room.
7. The narrow constricted passage between the Pop-Up junction and Main Corridor next to a large breakdown block. It is likely that this constriction controls the split of airflow between Grand Central Station and Main Corridor. Presently most of the airflow goes through Grand Central Station. If the constriction were enlarged, a greater proportion would enter the Big Room along Main Corridor. It is unlikely that this cold, dry air would reach the River Passage before drying out major portions of the Big Room.
8. Development will increase the temperature of the cave by several degrees. This will likely increase the amount of surface air entering the cave during the winter months by strengthening the chimney effect. A slightly warmer cave would also have less air leaving the cave during the summer.
9. The temperature in the entrance passages has a noticeable impact on the pattern of air exchange in the cave by creating a locally dense pocket of air which partially blocks summer airflow out of the cave. Equipment which could raise the temperature of the area such as transformers should not be placed in this area. Raising the temperature of this area would increase the amount of air entering the cave in winter months and reduce the amount of air leaving the cave during the summer months.

FIGURE 44

Direction of Air Flow Estimated From Surface Air Density

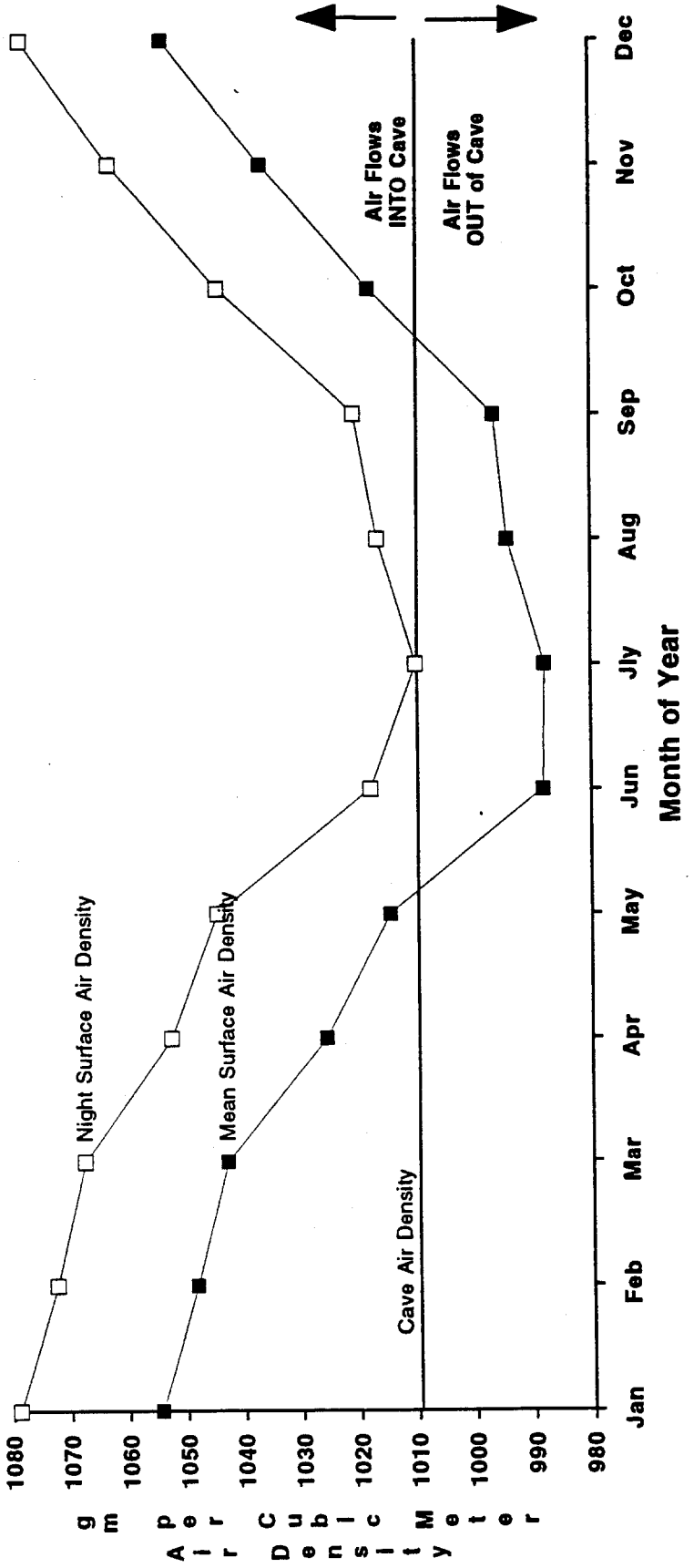
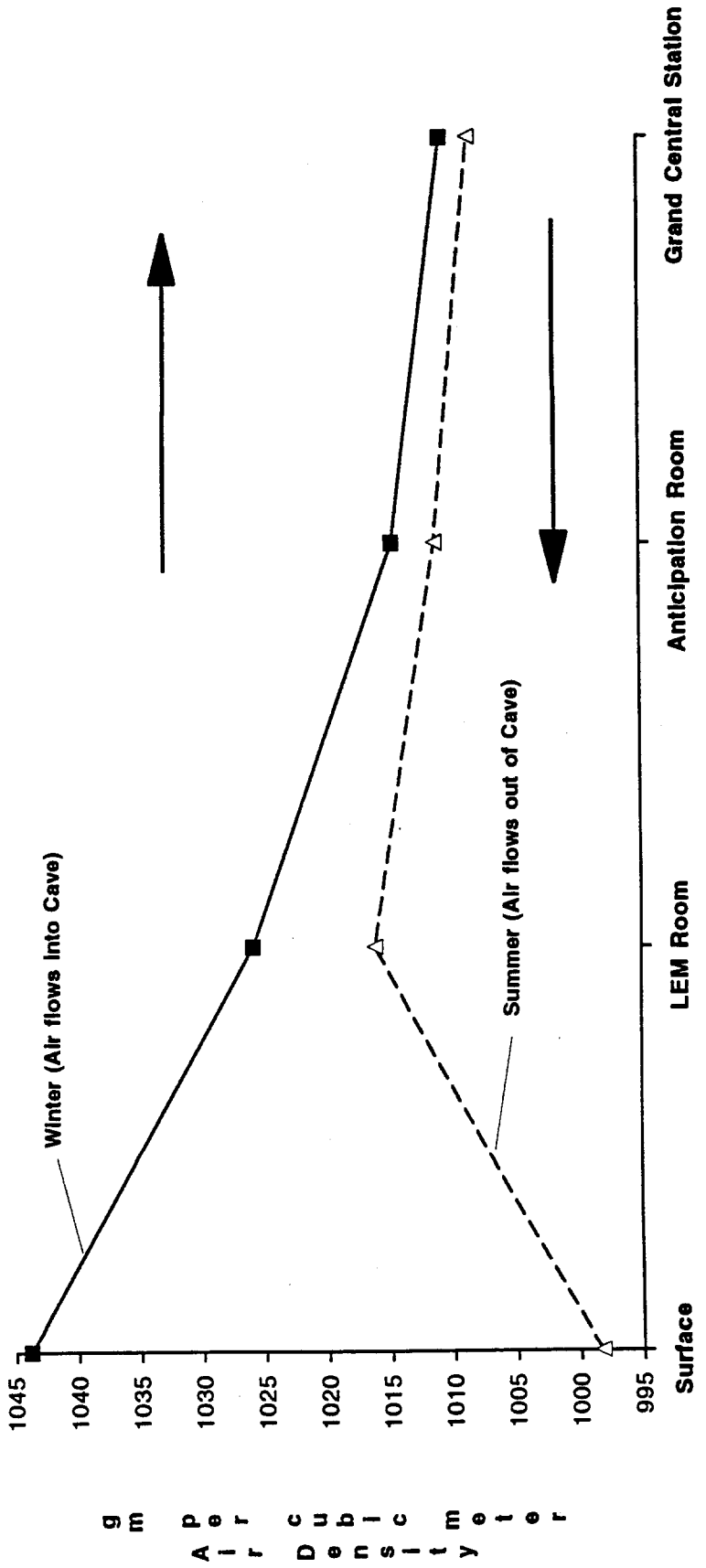


FIGURE 45
Seasonal Air Density Profile of Entrance Passages



CARBON DIOXIDE

ACPI has started a program of measuring the carbon dioxide concentration in the cave under the direction of Carol Hill. During her initial trips to the cave, a number of grab samples were taken in numerous locations throughout the cave. The results of these measurements are given in Table 11. Beginning in the summer of 1990, a more intensive CO_2 monitoring program was started by ACPI to monitor CO_2 concentrations at two locations on a monthly basis. The results of those measurements are shown in Table 11.

The high levels of CO_2 in the cave during late summer and autumn raise some concerns regarding the levels that may be present after the cave is open to the public. Visitors to the cave will add more CO_2 to the air and possibly raise it to unacceptable levels. Knowledge of the CO_2 levels and the seasonal variation can also provide insight into the rate of air exchange. The concentration of CO_2 is an important parameter in determining if the water which percolates into the cave will deposit or dissolve calcite. The growth of certain types of speleothems such as helictites depends on the concentration of CO_2 in the air.

TABLE 11
Kartchner Caverns Carbon Dioxide Levels
Drager Meter Measurements (Parts per Million)

LOCATION / DATE	23-Sep	24-Sep	2-Dec	13-Dec
Crow's Nest #1	3400	----	----	1500
Sue's Room #3	3500	----	----	1200
Mushroom #4	----	----	----	850
Pyramid Room #6	----	----	----	600
Cul-de-sac #7	----	3000	800	----
Rotunda Room #8	3250	----	----	1750
End of Echo #9	----	3000	----	----
Begin Echo #10	----	----	>3000	----
Mud Flats #12	----	----	1000	----
Sharon's Saddle #13	----	2500	400	----
Grand Central #16	----	----	250	----
Lower Throne #17	3300	----	----	1500
Throne Rm. Overlook #18	3500	----	----	1700
Lovers Leap #19	----	----	650	----
Mud Trench #20	----	----	----	900
Big Room Overlook #21	----	3000	400	----
Kartchner Towers #22	----	----	600	----
Grand Canyon	----	----	----	----
Bathtub Room	----	----	----	----
Thunder Room	----	----	----	----
Y Junct. to Angel's Wing	3500	----	----	700
Pirate's - Sue's Junction	----	----	----	1000

TABLE 12
MONTHLY CO2 MEASUREMENTS

Measurements in ppm by Diffusion Tubes, corrected to 854Mb pressure

DATE	Upper Throne Room	DATE	Sharon's Saddle
07/18/90	2910	07/26/90	3610
08/26/90	3925	08/23/90	4680
09/30/90	5400	09/27/90	4100
10/30/90	4935	10/23/90	2220
11/24/90	3827	12/05/90	1130
12/19/90	3296	12/19/90	1132
01/15/91	2430	01/17/91	852
02/14/91	1690	02/21/91	1147
03/24/91	2620	03/31/91	1190
05/05/91	2167	04/23/91	1746
05/29/91	1660	05/29/91	1190
06/11/91	2650	06/10/91	2130

Carbon Dioxide and Ventilation Rates.

The quantity of carbon dioxide (CO_2) gas contained in the cave air can be used to approximate the rate of air exchange between the cave and the surface.

The outside air contains approximately 300 parts per million (ppm) CO_2. Within the cave, CO_2 concentrations vary seasonally from approximately 1000 ppm in late winter to over 5000 ppm in late summer. The increased CO_2 content of the cave air is due to the release of CO_2 from drip water entering the cave. When CO_2 escapes from the drip water, calcite is deposited as cave formations. The amount and rate of CO_2 entering the cave follows an annual cycle, being dependent on the rate of drip water entering the cave and the biologic activity in the surface soils.

The chief advantage of CO_2 as a tracer is that it is predominantly removed from the cave by ventilation. By examining the measured concentrations of CO_2 in the cave, we can see that they vary by a factor of 3 to 5 over the course of a year. This indicates that either the rate at which CO_2 enters the cave is varying, the ventilation rate is varying or most likely both vary throughout the year. If we make the simplifying assumption that the rate at which CO_2 enters the cave is constant, we can determine the ventilation rate. While the assumption of a constant influx is certainly wrong, it will still allow us to determine an upper limit on the ventilation rate. During the winter months, the amount of biologic activity in the soil and, hence the CO_2 levels, decreases and the assumption of a constant influx may be approximated. The equation for the time-dependent concentration of a tracer being removed at a constant rate is:

$$\text{Concentration} = \text{Starting Concentration} \exp^{(-Kt)}$$

Where K = flow rate/ Volume (air exchanges per day)
t = time (days)

For the Throne Room, CO_2 levels decreased from 5400 ppm on 9/30/90 to 1690 ppm on 2/14/91, a period of 137 days. K is determined to be 0.0085 and the ventilation rate is 137 days.

For the Big Room at Sharon's Saddle, CO_2 levels decreased from 4100 ppm on 9/27/90 to 1130 ppm on 12/5/90, a period of 69 days. K is determined to be 0.0187 and the ventilation rate is 53.5 days.

The ventilation rates determined, 137 and 54 days, are certainly overestimations as some CO_2 is entering the cave during these time periods. The actual rates may be half of these estimates or 30 to 70 days for a complete air exchange. This is equivalent to 183,000 to 79,000 cubic feet per day of air entering the cave.

CO_2 Model Results

Carbon dioxide concentrations have been measured in the cave at two locations on a monthly basis (Figure 46 and Table 12). The upper Throne Room location has an annual average of 3125 ppm ±1200 and a range of 1660 to 5400 ppm CO_2. At Sharon's Saddle, the annual average is 2095 ppm ±1320 and ranges from 852 to 4680 ppm. Additional measurements of CO_2 concentrations were made at a number of locations throughout the cave in September and December 1989 (Table 11). The September measurements average 3200 ppm ±320 and range from 2500 to 3500 ppm. The December measurements are much lower with an average of 1040 ppm ±660 and range from 250 to 3000 ppm.

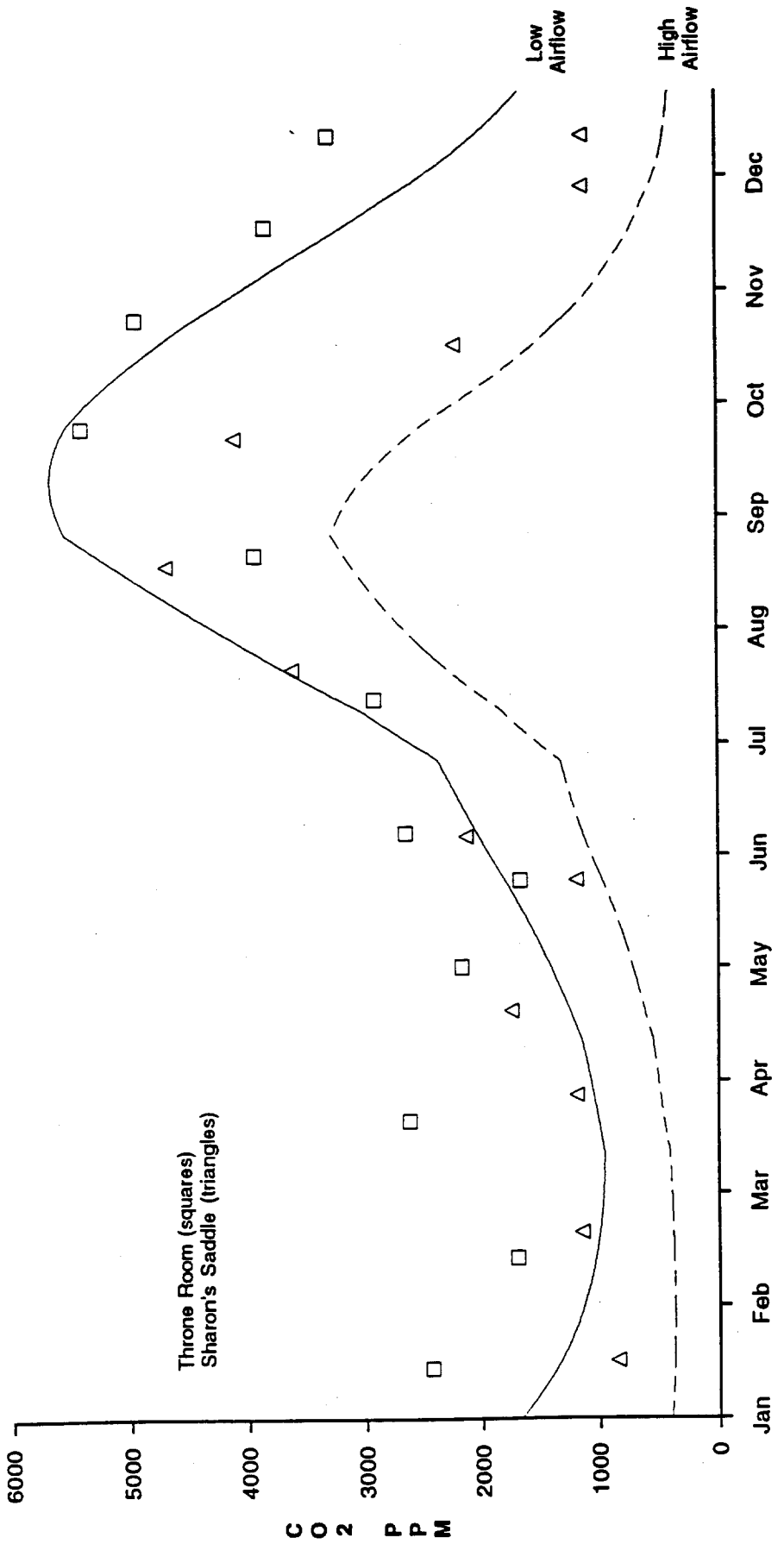
The primary source of the carbon dioxide is thought to be the CO_2 produced in the overlying soil and brought into the cave dissolved in drip water and by air exchange through small cracks in the ceiling. A small amount of CO_2 may be produced by the decomposition of bat guano, bat respiration and tree roots. Most, if not all, of the CO_2 is removed from the cave by the naturally-occurring ventilation of the cave with surface air.

A relatively simple model of CO_2 concentrations in the cave can be constructed from a knowledge of the cave volume, the rate at which CO_2 enters the cave and the ventilation rate. The volume of the cave is reasonably well known from the survey data. The airflow rate has been measured primarily during the winter at the natural entrance. The exact ventilation rate is unknown but has been estimated from the airflow measurements. Being able to reproduce the observed variations in CO_2 concentrations constitutes a verification of the estimated ventilation rate. The rate at which CO_2 enters the cave is not known, although we can make a few educated guesses based on the rate of rise and decline of the CO_2 measurements. These indicate that CO_2 can accumulate at rates of 40 ppm per day during the summer months. The actual rate of influx must be higher than this as this is the net rate and includes the rate at which CO_2 is lost from the cave. For the model, the rate at which CO_2 enters the cave is considered to be proportional to two other parameters. If we are correct in believing that the source is in the overlying soil, then it is reasonable to assume that the influx will be proportional to the rate at which drip water enters the cave. Second, we assume that the CO_2 in the soil is of biological origin and varies on a seasonal basis. We can estimate this variation from the Thornthwaite evapotranspiration. These two parameters were used to index the rate at which CO_2 enters the cave.

A number of trial values were used to determine the proper values for the ventilation rate and rate of CO_2 introduction which most closely fits the observations. The measured ventilation rate and inferred CO_2 influx were used as starting points.

FIGURE 46

Carbon Dioxide - Model Predictions & Measured Concentrations



The final model is based on an influx rate of CO_2 that varies from 20 ppm/day in winter to 80 ppm/day in summer. Two rates of ventilation have been used: a low estimate which corresponds to the measured airflow rate of 170,000 to 36,000 ft^3/day and a high estimate of 520,000 to 108,000 ft^3/day. The results of the model run for each of these ventilation rates is plotted in Figure 46 along with the measured CO_2 concentrations. The measured CO_2 concentrations are reasonably well fit by the low ventilation rate assumption. The high ventilation rate appears to provide lower overall CO_2 concentrations. A slightly better fit may be possible with an even lower ventilation rate during the winter months. The good overall fit, however, indicates that the range of ventilation rates is reasonably well known.

The model is sensitive to changes in the ventilation rate and the rate at which CO_2 enters the cave. Increasing CO_2 influx is equivalent to decreasing the ventilation rate. Conversely, increasing the ventilation rate is equivalent to decreasing the rate at which CO_2 enters the cave. We can estimate the possible range of errors. A good fit is given by a ventilation rate of 170,000 to 36,000 ft^3/day. It is unlikely that the rate at which CO_2 enters the cave is off by more than a factor of two. The ventilation rate could therefore be as high as 340,000 to 72,000 ft^3/day.

CO_2 from Development

The model used to confirm the CO_2 concentrations and ventilation rates can be used to estimate the impact that large numbers of visitors will have on CO_2 levels within the cave.

For low annual ventilation rates ranging from 36,000 ft^3/day in summer to 171,000 ft^3/day in winter and visitors adding an average of 53 ppm of CO_2 to the air each day, the model predicts CO_2 levels that range from 2,800 ppm to 11,000 ppm, with an annual average of 6,200 ppm.

For high ventilation rates ranging from 108,000 ft^3/day in summer to 520,000 ft^3/day in winter and visitors adding 53 ppm CO_2 to the air each day, the model predicts CO_2 levels that range from 900 ppm to 5,700 ppm with an annual average of 2,500 ppm.

Based on these model predictions, the CO_2 concentrations after development are estimated to range from 3,100 ppm to 9,000 ppm, with an annual average of 5000 ppm. This is an estimate for the whole cave based on average anticipated visitation. We can expect that, due to variations in the number of visitors and non-uniform mixing of air, the local concentrations may be much higher.

CO_2 can be a health risk at high concentrations, generally above 10,000 ppm (James and Dyson, 1981; Lewis, 1981). The 1976 NIOSH TLV for CO_2 is 5,000 ppm for an 8 hour exposure. "TLV stands for threshold limit value, an estimate of the average safe airborne concentration of a substance and represents conditions under which it is believed that nearly all workers may be repeatedly exposed day after day without adverse effect." A STEL of 15,000 ppm is also recommended. STEL stands for short term exposure limit, the maximum concentration for a continuous 15-minute exposure period. The estimated concentrations for the cave after development appear to fall between these two limits. As most of the exposure will be occurring during a tour of relatively short duration, there are likely to be no problems.

Higher CO_2 levels are likely to have several adverse impacts on the cave in addition to health issues.

- Increased CO_2 concentrations may enhance the growth of exotic plants and algae in the cave. Higher levels of CO_2 have been associated with faster growth of plants on the surface. While high CO_2 levels in caves have not been

shown to increase algal growth in caves, it is reasonable to expect faster growth.

- Higher CO_2 concentrations will also shift the chemical equilibrium of water percolating into the cave. This will cause less calcite to be deposited and cave formations will grow at a slower rate.
- The high CO_2 may also result in the air becoming more chemically aggressive. At the present time some areas of the walls and ceilings are being eroded by moist air condensing on these surfaces. Higher levels of CO_2 will result in the air becoming more aggressive and dissolving cave formations in other areas of the cave. The effect of aggressive air is noticeable on several draperies along Main Corridor. These draperies have several holes through them and a general ragged appearance. Changes in cave formations due to aggressive air can be detected on the photos taken at the photomonitoring points.

Estimates of CO_2 are based on lumped cave models which give values for the entire cave. CO_2 concentrations at specific locations in the cave may be much higher or lower than those predicted for the entire cave. It is still recommended that CO_2 concentrations be monitored at two locations on a monthly basis. Once the cave is open to the public, CO_2 monitoring should be continued until sufficient data has been obtained to verify the maximum CO_2 concentrations reached and to identify areas of abnormally high CO_2.

A benefit of higher CO_2 concentrations is that combustion is less likely. At 10,000 ppm, a match will not burn. At higher concentrations, it becomes increasingly difficult to support combustion. Also fire is extremely unlikely inside the cave since all materials become saturated with the humid air. The only naturally-occurring combustible materials are the relatively small accumulations of bat guano. However, the guano is quite moist and would be difficult to ignite.

Carbon Dioxide Balance

The only source of carbon dioxide is thought to be from the overlying soil. CO_2 is brought into the cave as a dissolved gas in water percolating through the limestone. The amount of CO_2 in the cave can be roughly calculated from the measured concentrations. CO_2 varies from 1000 ppm to 6000 ppm throughout the year. This is equivalent to a mass of 150 kg to 850 kg of CO_2. The amount of CO_2 which enters the cave must be at least 700 kg per year (the difference between the high and low concentrations) and may be as large as 2500 kg per year.

Water which percolates into the cave becomes saturated with carbon dioxide gas as it moves through the limestone. Once inside the cave, it releases CO_2 as it comes to equilibrium with the cave air. Based on estimated CO_2 levels in the soil, the amount of CO_2 released into the cave air can be roughly estimated. Approximately 100 mg of CO_2 can be released from each liter of drip water. The amount of water percolating into the cave has been estimated to be 0.3" per year (0.76 cm). Over the area of the cave, this is 220,000 liters per year. The amount of CO_2 released is about 22 kg per year. This is much less than the previous estimate of 600 kg to 2500 kg per year. The amount of water necessary to bring that much CO_2 into the cave is 8" to 30" per year. This is so much larger than what is observed that we must conclude that the primary source of CO_2 is not from water percolating into the cave.

If most of the CO_2 is not being carried into the cave by percolating water, then direct gas exchange must be occurring. Small cracks and fissures in the limestone may be

carrying soil gas rich in CO_2 into the cave. Soil gas typically will have CO_2 concentrations of 10,000 to 100,000 ppm CO_2. Knowing the approximate amount of CO_2 which reaches the cave and the concentration of CO_2 in the soil gas, we can estimate the amount of soil gas which must enter the cave to create the observed CO_2 levels. The gas exchange rate may range from 6000 m^3 to 250,000 m^3 per year. This is equivalent to 600 ft^3/day to 24,000 ft^3/day, still much less than the observed airflow at the natural entrance.

Soil gas is not only high in CO_2 but also in radon. The radon concentrations typically range from 200 pCi/l to 6000 pCi/l of soil gas. From the soil gas exchange rate previously determined, we can estimate the contribution soil gas makes to the radon levels in the cave. Assuming a soil gas concentration of 1500 pCi/l, then soil gas will contribute between 0.18 pCi and 7.3 pCi to each liter of air in the cave. This is less than 20% of the radon influx needed to maintain the observed radon levels in the cave.

Soil gas exchange appears to be consistent with the observed concentrations of CO_2, radon and airflow. During the winter, cold outside air enters the cave through the natural entrance, becomes warmer and rises out of the cave at a higher opening. For this to happen, the cave must be slightly pressurized in relation to the surface air. This would reduce the amount of soil gas exchange taking place. During the summer, opposite conditions apply. Warm air enters at the higher opening, becomes cooler and flows out the lower entrance. This indicates that the cave is generally slightly below surface pressure. The lower internal pressure will allow a higher rate of soil gas exchange. This will bring higher levels of CO_2 and radon into the cave during the summer months, exactly what is observed. This line of reasoning indicates that very small differences in air pressure may be responsible for the soil gas exchange rate. There is evidence that this is the case for some other caves. Ahlstrand has shown that fluctuations in atmospheric pressure are the major control of radon levels in New Cave at Carlsbad Caverns National Park. It is interesting to note that the average daily variation in barometric pressure observed at Kartchner Caverns (4 mb) would produce an air exchange of 23,000 ft^3/day. This is the same as the estimated maximum soil gas exchange rate. Most of the barometric-induced air exchange occurs through the natural entrance but some portion is likely to occur through soil gas exchange.

While a comparatively small amount of soil gas exchange apparently occurs, it is not the predominant air exchange mechanism for the cave. Air exchange through the natural entrance is the predominant mechanism.

CAVE MICROCLIMATE MONITORING RECOMMENDATIONS

In this study, 22 environmental stations were established and monitored on a monthly basis for 24 months. This has provided a detailed picture of conditions throughout the cave. Many of the stations were placed at the anticipated locations of potential entrances. Now that a suitable site has been chosen, the number of environmental stations can be reduced. Monitoring should be continued for two reasons. First, the construction phase appears to be a critical period for preserving the cave microclimate, particularly near newly constructed entrances. Second, once the cave is open to the public, monitoring data will be important to establish the amount of change in the microclimate. Records of changes at monitoring stations will be invaluable in the future for establishing if damaging changes have occurred and determining if the changes are due to internal or external factors.

Fewer monitoring stations will be needed during the construction phase and once the cave is open to the public. These stations will need to be located in areas of the cave which will be developed and at other significant locations. The number of stations should represent a mix of areas that predominantly covers areas that will be developed. There should still be one or two stations maintained in areas that are unlikely to be influenced by the development of the cave. These will continue to function as baseline stations. Continued use of the existing stations is favored because these already have a considerable amount of data. A total of 12 stations appears to be adequate for continued monitoring of the cave. The following is a list of important stations which should be kept in operation and monitored on a monthly basis:

Big Room Overlook EMS #21
Kartchner Towers EMS #22
Throne Room Overlook EMS #18
Lower Throne Room EMS #17
Start of Echo Passage EMS #10
Rotunda Room EMS #8
Cul-de-Sac EMS #7
Main Corridor EMS #14
Sharon's Saddle EMS #13
Mud Flats EMS #12
Grand Central Station EMS #16

One new station is proposed for the Big Room area of the cave. Presently there is no station in the center of the room in the area between the Bishop and the Lunch Spot. A new station should be constructed near the trail turn-off just before the Lunch Spot. This station should include the same equipment as the other monitoring stations.

Of the remaining 11 stations, 6 can be removed from the cave. The other 5 stations should have the thermometers and instrument stands removed. The evaporation pans can remain at these stations and measurements taken on an annual basis.

Granite Dells EMS #5	* Remove station
Scorpion Passages EMS #15	* Remove station
End of Echo Passage EMS #9	* Remove station
Lover's Leap EMS #19	*Remove station
Pyramid Room EMS #6	* annual evaporation
Mud Trench EMS #20	* Remove station
Tarantula Room EMS #11 (Remove unless a tunnel is constructed here)	
Crow's Nest Rock EMS #1	* annual evaporation
Pirate's Den EMS #2	* annual evaporation
Mushroom Passage EMS #4	* annual evaporation
Sue's Room EMS #3	* annual evaporation

New evaporation pans should be installed near the exit from the new proposed entrance tunnel. These will provide important information on the effectiveness of air control measures. In order to provide the greatest amount of useful information, the new evaporation pans should be installed at each end of any interior tunnels. The new entrance tunnel should have evaporation pans installed outside the exit portal and between each set of airlock doors. They should be placed several months prior to

any construction so that baseline data can be collected. They will also need to be placed so that they will not be disturbed after construction and while the cave is open to the public. Evaporation pans and temperatures must be placed at least 10 feet from any light fixtures and at a lower elevation than any nearby light.

The computer data logger systems in the Big Room and entrance passages should be kept in operation but some changes are recommended. The entrance system should be expanded to include temperature probes in the Crinoid Room and in the entrance sinkhole. The environmental monitoring station in Grand Central Station should also be tied into this system. The size of the Big Room data logger system can also be reduced. Three of the stations should be disconnected when the monitoring station is removed. It also appears that soil temperatures are redundant and so could also be removed at all locations. The proposed new station in the middle of the Big Room should be tied into the data logger. The soil temperature probe at the Big Room Overlook should be installed in the ceiling. The other temperature probes installed in various guano piles can be removed.

Carbon dioxide monitoring should be continued to provide important information on the ventilation rate and inflow of water to the cave. It is recommended that monthly monitoring be continued at three sites: Upper Throne Room, Kartchner Towers and Cul-de-Sac. CO_2 monitoring will be especially important once the cave is open to the public.

ALPHA RADIATION

Naturally occurring alpha radiation in caves has only in the past few years been recognized as a potential health issue in caves. In order to assess the levels of alpha radiation in Kartchner Caverns, ACPI hired the Ozark Underground Laboratory (OUL) (Aley, 1989, 1990) to conduct two alpha radiation surveys of the cave. ACPI has interpreted the results of these surveys to indicate that Kartchner Caverns has significantly high levels of alpha radiation. Although the observed alpha radiation levels appear high, they are well below any established safety criteria for visitors to the cave. However, the alpha radiation levels are high enough to be of concern for employees who may work within the cave for many years.

This section of the report is divided into several sections. The first deals with general information about alpha radiation in caves; the second section deals with the results of the measurements taken in Kartchner Caverns and the final sections deal with the various ways in which alpha radiation can be managed.

GENERAL INFORMATION ON RADON AND RADON DAUGHTERS

The following section provides background information concerning alpha radiation in caves. This information has been adapted from information provided by the National Park Service (NPS, 1990), which has numerous caves open to the public, and from publications by the Arizona Department of Geology (Spencer, 1986).

Radon gas gradually seeps from soil and fractured rock. Because it is chemically inert and forms no natural chemical compounds, radon can travel through permeable materials without adhering to them. Radon^{222} has a half life of 3.82 days and decays to radioactive daughter products that readily form chemical bonds. Caves can be effective traps for radon gas derived from surrounding rock and soil, especially when these materials are permeable and contain higher than normal concentrations of uranium.

Radon gas is an intermediate decay product of a chain of radioactive decays that begins with uranium and ends with lead. Radon gas is present in pore spaces in soil and rock as a result of liberation of radon from geologic materials. Radon is an inert gas and, unlike all other uranium-series decay products, does not form chemical bonds. As a result, a radon atom can move freely through the pore spaces of a porous and permeable geologic material without bonding to other mineral grains or substances. The mixture of air, radon and other gases in underground pore spaces is known as soil gas.

Diffusion of soil gas, or its movement through a permeable soil or fractured rock due to the random movements of gas atoms and molecules, results in transport of radon to above-surface environments or into underground cavities. The ability of radon to migrate through soil is highly dependent upon physical properties of the soil. Well-fractured rock and coarse, well-drained soils are likely to be highly permeable to radon, whereas clays and muds, particularly if wet, should not permit much radon movement. Radon originating from depths greater than a few feet generally does not reach the surface because it decays so quickly. As a result, uranium concentrations of only the top few feet need be considered in evaluating possible radon levels.

When radium^{226} decays to radon^{222}, it releases a high-energy alpha particle. The alpha particle is like a bullet from a gun and, obeying the laws of physics, the newly formed radon^{222} atom undergoes recoil. If the radon atom is near the surface of a mineral grain, it can be knocked out of the grain by recoil. In some materials such as

clay, radon is loosely trapped in the mineral's molecular structure and can migrate out without the assistance of recoil. This more gradual process of migration is known as diffusion. Radon atoms are liberated from geologic materials by both recoil and diffusion.

Radon cannot be seen, smelled or tasted and can only be detected by special instrumentation. Shortly after radon is released into the air, it disintegrates into new elements. These new elements are atomic-sized particles known as radon decay products or radon daughters. A few seconds after formation, they become attached to the airborne dust and condensation particles in the cave air and can be inhaled. The radon daughters can then disintegrate by radioactive decay, releasing a high energy alpha particle which can be injurious to lung tissue.

Most alpha radiation is due to radon daughters, although a small amount is due to thoron (Radon ^{224}, a decay product of Thorium) daughters. Radon is a radioactive decay product of uranium and radium, which are found in most rocks and soils. The radon gas decays to form solid particles called "daughters', and these too decay, emitting alpha particles.

Radon daughter concentrations are measured in "Working Levels" (WL). Radon gas is measured in pico Curies per liter of air (pCi/l). The theoretical conversion is that 1 pCi/l equals approximately 0.01 WL; the conversion is approximate since we are comparing radon gas with its decay product, radon daughters. If radon daughters are removed by processes that leave the parent radon gas, then the conversion will change. Measurements in Kartchner Caverns indicate that this conversion is approximately correct.

In outdoor air, radon is diluted to such low concentrations that it is usually nothing to worry about. However, inside an enclosed space (such as a cave), radon can accumulate to harmful levels.

ADVERSE HEALTH EFFECTS

Before discussing health effects, it should be understood that the hazard is only to the lungs; radon is not a hazard outside of the body. The energy produced by the radon is not very penetrating and is harmlessly stopped by the skin. However, once radon daughters are inhaled into the lungs, the soft tissues of the lung cannot stop the energetic alpha particle released by the radon daughter, and the lung tissue can be injured.

The spontaneous decay of radon while in the lungs is not a major source of radiation because almost all radon is expelled after each inhalation. Polonium^{218}, the immediate decay product of radon^{222}, begins a sequence of four decays with a total half life of about 50 minutes before reaching lead^{210}, which has a half life of 22 years. Polonium and its daughter products are chemically reactive and typically are highly charged immediately after decay. Newly formed polonium^{218} and its decay products tend to adhere to the first solid with which they come in contact, including lung tissue and airborne dust particles that can be temporarily trapped by the lungs. The residence time of individual radon-daughter atoms and dust particles in the lungs is usually longer than the half lives of the immediate decay products of radon. Two of the four decay steps between polonium^{218} and lead^{210} are alpha decays that can cause significant molecular disruption in adjacent lung cells because of the large mass and high energy of ejected alpha particles.

Radiation exposure of human lung tissue results from inhalation of radioactive radon-decay products that adhere to lung tissue or to airborne particles that become

trapped in the lungs. Due to inhalation of these products, the lungs of most people receive more radiation than any other body organ.

The only known adverse health effect associated with exposure to elevated levels of radon is an increased risk of developing lung cancer. Not everyone exposed to elevated levels of radon will develop lung cancer, and the time between exposure and the onset of the disease may be many years.

The risk of developing lung cancer from exposure to radon depends upon the concentration and the length of exposure. Exposure to a slightly elevated radon level for a long time may present a greater risk of developing lung cancer than exposure to a significantly elevated level for a short time.

Radon has been detected in many caves, mines and occasionally in homes in certain geologic environments. The Environmental Protection Agency (EPA) has determined that there is little danger to the public who visit caves due to their short time spent underground. However, levels of radon daughters have been detected in underground areas that may pose a potential health hazard to employees who work in these areas for longer periods.

Another significant factor that will increase the chances of developing lung cancer is smoking. Tobacco smoke and exposure to radon progeny are both lung carcinogens and their effects are greatly magnified when combined. In studies of underground miners, it was found that miners who smoked were ten times more likely to develop lung cancer than those who did not smoke. Employees who smoke are strongly encouraged to quit and smoking should not be allowed inside the cave by employees or visitors.

FEDERAL STANDARDS AND GUIDELINES FOR RADON

Several government agencies have standards and guidelines for radiation, but no single agency has dealt specifically with radon daughters in caves (National Park Service, 1990). Standards for occupational exposure to radon daughters use the following terms. The concentration of radon daughters in the air is referred to as the Radiation Level. The Exposure Level is the product of the alpha Radiation Level and the time spent breathing in that air. A person's exposure to alpha radiation is referred to in terms of Working Level Months (WLM). A WLM is equal to 170 hours spent in an area with an alpha radiation level of 1.0 WL or any area where the number of hours multiplied by the alpha radiation level is equal to 170. For example, 85 hours spent in an area with 2.0 WL of alpha radiation would result in an exposure of 1.0 WLM. Spending 340 hours in an area with 0.5 WL alpha radiation would also result in an exposure of 1.0 WLM.

The Environmental Protection Agency (EPA) has determined that because of their short time spent underground, there is no significant health hazard to the public from exposure to radon in caves. However, there is sufficient airborne alpha radiation from the radon progeny to pose a potential health hazard to the employees or to other persons exposed for long periods of time.

The Mine Safety and Health Administration (MSHA) has an established radon daughter standard of 4 Working Level Months per year for mining operations. However, MSHA states that mines will use ventilation controls when radon daughter levels approach or exceed 1.0 working level.

Other government agencies have suggested lower levels of exposure. The Occupational Safety and Health Administration (OSHA) regulates radiation exposure

in general industry. OSHA's radiation standard for radon is 30 pico Curies per liter maximum exposure limit or 1.8 Working level months per year.

The National Institute for Occupational Safety and Health (NIOSH) in 1988 published a recommended occupational guideline standard of 1.0 working level month per year for exposure to radon in underground mines, with a lifetime exposure level of 30 working level months. NIOSH stated that underground miners may also be exposed to other substances, such as arsenic, hexavalent chromium, nickel, cobalt, asbestos, and diesel exhaust, that may increase the potential for developing lung cancer.

The National Park Service (NPS), which administers a number of public show caves, is currently proposing a guideline of 3.5 Working Level Months per year and a lifetime cumulative alpha radiation exposure of no more than 105 Working Level Months for any employee (based on a 30-year career). Final regulations have not yet been formally adopted by the NPS.

ALLOWABLE PUBLIC EXPOSURE

ACPI has researched the available literature regarding guidelines for permissible exposure levels for the general public. The following statement is taken from "Air Exchange and ^{222}Rn Concentrations in the Carlsbad Caverns", M.H. Wilkening and D.E. Watkins, Health Physics, Vol 31, pp 139-145.

> "Although there are no explicit guidelines for exposure of the general public to radon and its daughters, both the International Commission on Radiation Protection and the National Committee on Radiation Protection have recommended that individuals in the general public be limited to exposures at levels one-tenth as high as those for occupational exposure. Also for a suitably large sample of the general population, the general guideline is another factor of three smaller."

The average radon daughter level in Kartchner Caverns is approximately one Working Level. Applying the above guidelines would allow the general public to spend up to 20 hours within the cave based on a permissible standard of 3.5 working level months for employees. A tour of the cave is anticipated to take less than 2 hours. It would appear that the visitors to the cave would experience less than one-tenth of the guideline exposure.

The highest radon daughter levels that have been measured in Kartchner Caverns are about 5 working levels. These high levels are known to occur in only one small area of the cave. Development of the cave is likely to lower the peak levels found in the cave through increased air circulation. Because the high levels are found for only a few months of the year in a restricted area, they would not significantly add to the exposure of the visiting public.

Magnitude of the Health Risk

Health consequences of radon exposure to underground miners are the primary basis for determining health risk to people exposed to lower, more common radon levels in houses and other buildings. Most estimates of lung-cancer risk due to low-level radon daughter exposure in homes and buildings use a linear extrapolation from high exposure rates experienced by some groups of underground miners. In a linear extrapolation, exposure and risk are proportionally related; for example, half the exposure would constitute half the risk.

There is some question about whether the exposure rates determined for miners are applicable to the much lower exposures encountered in buildings and most caves. Mines typically contain large amounts of dust and exhaust from equipment and miners

are not a representative sample of the general population. Despite these differences, most risk assessments are based on studies of uranium miners.

The Environmental Protection Agency (EPA) has used the risk coefficients determined for uranium miners to project lung cancer rates at lower exposure levels. The EPA has determined lifetime lung cancer risk coefficients that range from 2.4 to 9.4 X 10^{-4} per WLM. Other studies have generally recommended somewhat lower risk estimates. A comparison of risk estimates from 7 studies compiled by Nazaroff gives an average lifetime risk coefficient of 2.1 X 10^{-4} per WLM. The lowest risk coefficient cited in any study was approximately 1 X 10^{-4} per WLM (Nazaroff and Nero, 1988).

If we use the NPS proposed guidelines of 3.5 WLM per year and a lifetime maximum exposure of 105 WLM as reasonable maximum exposure estimates, we can calculate the lifetime lung cancer risk. This is equivalent to an increased risk of contracting lung cancer of between 2.5% and 9.9% based on EPA risk coefficients and 2.2% based on the average of other studies.

We can compare these estimates with other risks commonly faced by workers in other industries (NCRP, 1987. The rate of fatal accidents in American industry is about 1.1 per 10,000 workers per year. Based on 30 years of work, the risk is about 0.33%. The riskiest industry cited is mining with a fatal accident rate of 6 per 10,000 workers per year. Based on 30 years of work, the risk is 2.0%. The estimated range of risk associated with radon daughter exposure can be the same as or greater than that of jobs that are commonly perceived of as being risky.

For comparison, the low end of the estimate (2.2%) is slightly greater than the risk of dying in an auto accident. The high end of the estimate (9.9%) is comparable to the risk associated with cigarette smoking. These comparisons indicate that exposure to the levels of radon daughters expected to be found in the cave can be a significant risk for those working in the cave for many years. Exposure and risk to the general public is very much smaller because they will be in the cave for a very short period of time. Based on a one and a half hour tour length, the risk to the public is approximately the same as that associated with a 60-mile automobile trip.

RADON DAUGHTER LEVELS IN OTHER CAVES

For comparison, the following table lists radon daughter levels encountered in National Park Service caves. The original table is from a paper by Yarborough and Ahlstrand, 1977.

TABLE 13
Radon Daughter Working Levels in NPS Caves

Cave	High	Low	Average
Lehman Cave, NV	0.37	0.10	0.21
Jewel Cave, SD	0.28	0.13	0.21
Oregon Caves, OR	0.35	0.02	0.15
Round Spring Cave, MO	0.60	0.003	0.29
Carlsbad Caverns, NM	1.03	0.04	0.27
Mammoth Cave, KY	1.24	0.39	0.73
Crystal Cave, CA	1.49	0.83	1.12
Great Onyx Cave, KY	1.22	0.68	1.00

ALPHA RADIATION MONITORING BY OUL

Two series of alpha radiation measurements were made by the Ozark Underground Laboratory (OUL) in Kartchner Caverns, one in September and another in December, 1989. Five-minute air samples were passed through Gelman glass fiber filters type A-E using a Mine Safety Appliance Company portable pump Model S. The filters were analyzed using a Ludlum Model 2000 scaler with a scintillation detector. Filters were "read" 40 or more minutes after, but less than 90 minutes after, sample collection; for much of the cave, this required that all equipment be taken underground. The sampling protocol used was identical to that routinely used in alpha radiation monitoring in caves. These measurements were made primarily to help characterize cave microclimates and airflow patterns within Kartchner Caverns. Results of these measurements and additional measurements by ACPI are included in Appendix F.

ACPI RADIATION MONITORING PROGRAM

Measurements by OUL demonstrated that alpha radiation levels within Kartchner Caverns were high enough to be of concern for the long-term health of employees. However, the OUL measurements were taken only twice and do not provide an adequate picture of the variations that can be expected throughout the year. Nor are the OUL measurements sufficiently detailed to be useful in characterizing the microclimate of the cave. In order to better understand the alpha radiation levels, ACPI has taken a comprehensive approach to alpha radiation monitoring. This includes:

- Radon gas measurements
- Expanded monthly program of alpha radiation measurements
- Individual radon daughter measurements
- Thoron working level measurements
- Measurements of various radon daughter parameters
- Development of predictive models of radon and radon daughter concentrations in the cave.
- Experiments in removing radon daughters from the cave air

Expanded Alpha Radiation Measurements

In December 1990, ACPI began a program of intensive alpha radiation monitoring in the cave. A series of standard measurement locations were established in order to characterize the alpha radiation levels of those areas of the cave considered to be most likely to be developed. The strategy was to divide the cave into a number of segments that could be sampled by walking along a section of trail. The resulting measurements give an average alpha radiation level for that area of the cave. Each segment was sampled on a monthly basis.

The following trail segments were used:

Cul-de-Sac - stationary sample at the EMS#7 instrument table.
Big Room Overlook from T99 to PP51.
Strawberry Room (PP49) to start of Pool Room.(sta. O-57)
Echo Passage - stationary sample at EMS#10 instrument table.
Entrance of Echo Passage (T97) to top of Rope Traverse (PP28)
Bottom of Rope Traverse (PP27) to 'Y' Junction (sta. G38).
'Y' junction to Grand Central Station (EMS#16).
Top of ladder at 'Y' Junction (PP20) to Sharon's Saddle (PP21)
Kartchner Towers (G50) to Start of River Passage (PP24).
Throne Room Trail from PP91 to PP81.

Rotunda Room from EMS#8 to edge of mud (PP76).
Mud Trench from Doorway (PP63) to Start of Mud Trench (PP61).
Angel Wing Trail Junction -stationary sample.

Alpha radiation levels were determined by the Kusnetz method. At each sampling location, a 5-minute air sample was drawn through a filter attached to a battery powered portable air pump. Alpha activity on each filter is determined by counting the filter with a scintillation counter within 40 to 90 minutes of the end of sampling.

Results of these measurements are included in Appendix F. The combined distribution of 275 alpha radiation measurements by ACPI and OUL are shown in Figure 47. This illustrates that the levels found within the cave are bimodal. In general, the majority of the measurements (263) are below 3 working levels and average 0.77 Working Levels. A second group of 12 measurements clusters at higher values above 3 Working Levels and averages 3.96 Working Levels. These higher levels are all found near the start of the Echo Passage during winter months. Measured alpha radiation levels in the cave appear to exhibit a seasonal pattern, with lower levels in the winter and higher levels in the summer (Figure 48).

It is thought that alpha radiation in caves is dependent on the rates of air exchange with the surface, number and size of entrances and cave geometry (Yarborough, 1980; Ahlstrand and Fry, 1980; Wilkening and Watkins, 1976). Low air exchange rates allow radon and radon daughters to accumulate in the cave, resulting in higher alpha radiation levels. High rates of air exchange dilute the radon concentration and results in lower alpha radiation levels. Air exchange is frequently the result of differences in temperature between the cave and the surface. It is reasonable to expect that alpha radiation levels will be correlated to surface temperatures and this has been shown to be the case for caves such as Carlsbad Caverns and Lehman Cave (Wilkening and Watkins, 1976; Quinn, 1988). Measured alpha radiation levels have been plotted against mean surface temperatures in Figure 49. Additional plots of alpha radiation levels for various sections of the cave and for daily temperatures are found in Appendix F. Figure 49 shows that high alpha radiation levels are found at times of both high and low surface temperatures. The lowest alpha radiation levels are found at times when the surface temperature is approximately equal to the cave temperature. The correlations show that there is a significant but weak correlation. Surface temperature accounts for only a very small portion of the effect; less than 4% of the total variance in alpha radiation levels over periods of a few days.

It is also likely that alpha radiation levels are correlated to atmospheric pressure (Ahlstrand, 1980; Quinn, 1988). The source of radon is in the rocks and sediments of the cave, a drop in atmospheric pressure will draw air that is high in radon out into the cave. Figure 50 shows a plot of alpha radiation levels plotted against surface barometric pressure. This indicates that for higher barometric pressure, lower alpha radiation levels are observed. This is the expected relationship. However the alpha radiation levels should correlate to the change in barometric pressure. A drop in pressure would draw additional radon gas out of small cracks and fissures. A rise in pressure would retard the escape of radon into the cave resulting in lower levels. This is not the relationship which has been found at Kartchner Caverns. A plot of daily change in surface air pressure against alpha radiation levels indicates that drops in pressure are associated with lower alpha radiation. Rises are associated with higher alpha radiation levels, the exact opposite of what was expected (Appendix F). This may indicate that alpha radiation levels are influenced by changes that occur over

FIGURE 47

Distribution of Alpha Radiation WL

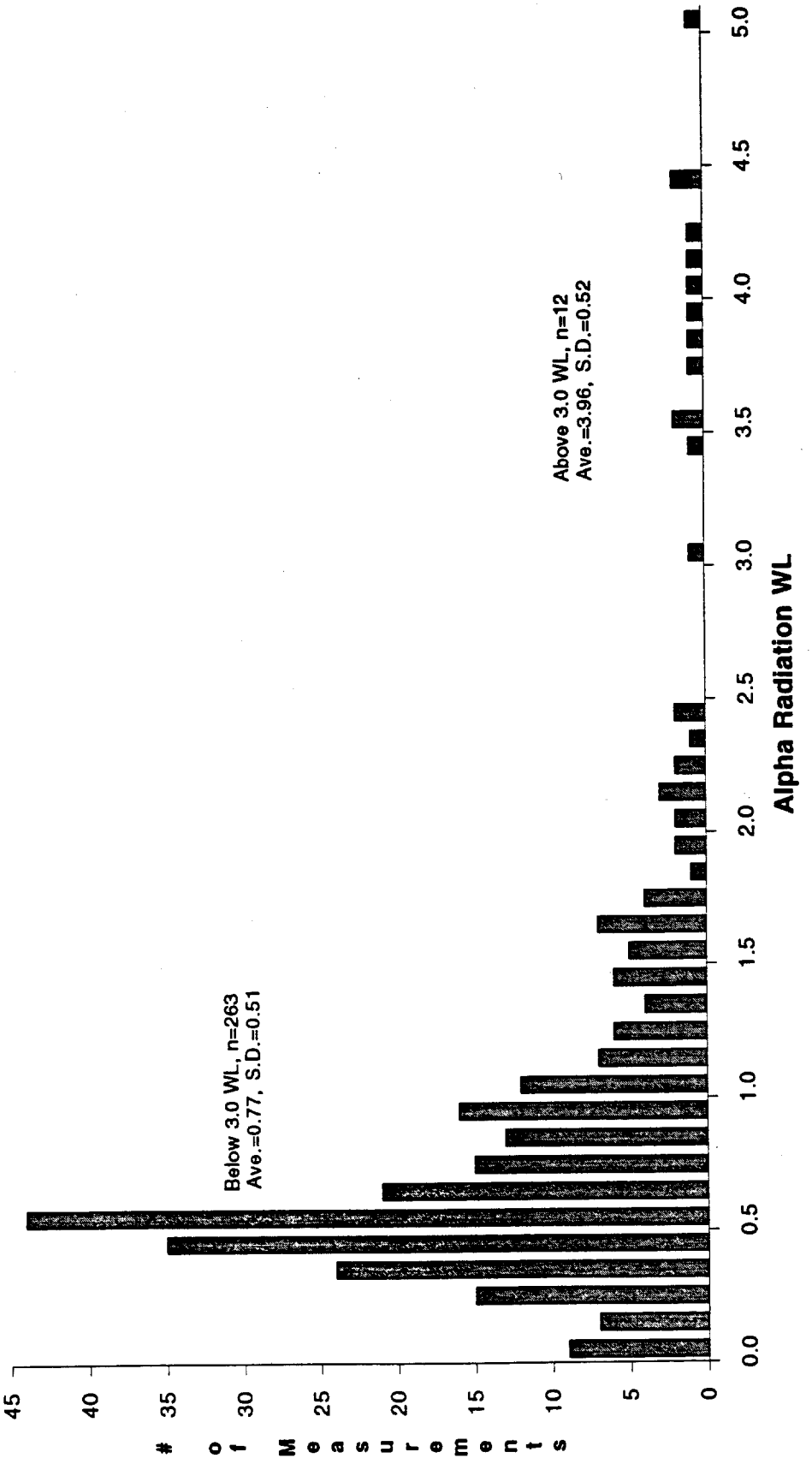
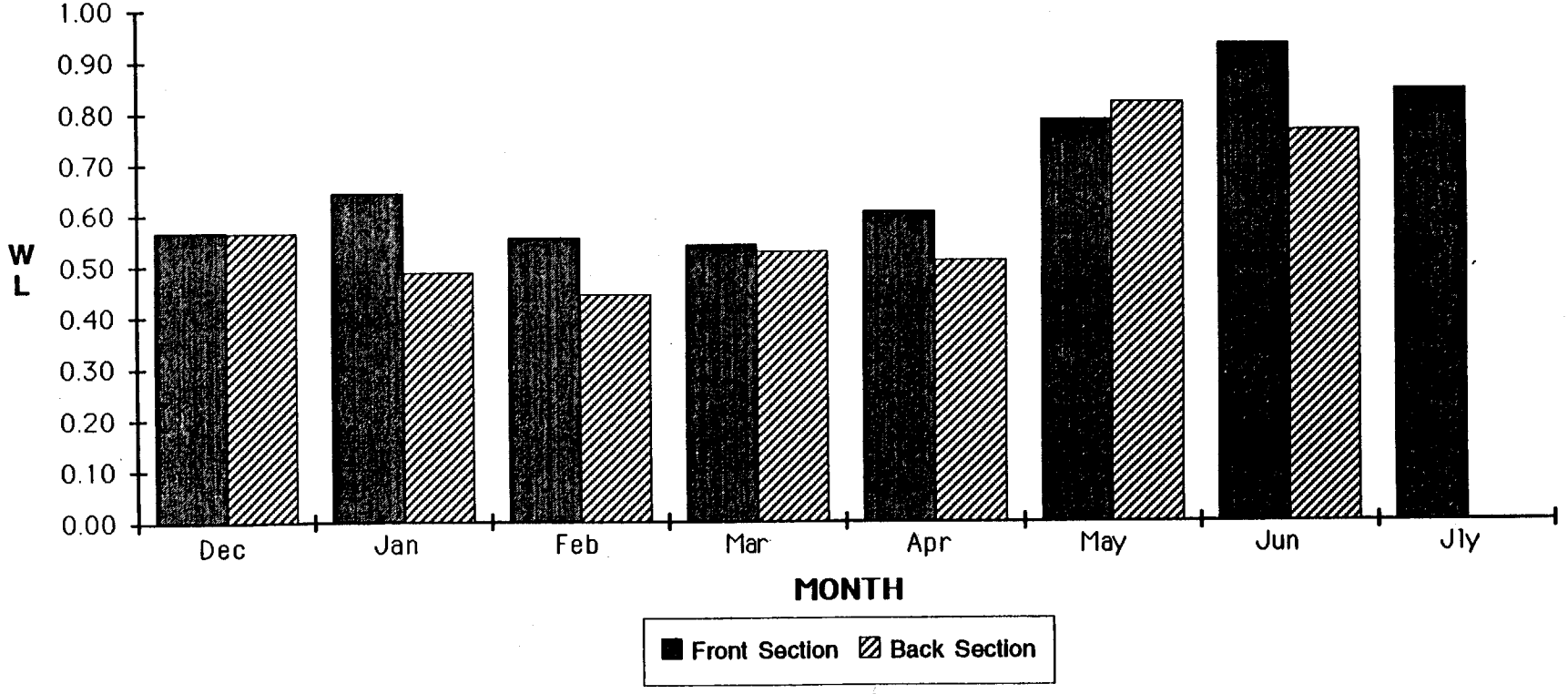


FIGURE 48

Average Monthly Radon Working Level

(Excluding Echo Passage)



Arizona Conservation Projects, Inc. 1992

FIGURE 49

Alpha Radiation vs. Surface Temperature (without Echo Passage)

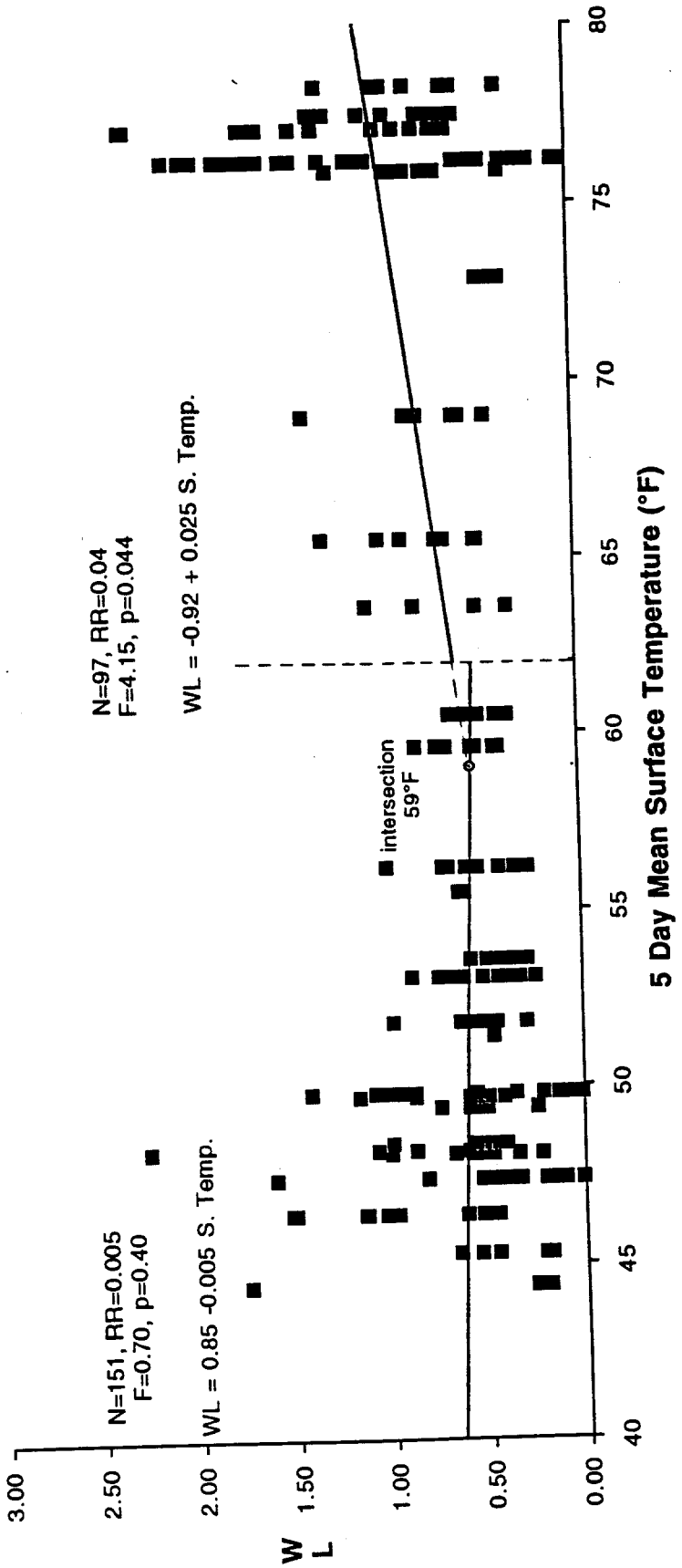
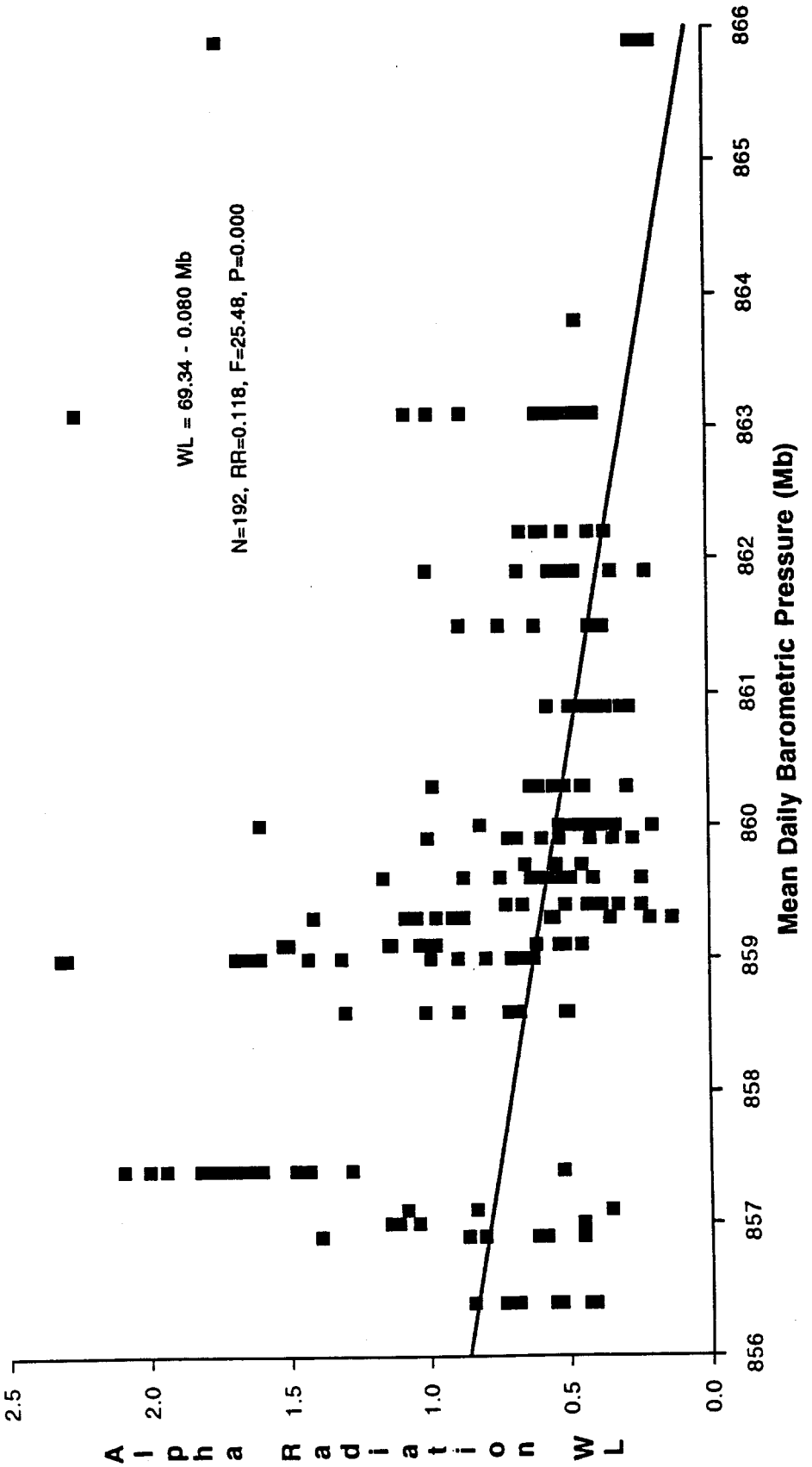


FIGURE 50

Alpha Radiation vs. Barometric Pressure



longer periods of time than a day or are influenced by the sum of the pressure changes.

The distribution of alpha radiation with respect to surface temperature indicates that air exchange is a complex phenomenon in Kartchner Caverns. A more complete interpretation of the relationship between alpha radiation and surface temperatures is given in the section of this report dealing with air exchange and general air circulation patterns within the cave.

The following generalizations have been made based on the measurements of alpha radiation in the cave.

- Measured levels of alpha radiation in the cave range from 0.01 WL to 5.0 W.L.
- The distribution of alpha radiation levels is bimodal; i.e., significantly higher levels exist in the restricted area near the Echo Passage during winter months.
- The distribution for the majority of the cave, (263 measurements) has an average of 0.77 Working Levels.
- The Echo Passage and vicinity has an average of 3.96 Working Levels during the winter (12 measurements).
- Alpha radiation levels are generally lowest during the winter months.
- Alpha radiation levels are generally highest during the summer months.
- Alpha radiation levels are relatively constant at temperatures below 60°F.
- Alpha radiation levels increase with increasing temperatures above 60°F.
- High alpha radiation is found at both high and low surface temperatures.

Alpha Radiation From Thoron

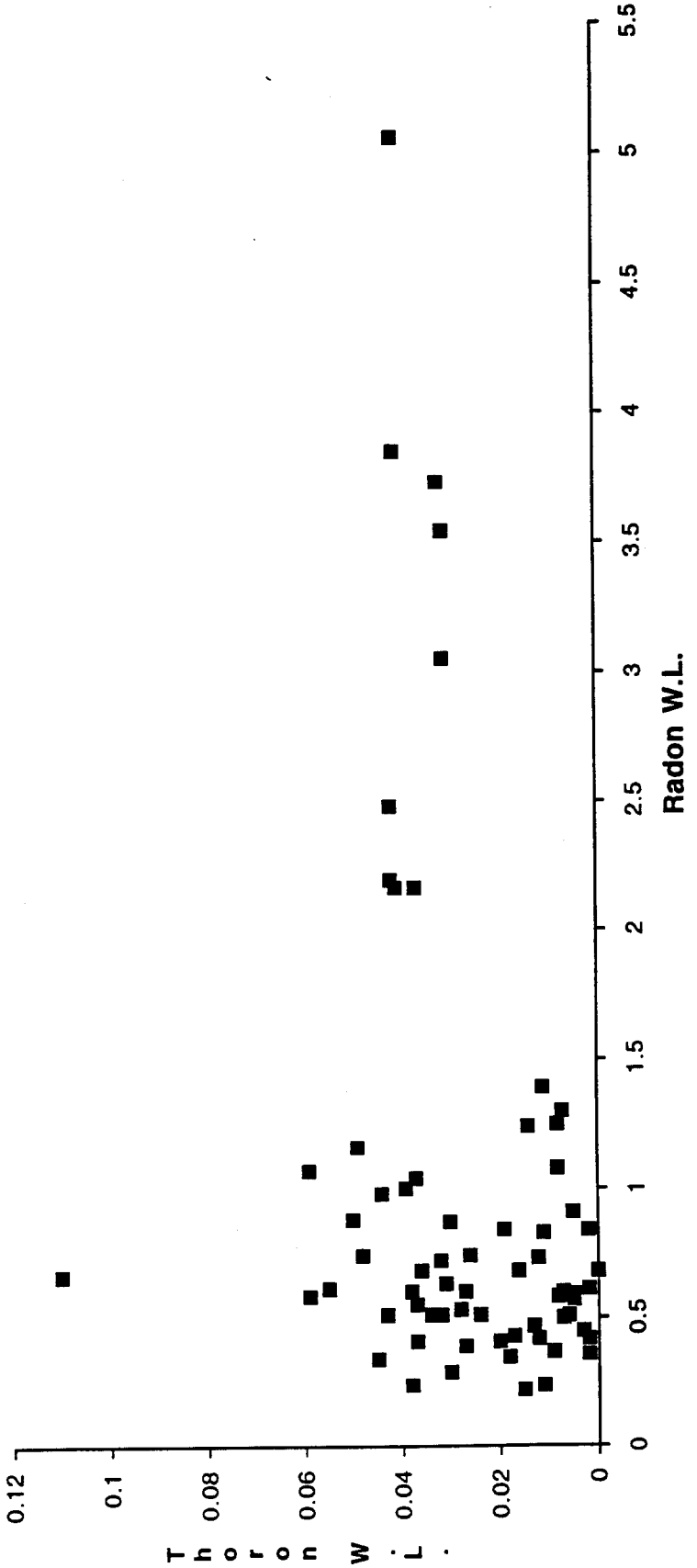
Not all alpha radiation is the result of radon decay. Another series of radioactive decays also produces alpha radiation (Harley, 1988). This series is called the thorium series. The principle decay product of this series is ^{212}Pb which has a half life of 10.6 hours. Total alpha radiation is the combined working level of both radon daughters and thoron. Thoron working levels can be determined from the same filters used to measure radon working level. The filters are counted from 5 hours to 17 hours after sampling. Thoron working levels have been determined for 73 samples. Average alpha radiation contributed by thoron is 0.026 working level. Only one measurement has produced a thoron level above 0.10 working level.

Correlations have also been sought between thoron alpha radiation levels and radon daughter levels. The results of these correlations are shown in Figure 51. No correlation is apparent between the two sets of measurements. This is surprising as one would expect that each would be given off by the parent material at similar rates. The fact that no correlation is displayed may be due to the low thoron levels found. These are typically at such low levels that there is considerable error associated with each measurement. Individual thoron measurements have a typical accuracy of ±25% at these low levels.

Correlations were also sought between thoron levels and mean surface temperatures. The results of this correlation are given in Appendix F. This indicates that, in general, thoron working levels appear to decrease with increasing surface temperature. The plot may also be interpreted as showing a slight increase in thoron levels at times when the surface temperature is approximately equal to the cave temperature. The amount of data and range of temperatures does not appear to be sufficient to draw a firm conclusion about the relationship between surface temperatures and thoron levels.

FIGURE 51

Thoron W.L. vs. Radon W.L.



Measurements of the alpha radiation contributed by thoron show that it contributes only a small amount to the overall alpha radiation levels found in the cave. It is recommended that 0.03 working level be added to the radon daughter working levels to determine the total alpha radiation exposure in the cave.

Radon Gas Concentrations

Alpha radiation levels in the cave are predominantly due to the presence of radon gas which enters the cave from the surrounding rock and sediments. Measurements of the alpha radiation levels in the cave are measurements of the radon decay products. If radon gas was in radioactive equilibrium with its decay products and there was no removal of the decay products by ventilation or plateout the conversion would be 100 pCi/l radon would produce 1.00 Working Level. This is almost never encountered in the natural world where radon decay products are removed by a number of processes. By measuring the concentrations of radon and the individual decay products we can determine how significant these removal processes are in the cave. This has been done utilizing two independent approaches. The first measures radon gas concentrations with an alpha track detector. The second method measures the concentrations of the individual radon daughters.

A series of radon gas measurements were made by ACPI utilizing alpha track detectors. The detector is a small plastic film which is damaged by alpha radiation. By chemically treating the film, the damaged areas are etched and enlarged. By counting the number of alpha tracks and knowing the length of exposure, the average radon gas concentration can be determined. Typically the detectors were left in the cave for three to four weeks. These tests give a long-term average of the radon gas concentrations in the cave. The results of the alpha track radon measurements are given in Table 14.

TABLE 14
Alpha Track Radon Gas Measurements

Location	Start Date	End Date	Radon (pCi/l)
Big Room near Bishop	05/05/89	07/10/89	162.0
Kartchner Towers EMS 22	03/07/90	03/31/90	66.0
Throne Room EMS 18	05/05/91	05/29/91	58.5
Throne Room EMS 18	12/19/90	01/15/91	52.1
Echo Passage EMS 10	12/05/90	12/18/90	368.7
		Average (all)	141.5 ±135
		Average (w/o Echo)	84.7 ±52

Additional measurements have been performed to determine the concentrations of the individual radon daughters. The methods used were the Tsivoglou method as modified by Thomas (Harley, 1988; Nazaroff and Nero, 1988). This method gives the concentrations of each of the three radon daughters and also the total working level of the combined daughters. A total of 17 measurements were taken. The results of these measurements are shown in Table 15 and Appendix F. The average concentration for the first radon daughter, Radon A, was 101 pico Curies per liter. The concentrations ranged from a high of 241 pico Curies per liter to a low of 39 pico Curies per liter. Radon A has a short half life of approximately three minutes. Because of the short half

TABLE 15
Individual Radon Daughter Measurements

Date	Location	Sample #	Time	WL Kusnetz	Walking Standing	Radon-A pCi/l	Radon-B pCi/l	Radon-C pCi/l	WL Thomas
02/24/91	Mud Flats	1	12:04	0.60	S	61	62	64	0.63
02/24/91	Kartchner Towers	3	15:27	0.63	S	66	61	61	0.62
02/24/91	Start Echo Passage	2	13:17	2.19	S	208	219	210	2.14
03/24/91	Grand Canyon	2	11:58	0.53	S	99	61	42	0.58
03/31/91	Ladder to Gr.Central	5A	18:23	0.40	W	39	32	40	0.36
03/31/91	Big Rm.Overlook	1	12:15	0.49	W	59	48	51	0.50
03/31/91	Traverse to Ladder	1A	16:47	0.45	W	62	43	38	0.43
03/31/91	Echo to Traverse	5	15:31	0.46	W	83	51	36	0.49
05/05/91	Grand Canyon	2	11:43	0.58	S	84	60	49	0.58
05/16/91	River Entrance	4	14:04	0.35	S	46	35	33	0.35
05/16/91	Grand Central	1	11:01	0.51	S	66	53	43	0.51
05/16/91	Bat House floor	2	12:39	1.08	S	143	118	97	1.13
05/29/91	Upper Throne	1A	14:21	0.45	W	57	53	40	0.48
05/29/91	Lower Throne	2A & 3A	15:24	0.61	S	84	58	50	0.58
05/29/91	Grand Canyon	2	11:38	0.58	S	175	66	33	0.65
06/21/91	Pop-up	5A	17:46	0.62	S	147	63	34	0.61
06/25/91	Thunder Room	1	10:33	1.24	S	241	153	93	1.40
					Average	101	73	60	0.71
					Standard Deviation	±60	±48	±43	±0.45

life, it is likely to be in equilibrium with the parent radon gas. The fact that the average Radon A (101 pCi/l) is within the range of measured radon gas concentrations reinforces this conclusion. The next radon daughter is Radon B. The average concentration was found to be 73 pico Curies per liter and to range from a high of 219 pCi/l to a low of 35 pCi/l. The half life of Radon B is 27 minutes. The third radon daughter is Radon C with a half life of 20 minutes. The average concentration was found to be 60 pico Curies per liter and ranged from a high of 210 pCi/l to a low of 33 pCi/l.

The Thomas method also allows the total working level to be calculated from the concentrations of the individual daughters. This can be compared to the working level determined from the Kusnetz method which has been used for all other alpha radiation measurements. A comparison of the two methods indicates that the average Kusnetz method is 0.69 working level and the average Thomas is 0.71 working level. Considering the other uncertainties involved in each method, the agreement is excellent.

If none of the radon daughters are removed by air exchange or other removal processes, then the concentrations of each radon daughter will be equal to the parent. This is true in the case of four of the measurements. This indicates that for some areas of the cave there is little or no removal other than by radioactive decay. The remaining measurements show that the concentrations of each daughter is smaller than the preceding daughter. This indicates that some removal process is at work. Radon daughters can be removed by either air exchange or by becoming attached to surfaces. In order for air exchange to be a significant factor in removing radon daughters, the exchange rate must be relatively large compared to the half life of the radon daughters (Beckman and Holub, 1979). Because the half life of each radon daughter is less than half an hour, the air exchange rate must be at least once every hour or so to make a measurable decrease. This volume of airflow is only found in the entrance passages. The other alternative is that the individual radon daughters are being removed by plateout onto cave surfaces. Removal processes have never been studied in caves before but there is extensive literature regarding plateout removal rates in buildings. The behavior of the individual radon daughters can be modeled based on the expected rates of plateout removal. This is discussed in detail in the section of this report dealing with modeling the removal process. The conclusion of the modeling study is that the concentrations of the individual radon daughter products is due to plateout removal rather than removal by air exchange.

The measurements of the individual radon daughters and radon gas show that these are in near equilibrium within the cave. Radon gas concentrations were measured to average 85 pCi/l with the alpha track detectors and 95 pCi/l assuming equilibrium with ^{218}Po. Alpha radiation levels in the cave average 0.77 Working Level. These measurements indicate that 100 pCi/l of radon gas will produce between 0.91 WL and 0.81 WL of alpha radiation. The equilibrium ratio would be approximately 0.85 at Kartchner Caverns.

Supplementary Radiation Measurements

ACPI has instituted an expanded program of alpha radiation monitoring to supplement the two groups of measurements performed by OUL. Due to delays by OUL in starting the alpha radiation monitoring, ACPI began a program of monitoring in-cave radiation levels. The first portion involved a more comprehensive series of measurements throughout the cave on a regular basis. A portable geiger counter,

called a Radalert, which is sensitive to alpha, beta and gamma radiation, was used. Bedrock surrounding the cave blocks out most of the external background gamma radiation. The primary source of radiation within the cave is alpha and beta radiation from the decay of radon and radon daughters. Readings from the Radalert geiger counter correlate roughly to measured radon daughter concentrations but there is a wide spread to the data (Figure 52). The correlation is not good enough to allow alpha radiation working levels to be reliably predicted from Radalert measurements. The Radalert instrument has been found to be susceptible to several confounding effects. Radioactive decay products will accumulate on the Radalert, leading to overestimates on subsequent readings. The Radalert is also particularly sensitive to beta particles and this causes readings to be dependent on the ratios of the radon daughters (Curtiss, 1949; Evans, 1980). A discussion of the strengths and weaknesses of the Radalert is included in Appendix F. These problems limit the usefulness of the Radalert in determining alpha radiation levels from a single reading but the errors appear to average out over many readings taken at different times. The Radalert has proved to be useful in identifying areas of unusually high or low alpha radiation and in determining the seasonal variations throughout the cave. The pattern of radiation levels measured with the Radalert is thought to follow the same seasonal pattern and distribution as alpha radiation levels in the cave. The Radalert measurements are intended to supplement recognized methods of determining alpha radiation levels.

Radalert measurements were collected from September 1989 to May 1991 at each of the environmental monitoring stations and a number of other standardized locations. Readings were taken on an approximately monthly basis. In total, 684 measurements were taken. The average Radalert measurement was 29.7 counts per minute which is approximately equivalent to 0.7 Working Levels. The results of these measurements are summarized in Figures 53 and 54, which illustrate the monthly variations in Radalert counts for various sections of the cave. Radalert readings are typically low during the winter months from November to April. During the winter, the average monthly Radalert reading is 23.4 counts per minute, approximately equal to 0.5 working level of alpha radiation. The summer months, May to September, produce the highest readings, 38.2 counts per minute, which is approximately equal to 0.9 working level.

The levels of alpha radiation are thought to be dependent on the rate of air exchange with the surface. Higher rates of air exchange will tend to dilute the concentration of alpha radiation. Lower rates of air exchange will allow radon and radon daughters to accumulate and results in higher alpha radiation levels. If we assume that the air exchange rate is related to the difference between cave temperature and surface temperature, we can look for correlations between cave Radalert measurements and surface temperatures. Figures 55 and 56 and Table 16 show average monthly Radalert measurements correlated to mean monthly surface temperatures. These figures show that, for all areas of the cave, there is a significant increase in Radalert counts and, presumably alpha radiation, with increased surface temperature. The trends observed are not what would be expected from a simple model of air exchange produced by temperature differentials. If air exchange were driven by temperature differentials, then we would expect the minimum air exchange to occur when surface temperatures are near the cave temperature. When surface and cave temperatures are equal there should be little air exchange and presumably higher alpha radiation levels. Higher or lower temperatures would induce more air exchange and presumably lower radiation levels. The fact that Radalert

FIGURE 52

Correlation of Radalert to Radon WL

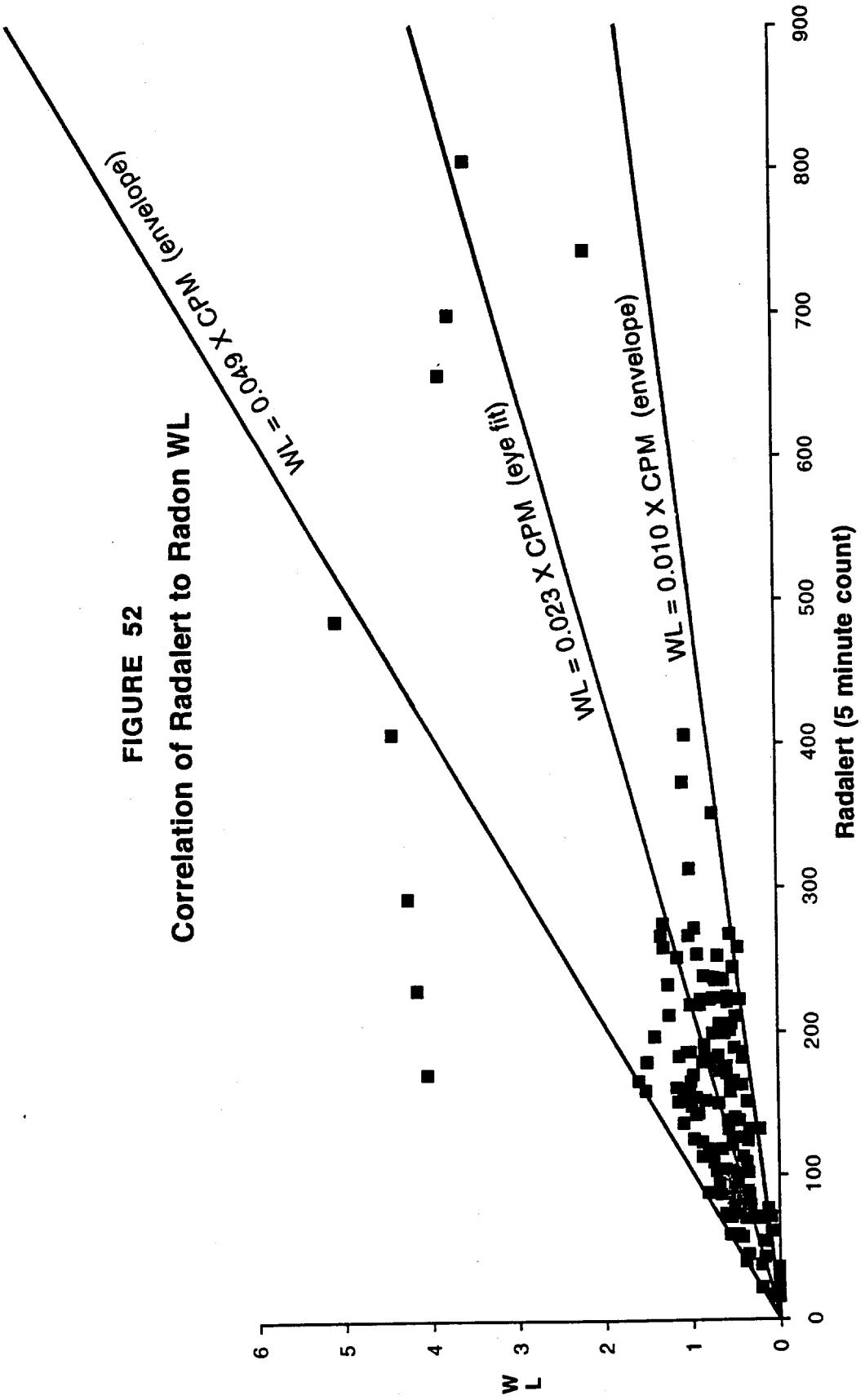


FIGURE 53

Kartchner Caverns - Monthly Average

Radalert by Area

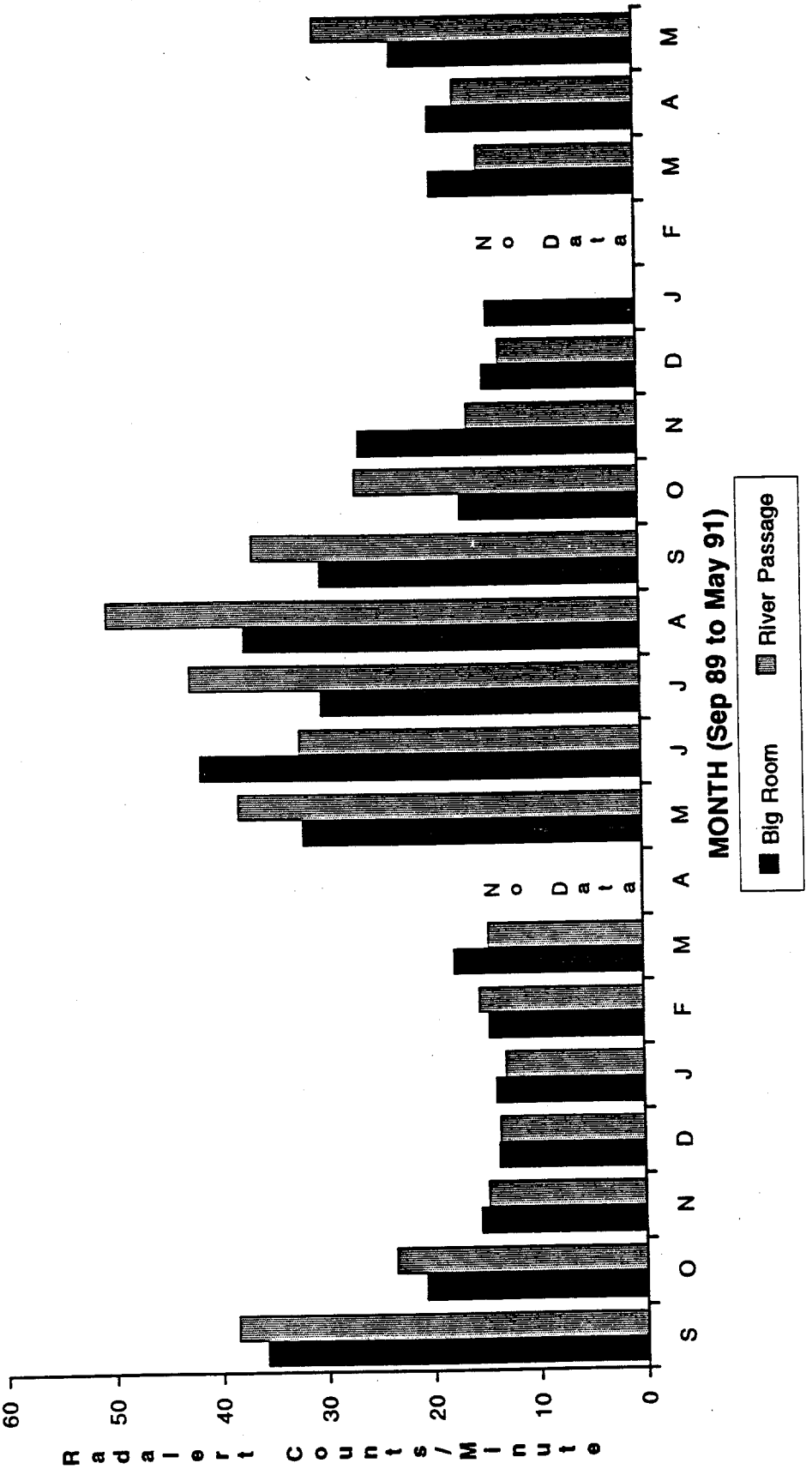


FIGURE 54

Kartchner Caverns - Monthly Average

Radalert by Area

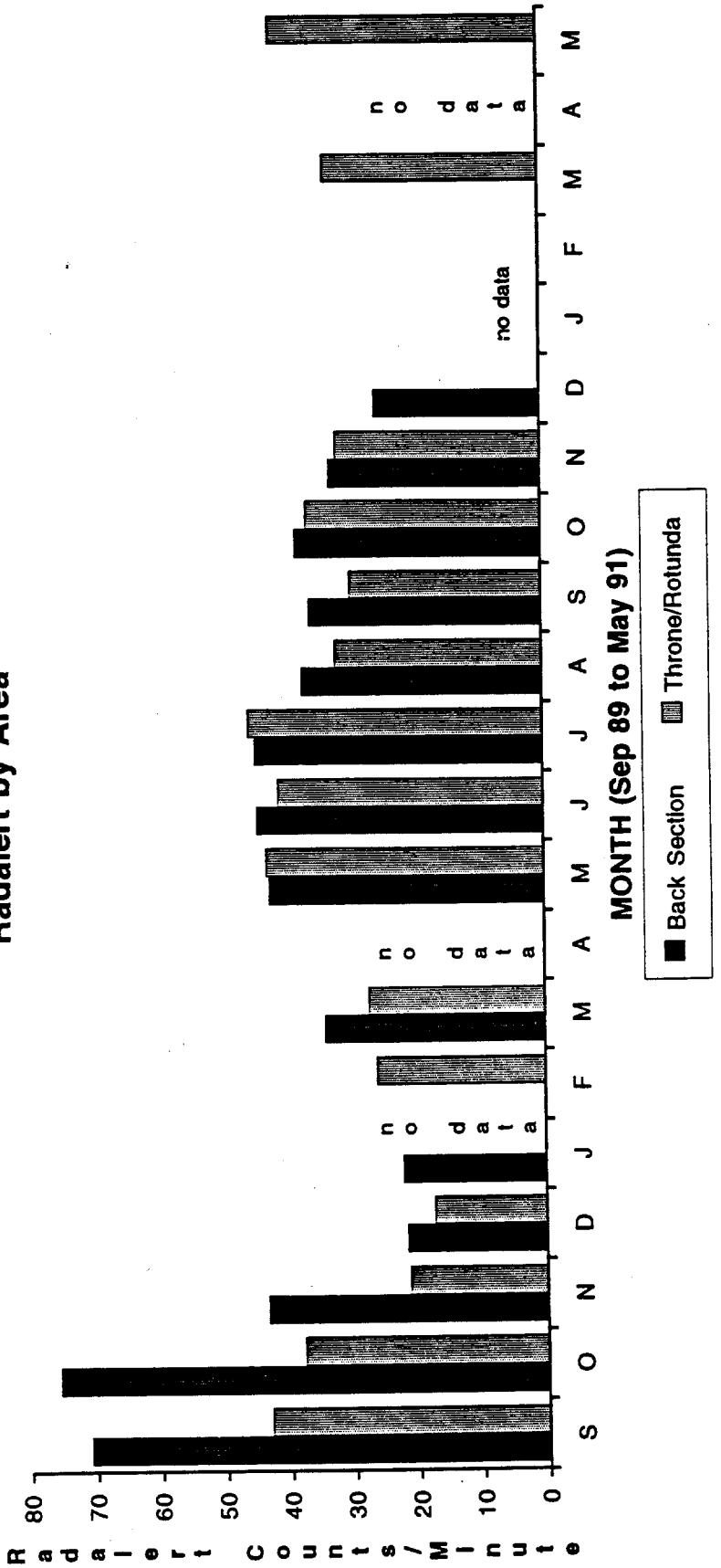


FIGURE 55

Big Room Radalert Counts vs. Surface Temperature

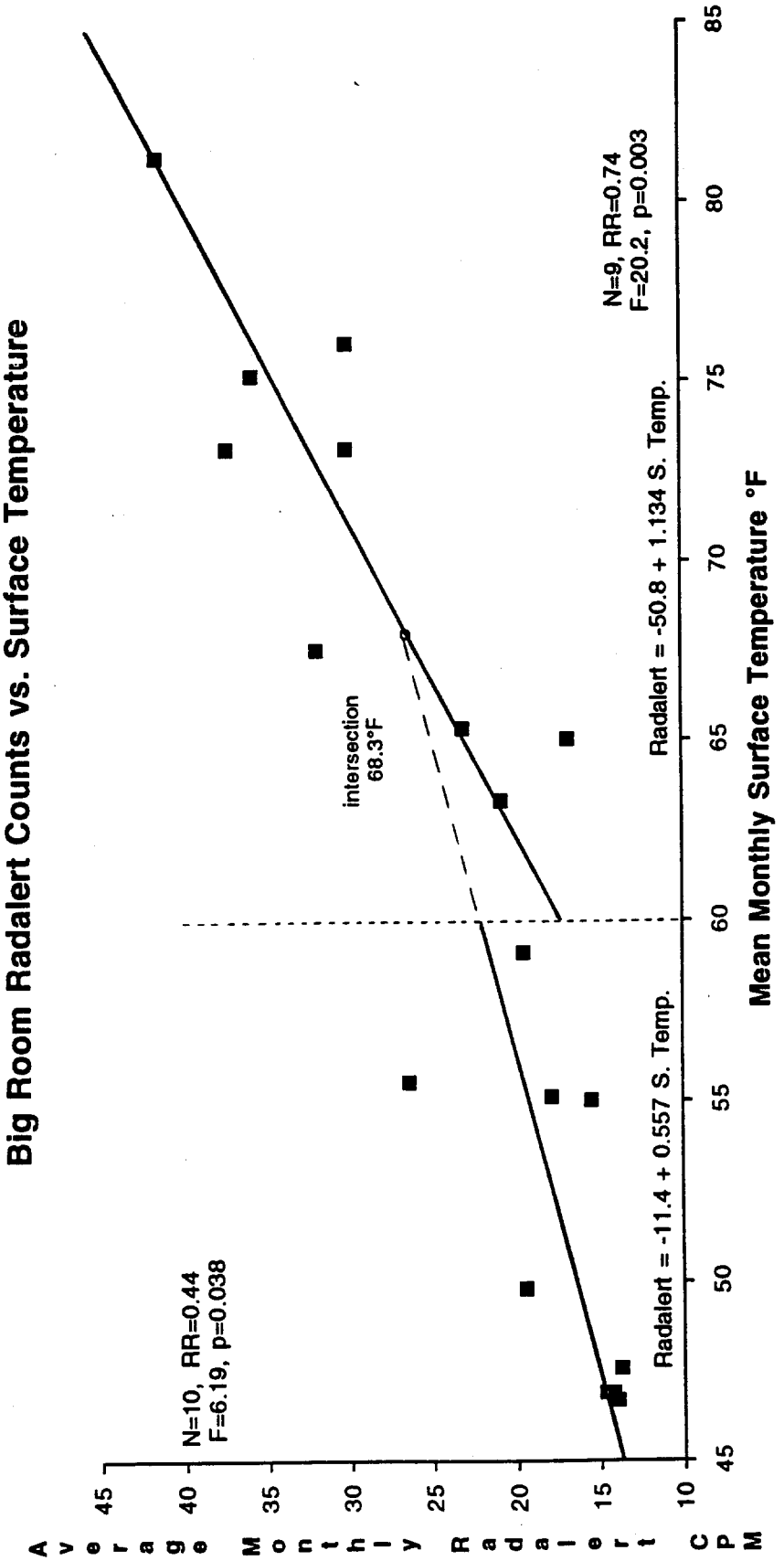
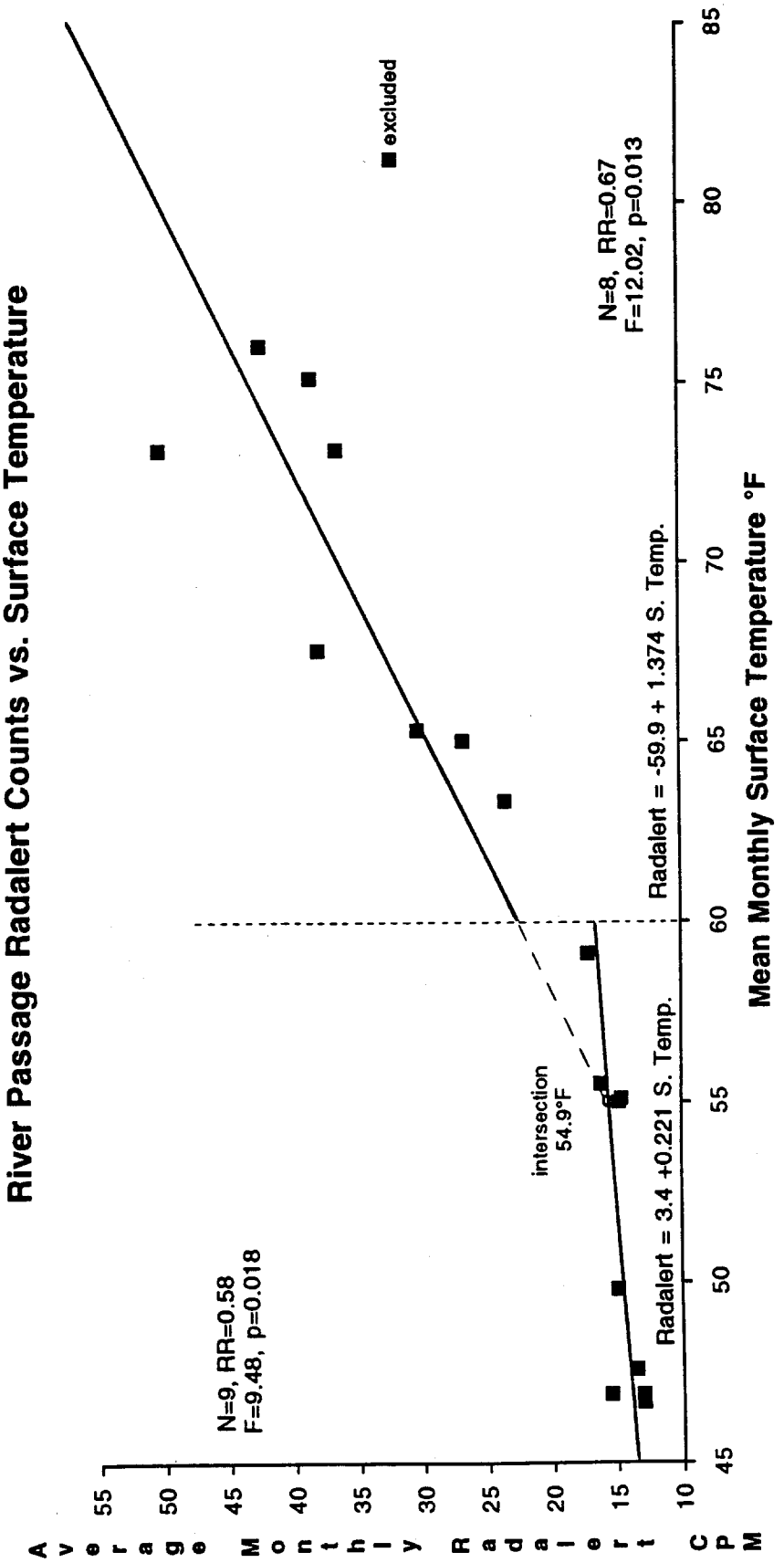


FIGURE 56


River Passage Radalert Counts vs. Surface Temperature
Average Monthly Radalert CPM
Mean Monthly Surface Temperature °F
excluded
N=8, RR=0.67
F=12.02, p=0.013
Radalert = -59.9 + 1.374 S. Temp.
N=9, RR=0.58
F=9.48, p=0.018
Radalert = 3.4 +0.221 S. Temp.
intersection
54.9°F
45
50
55
60
65
70
75
80
85
10
15
20
25
30
35
40
45
50
55

measurements continue to increase with increased temperature rather than showing a peak when surface temperatures are equal to cave temperatures indicates that the cave air exchange is not a simple convective system driven by temperature differentials between the cave and surface. Air exchange and cave air circulation patterns are more fully covered in the air exchange section of this report.

A tabulation of all measurements is included in Appendix F. From the collected data the following observations can be made:

- The lowest Radalert readings are in the Big Room and River Passage.
- The highest Radalert readings (besides Echo Passage) are in the Back Section and Throne/Rotunda Rooms.
- Measured Radalert levels fluctuate seasonally, with the lowest readings in December and January. The highest readings are in July and August.
- The ratio of lowest (winter) to highest (summer) is approximately 2.5.
- Average monthly Radalert measurements have a significant correlation with surface temperatures for the Big Room (Figure 55), River Passage (Figure 56) and Throne/Rotunda Rooms.

TABLE 16
Average Monthly Radalert
Counts per minute

	Big Room	Back Section	Throne/ Rotunda	River Passage	Surface Avg.Temp.
1989					
Sep.	35.8	70.9	43.0	38.6	75.0°F
Oct.	20.8	75.6(High)	37.8	23.5	62.6°F
Nov.	15.5	43.5	21.3	14.8	55.0°F
Dec.	13.8(Low)	21.4(Low)	17.4(Low)	13.6	47.7°F
1990					
Jan.	14.0	22.5	N.A.	13.0(Low)	46.7°F
Feb.	14.6	N.A.	26.3	15.5	47.0°F
Mar.	17.9	34.6	27.4	14.6	55.2°F
Apr.	N.A.	N.A.	N.A.	N.A.	62.8°F
May	31.9	44.2	43.3	38.0	67.5°F
Jun.	41.6(High)	43.9	41.4	32.2	81.2°F
Jul.	30.1	44.9	45.9(High)	42.5	76.0°F
Aug.	37.3	39.3	32.2	50.3(High)	73.1°F
Sep.	30.1	36.6	29.8	36.5	73.1°F
Oct.	16.9	38.3	36.6	26.8	65.0°F
Nov.	26.4	32.9	31.9	16.2	55.5°F
Dec.	14.7	25.9	N.A.	13.1	46.9°F
1991					
Jan.	14.2	N.A.	N.A.	N.A.	46.9°F
Feb.	N.A.	N.A.	N.A.	N.A.	52.7°F
Mar.	19.5	N.A.	33.6	14.9	49.8°F
Apr.	19.5	N.A.	N.A.	17.1	59.1°F
May	23.1	N.A.	42.0	30.3	65.3°F
Average	23.0	41.0	34.0	25.1	
Std. Dev.	±8.9	±15.7	±8.5	±12.1	
Variance	0.39	0.38	0.25	0.48	
Low Month	Dec	Dec	Dec	Jan	
High Month	Jun	Oct	Jul	Aug	

Sources of Radon

One might suppose that, by identifying materials that were high in uranium and removing them, we could reduce the emission of radon gas. Unfortunately the amount of uranium needed to support the observed levels of radon is quite small; in the range of a few parts per million. Nevertheless, it is helpful to determine if we can identify a single major contributor of radon gas in the cave. Small samples of various materials from the cave and surface have been examined to determine the approximate alpha activity. See Appendix F for a complete listing of the results of these tests. This screening step identified that only the mud from the Subway passage and mud from the Echo Passage had substantially higher alpha activity than other materials from the

cave. The remaining samples of bedrock, sediments, speleothems and fault gouge had only one-third the activity of the mud samples. This indicates that, while the mud from the rear of the cave has the highest activity, the range of activities found in the cave is not large. A single sample of the Subway mud was analyzed and found to contain 9 ppm of uranium, still a quite low value. In the process of age dating the speleothems, the uranium content was also determined. These range from 0.06 to 0.31 ppm, also quite low. As no materials with large uranium contents have been found, we must assume that the high radon levels are primarily due to low air exchange rates which allow radon gas to accumulate.

Models of Radon and Radon Daughters in the Cave

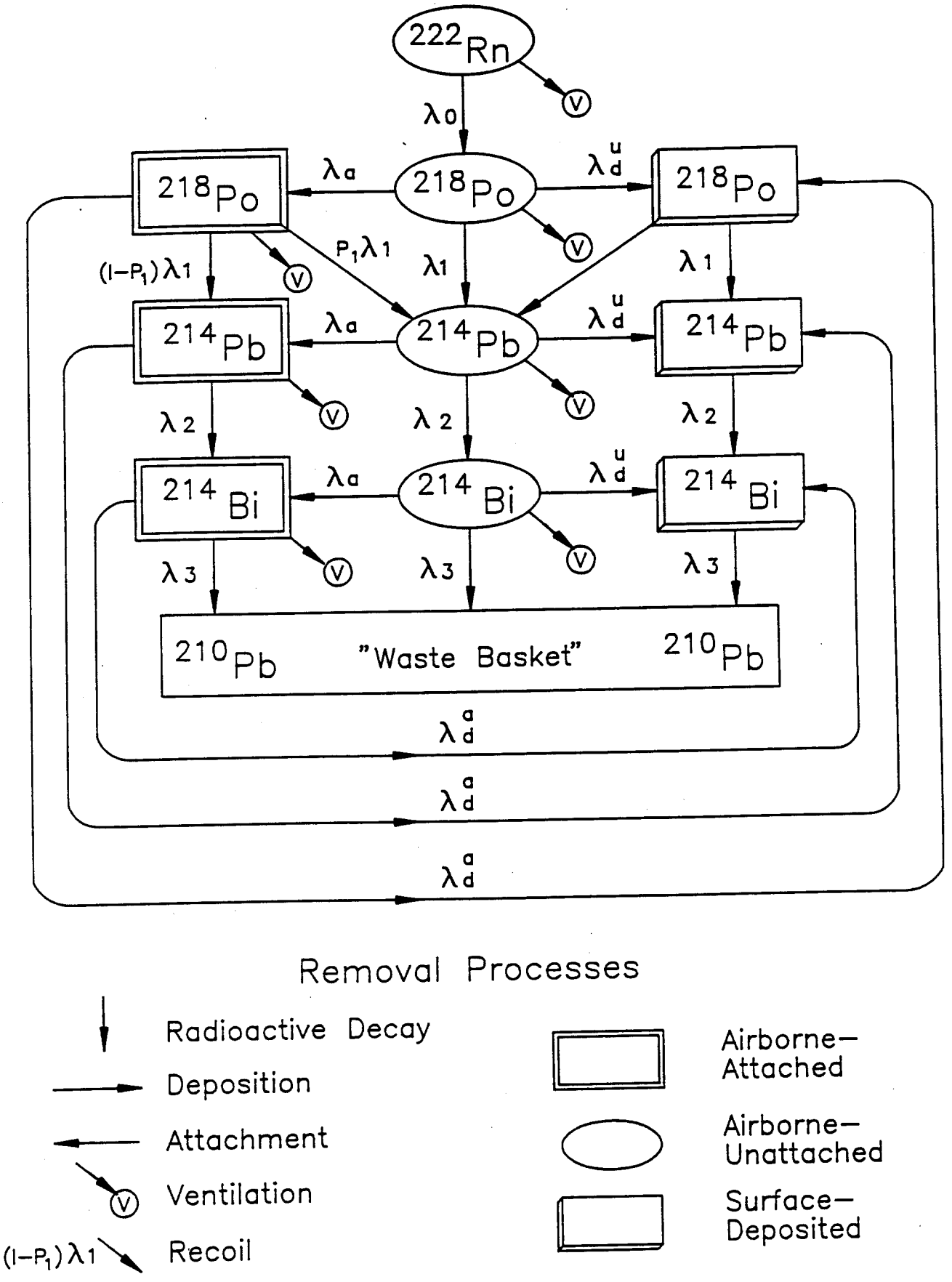
Many of the processes that allow high levels of radon and carbon dioxide to accumulate in the cave are also those which maintain the moist cave environment. Valuable insight into the operation of the cave's microclimate can be gained by modeling the behavior of radon within the cave. An additional benefit is the ability to make generalized predictions of the consequences of developing the cave for public viewing. Two models of radon and radon daughter concentrations have been considered. The first, the Jacobi Model (Nazaroff and Nero, 1988), considers those factors which create the individual radon daughters and the removal processes. The second, the Radon Entry Model (Wilkening and Watkins, 1976; Evans, 1980), considers the rate at which radon enters the cave and is removed by decay and ventilation.

Radon Daughter Concentration Model

In 1972, Jacobi published a mathematical model for predicting the concentrations of airborne radon daughters under the influence of various sources and removal processes. The initial model was formulated for use in uranium mines, but the same processes are active inside buildings and caves. The model is generally referred to as the Jacobi Model (Nazaroff and Nero, 1988).

The Jacobi Model can be described as consisting of 11 cells with a number of interconnecting paths. The three main rows in Figure 57 correspond to the three radon daughters (^{218}Po, ^{214}Pb and ^{214}Bi) that are tracked by the model. The model follows the decay and removal of the daughters until ^{210}Pb is reached in the bottom row. The final decay product, ^{210}Pb, is not considered to be a health concern and is therefore the end of the model. The three columns correspond to the three physical states possible for each daughter: airborne-attached, airborne-unattached and surface-deposited. All downward-pointing arrows depict changes in the radon daughters from radioactive decay. Right-pointing arrows, including those around the bottom of the figure, represent a deposition process that removes material from the air onto surfaces. Left-pointing arrows represent attachment to aerosol particles. The slanting arrows that terminate on circles represent removal of airborne products by ventilation and filtration. The two remaining slanting arrows represent recoil processes which detach radon daughters from aerosols or surfaces.

Several assumptions are made in the model. First, the model assumes that radon is well mixed throughout the volume being considered. This is likely to be the case for radon which has a half life of several days. However, the individual daughters have half lives that range from a few minutes to half an hour. It is unlikely that air within the



Removal Processes

Radioactive Decay

Deposition

Attachment

Ventilation

$(I-P_1)\lambda 1$ Recoil

Airborne—Attached

Airborne—Unattached

Surface—Deposited

FIGURE 57

Jacobi Radon Decay Product Model

Removal Process Flowchart

cave is well mixed on this time scale. Second, all surfaces are considered to be equally effective in removing radon from the air. The model is also a steady state model and is only valid for conditions which remain constant over a period of time that is long compared to the removal rates.

Application of the model is dependent on knowing the rates at which the various radon daughters are created by radioactive decay and removed by various processes. The rates at which the individual daughters are created by radioactive decay are well known physical constants. The rates at which the daughters are removed by ventilation, deposition and attachment is quite variable but have been studied extensively in recent years. Five additional parameters are needed to describe the deposition and removal processes.

1) Ventilation rate in air exchanges per hour. Based on measurements of airflow and air exchange rates necessary to maintain the observed concentrations of atmospheric gases, the ventilation rate used is one air exchange every twenty days. Note that this is much greater than is encountered in buildings and most mines. The ventilation rate is much less than the decay constant of radon or any of the daughters. As a result, ventilation is a minor mechanism for the removal of radon and radon daughters in the undeveloped cave.

2) Aerosol attachment rate. Most air contains copious numbers of small aerosol particles. These particles range in size from almost atomic dimensions up to several micrometers in diameter. Aerosols play an important role in the behavior of radon daughters in the indoor environment. Radon daughters can attach themselves to aerosol particles and the subsequent behavior is so different that the attached are distinguished from the free or unattached radon daughters. Under normal indoor building conditions the attachment rate is 50 to 500 h^{-1}. The attachment rate is, however, proportional to the concentration of aerosol particles. Very little work has been published regarding the concentrations of aerosols in cave air. It is generally accepted that cave air is very 'clean' and contains few particles. A study at Lehman Caves measured the concentration of condensation nuclei and found levels of 50 to 600 per cm^3, with an average of approximately 250 per cm^3 (Went, 1970). Measurements of the unattached fraction of ^{218}Po at Kartchner Caverns indicates that the concentration must be below 2000 per cm^3 (See Appendix F for a summary of these measurements). These levels are several orders of magnitude lower than what is generally found in buildings. Consequently, the proper attachment rate to use in modeling cave air is much smaller than used for buildings. A value of 1.3 h^{-1} will be used for existing conditions.

3 and 4) Two values of deposition rates onto surfaces are needed in the model. Radon daughters, whether attached or unattached, tend to deposit on, and stick to, exposed surfaces. Since radon daughters removed from the air are no longer available to be inhaled, surface deposition augments ventilation as a means of removing radon daughters from the air. The term 'plateout' is generally used to describe the surface deposition of radon daughters.

3) Unattached plateout rate. The unattached plateout rate appears to have a theoretical minimum value of 0.54 m/hr in stagnant air. Increased air motion will also increase the deposition rate. Values of 7 to 22 m/hr have been suggested as representative of normal building conditions. Several tests have also been conducted in small chambers containing air with no aerosols. These experiments give values of 1.2 to 1.7 m/hr for the unattached plateout rate. Because the cave air is also unusually low in aerosols, these values will be used in modeling cave conditions.

4) Attached plateout rate. The same experiments determined that the plateout rate for the attached radon daughters was less than 0.09 m/hr.

5) The last parameter is the probability that the decay product will recoil and detach from an aerosol particle when ^{218}Po decays. The recommended value of 0.83 has been used in all calculations.

The actual values used in the model must also be adjusted based upon the shape of the container; in this case, the cave rooms. This is a function of the ratio of surface area to volume. In the case of Kartchner Caverns, the surface to volume ratio is about 0.2 m^{-1}.

Application of the Model to Undeveloped Conditions in the Cave.

Based on the measurements taken with alpha track detectors and measurements of ^{218}Po, the average concentration of radon is estimated to be 100 pCi/l. The unattached fraction has been measured to be 0.52. The unattached fraction of ^{218}Po is 0.82. From these measurements, the values of the various parameters can be determined so as to best fit the measured values.

The effect of development of the cave on alpha radiation levels can be estimated from the Jacobi Model. Several important parameters of the model will change. The principal change brought about by development will be an increase in air circulation caused by convective heating from lights and visitors. This will result in a more uniform mixing of cave air and bring the air into more frequent contact with cave surfaces. This will increase the rate at which radon daughters will plate out. The rate at which the air will circulate is estimated to increase by a factor of three. The number of condensation nuclei will also increase. These will be produced by visitors and condensation of water vapor near cooler surfaces. The number of condensation nuclei is estimated to double. The results of the Jacobi Model for a range of undeveloped and anticipated developed conditions is tabulated in Table 17 and complete results are given in Appendix F. These values have been calculated for a 100 pCi/l concentration of radon gas. For higher or lower concentrations of radon, the resulting values will change proportionally.

The model results indicate that alpha radiation measured in Working Levels will decrease by approximately 15% as a result of development. The amount of unattached potential alpha energy (PAEC) is also projected to decrease for some development conditions. The unattached fraction of PAEC is thought to be the most harmful form of radon daughters. The last model run illustrates the effect of large amounts of condensation fog. This may occur after development during certain times of the year. High concentrations of fog would increase the Working Level of alpha radiation to approximately pre-development levels. The unattached PAEC would decrease to a very low level.

Application of the Jacobi Model indicates that development of the cave will tend to decrease alpha radiation levels. These results are based on measurements of the undeveloped conditions in the cave and assumed conditions after development. Alpha radiation levels should be monitored after development in order to verify these results.

TABLE 17
Results of Jacobi Radon Daughter Model

Model Run	Cave Conditions	Working Level	Equilibrium Ratio	Unattached PAEC*
#1	Undeveloped	0.83	0.83	0.33
#2	Undeveloped	0.71	0.71	0.15
#3	Undeveloped	0.88	0.88	0.14
#1	Developed	0.70	0.70	0.16
#2	Developed	0.68	0.69	0.04
#3	Developed**	0.80	0.80	0.01

Based on 100 pCi/l Radon Concentration
* PAEC = Potential Alpha Energy Content
** Dense condensation fog.

Radon Entry Model

Radon enters the cave from the walls of the cave and from cave sediments. As radon is an inert gas there are only two ways in which it is removed from the cave. The primary mechanism is by radioactive decay into the daughter products. The half life of radon is 3.82 days and if it were not constantly entering the cave, 99% would have decayed within 25 days (Evans, 1980). The second process which removes radon from the cave is air exchange with the surface (Wilkening and Watkins, 1976). A simple model of radon levels within the cave can be constructed based on these two processes. The only parameters are the rate of radon entry and the ventilation rate. The model must also be consistent with the following general conditions which have been observed inside the cave.

- Average radon gas concentration is 100 pCi/l.
- Peak radon concentrations of 400 pCi/l.
- Radon daughter concentrations and presumably radon gas concentrations vary by a factor of two on an annual cycle, being lowest in the winter and highest in the summer.
- Air exchange rates are at least 140,000 cubic feet per day but are less than 1,000,000 cubic feet per day.
- Uranium concentrations are not unusually high in any of the rock or sediments in the cave. Presumably, since radon is a decay product of uranium, the radon emissions will also be low and within typical values.
- The volume and surface area of the cave are approximately known from the survey data and airflow measurements.

The model will be set up as a steady state system with the influx of radon and the ventilation rate being constant for a period that is long compared to the removal rates. The cave is also treated as a lumped system which assumes that radon levels are uniform throughout the cave and surface air is well mixed with cave air. Neither of these assumptions is likely to be correct and so we can only expect the model to predict the gross behavior of the cave.

The influx of radon is first estimated to be 0.45 pCi per square meter per second. This is a general average influx rate for most materials (Harley, 1988). Based on the surveyed volume and estimated surface area, this corresponds to 0.92 pCi/l per hour

inside the cave. The decay constant for radon can be determined from the half life and is precisely known.

We can first solve the model to determine the ventilation rate which would allow radon to build up to the observed average level of 100 pCi/l and peak concentrations of approximately 400 pCi/l.

TABLE 18
Maximum Radon Concentration for Various Influx Rates

	Radon Influx Rate		
	0.76 pCi/l/hr	2.0 pCi/l/hr	3.0 pCi/l/hr
Maximum Radon Concentration	100 pCi/l	265 pCi/l	398 pCi/l

The influx rates needed to produce the observed radon levels are moderate and consistent with the low uranium content of the rocks and sediments (Wrucke, et al). The fact that radon levels are significantly different in various areas of the cave indicates that the radon influx rate is also variable throughout the cave. The model shows that variations in the influx rate are directly proportional to the maximum radon concentration.

The impact of various ventilation rates can also be examined with the aid of the model. The air on the surface has a very low radon content compared to the air in the cave. Surface air brought into the cave will dilute and transport radon out of the cave, resulting in lower radon concentrations. The model can be used to assess the importance of ventilation in determining the radon concentration and also to investigate the effect of artificially increasing the ventilation to control radon.

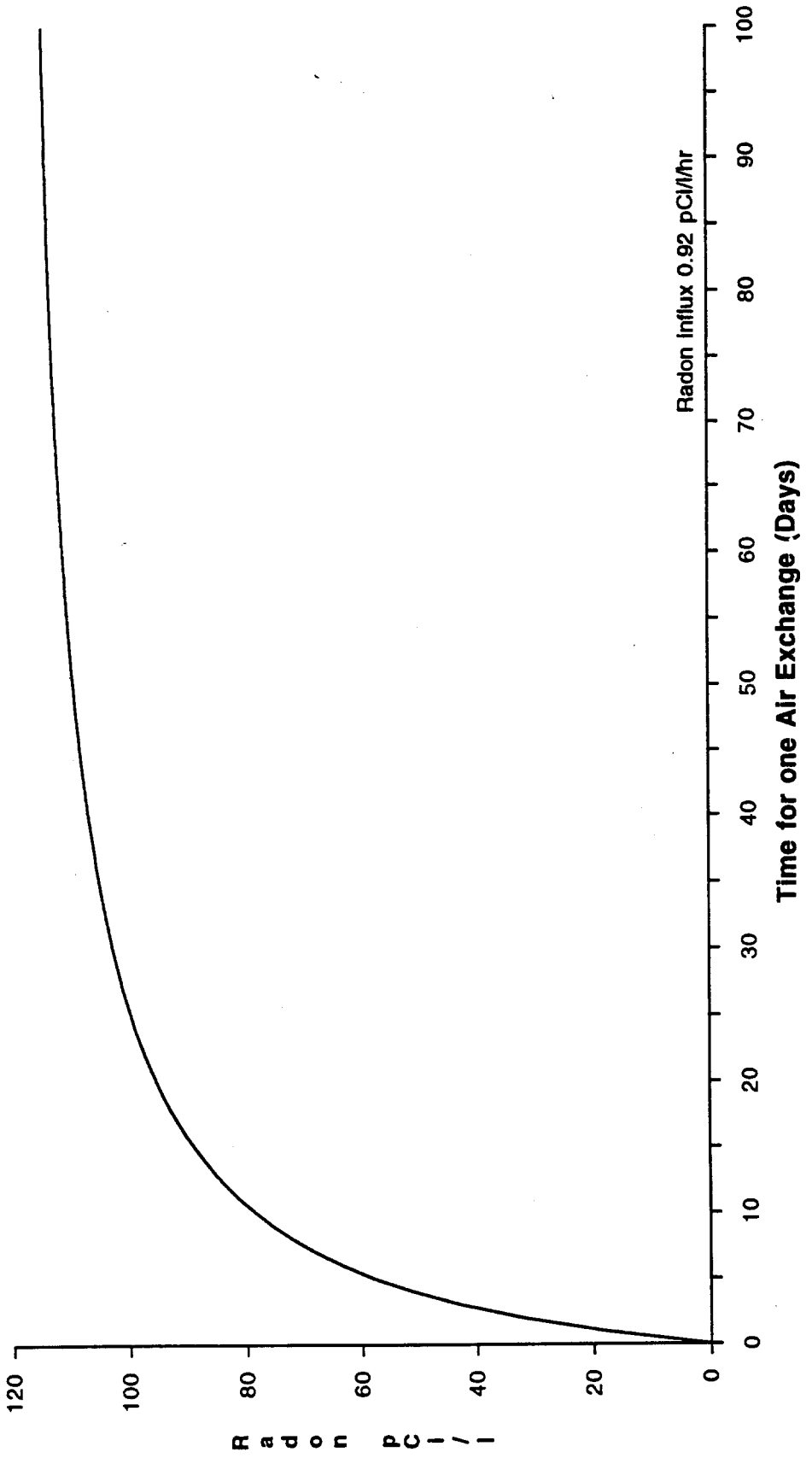
Figure 58 is a graph of radon concentration in the cave for various rates of ventilation ranging from 100 days to 1 day. This indicates that ventilation has little effect on the radon levels within the cave until the ventilation rate is less than 30 days. (A change in ventilation rate from one air exchange per 100 days to one per 33 days will lower radon concentration by only 10%.) The observed ventilation rates range from 12 to 40 days and translate to radon concentrations of 83 to 107 pCi/l. This is in good agreement with the observed range of radon levels measured in the cave.

From Figure 58, we can determine the amount of artificial ventilation necessary to lower the radon concentration. To obtain a 50% reduction (to 42-53 pCi/l), the ventilation rate would have to increase to 3-5 days. This is equal to 1,800,000 to 1,100,000 ft^3/day of air exchange. A more modest decrease of 25% would still require air exchange rates of 900,000 to 500,000 ft^3/day. It is also important to realize that no amount of ventilation can totally eliminate the radon concentrations. A ventilation rate of one air exchange every 4 hours (1,400,000 ft^3/hr) would be needed to obtain a radon concentration below the recommended 4 pCi/l EPA action level for dwellings.

The results of the ventilation model were also compared to the measured alpha radiation levels in the cave. The model was run for two reasonable rates of air exchange that were varied by month of the year with the highest rates of air exchange occurring during the winter. Calculations were made for each month and assume that equilibrium conditions are reached during that month. The results of these

FIGURE 58

Radon Levels with Ventilation



calculations are shown in Figures 59 and 60. Each graph also shows the average monthly alpha radiation levels measured in the cave. Alpha radiation is plotted in Working Levels while the predicted radon levels are given in pico Curies per liter. Radon is the precursor of the radon daughters measured as alpha radiation, but because other factors influence the concentrations of radon daughters no one single conversion factor is applicable to all conditions. No single direct conversion factor is implied by these figures between Working Levels and radon levels. The comparison is based on the relative changes of each variable throughout the year. The best fit between the two sets of data is obtained using the low air exchange rate of 170,000 to 36,000 cubic feet per day. Higher rates of ventilation predict less variation than is observed in alpha radiation levels. There are two possible explanations. The true ventilation rate may be quite low. A rate of 170,000 cubic feet per day is the rate which has been measured at the Blow Hole and this may represent the majority of the air entering the cave. A second possibility is that the influx of radon into the cave is not constant but may actually increase during the summer months. It may be that additional radon is brought into the cave by water seeping into the cave. This hypothesis could be tested by measuring the radon concentration of drip water several times a year.

POSSIBLE ALPHA RADIATION MITIGATION STRATEGIES

The levels of alpha radiation measured in Kartchner Caverns are a significant concern only for the long-term health of those who may work within the cave for many years. The Working Level (WL) is the common unit for expressing radon daughter exposure rates. From a limited number of alpha radiation measurements by OUL, the annual average alpha radiation in Kartchner Caverns was estimated to be 0.9 to 1.0 WL. The levels are estimated to range from 1.6 WL in the highest month to 0.6 WL in the lowest months. More comprehensive measurements of alpha radiation by ACPI indicate that the average is 0.77 working level from radon and 0.03 working level from thoron for a total of 0.80 working level. Note, however, that alpha radiation has not been measured for all months of the year. No measurements have been taken for the months of October, November, July or August. The omission of these months may indicate that the measured average alpha radiation level is not a true representation of the actual average alpha radiation levels in the cave. The measured average level of alpha radiation and range of variability are consistent with the Radalert measurements and this leads us to believe that 0.80 WL is a representative average. Based on the current standards for public and privately owned show caves (3.5 to 4.0 working level months per year), workers could spend 757 to 865 hours per year within Kartchner Caverns.

The recommended approach to managing the alpha radiation levels is to limit the exposure time of employees. However, there are uncertainties as to the effect development will have on alpha radiation levels within the cave. The present "average" is based on measurements taken at specific locations and development of the cave may shift the pattern of alpha radiation within the cave. It is also likely that employees will spend varying amounts of time in different areas of the cave,depending on which areas are shown to the public. As will be seen in the following discussion, the alpha radiation levels are tied into the overall moisture balance of the cave. Attempts to mitigate alpha radiation levels may have the side effect of destroying the beauty of the cave. Nevertheless, the State may wish to do some preliminary

FIGURE 59

Predicted Radon Levels For Low Air Exchange Rate

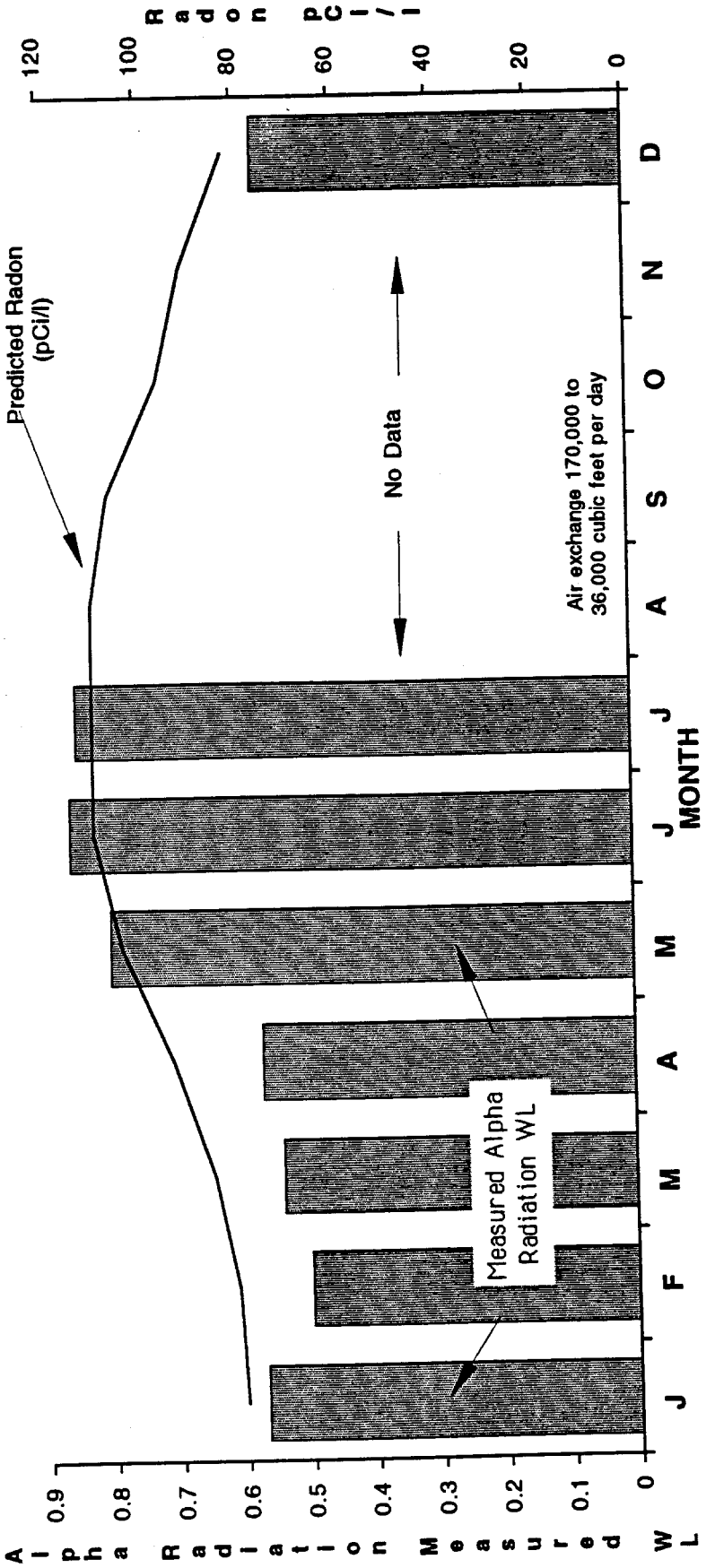
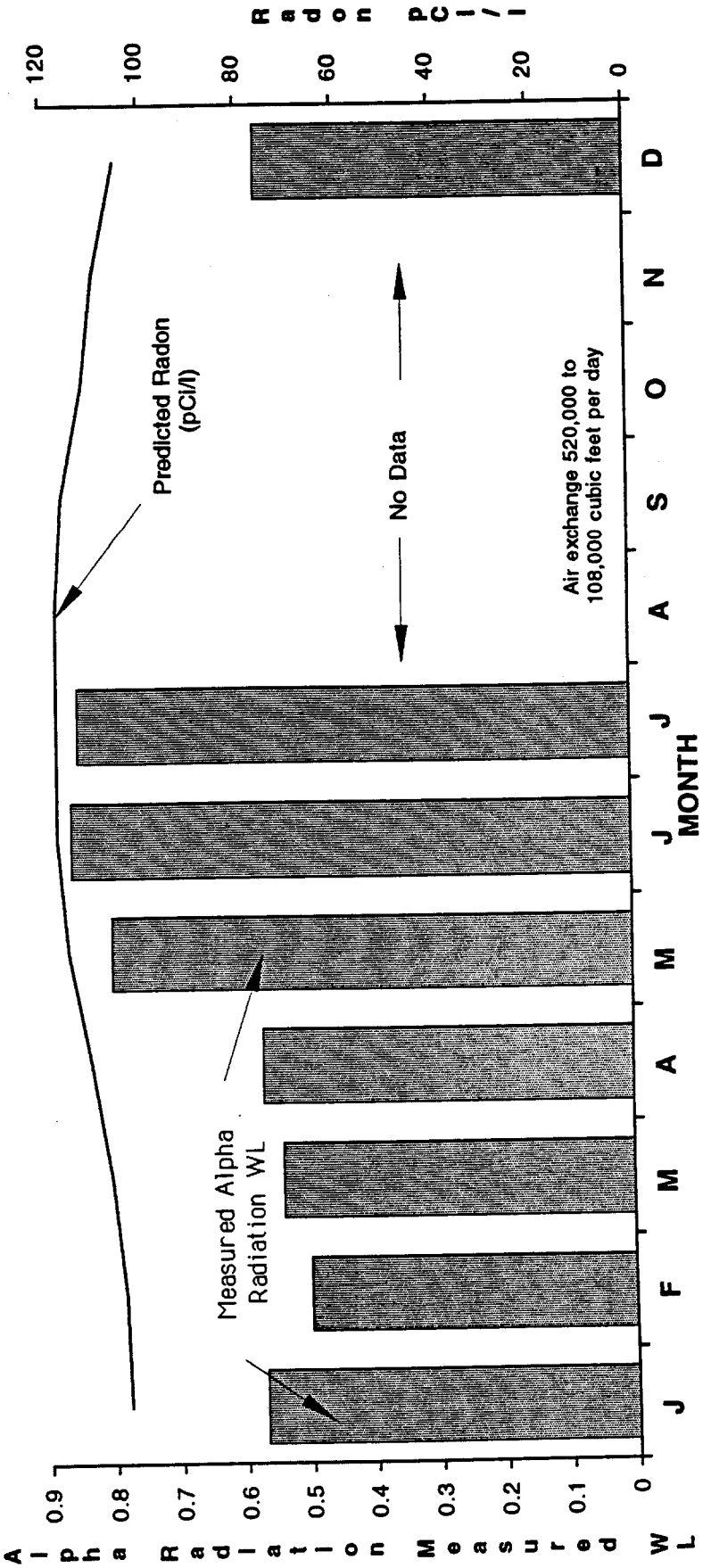


FIGURE 60

Predicted Radon Levels For High Air Exchange Rate



assessment of possible mitigation methods now in order to determine if they would be feasible.

The radon levels within Kartchner Caverns average approximately 100 pCi/l and vary by a factor of two on a seasonal basis. Radon daughters resulting from the radioactive decay of radon average approximately 0.8 Working Level. These concentrations are high enough to be of concern to those who will work within the cave. Prolonged exposure to radon daughters for many years has been shown to cause lung cancer. Therefore, a number of possible methods for reducing the concentrations of radon and radon daughters has been examined.

The nature of the radioactive decay sequence provides three approaches to mitigating the problem. First, it is necessary to understand that radon gas and radon daughters have very dissimilar properties. While radon daughters are the actual health risk, radon gas is the direct source of radon daughters. Radon gas has a much longer half life than radon daughters (by a factor of over 100.). If radon gas is eliminated or reduced, then the radon daughters will also be eliminated or reduced. The three approaches can be categorized as follows:

- Control of Radon Gas
  - Removal of radon source
  - Removal of radon gas from the air
  - Ventilation to remove radon gas

- Control of Radon Daughters
  - Ventilation to remove radon daughters
  - Air circulation to increase radon daughter plateout
  - Filtering air to remove radon daughters
  - Passive filtration of air to remove radon daughters

- Protection of the individual
  - Personal protection methods
  - Manage the length of employee exposure

Control of Radon Gas

Removal of radon gas. One of the chief difficulties in removing radon gas is that it is an inert gas and does not readily react with other materials. Two methods have been used to directly remove radon from the air. The first is condensing radon from the air by cooling to very cold temperatures. Radon will liquefy and condense out of the air at a temperature of -79°F. Cooling air to this temperature would also remove all of the moisture from the air and require large amounts of power. This method is clearly not feasible inside the cave.

The second method is removal of radon gas by charcoal adsorption (Hopke, 1987; Evans, 1980). This is the method used in some types of radon detectors. A radon removal device of this type would consist of a volume of activated charcoal with cave air pulled through with a fan. Because the half life of radon is 3.82 days, only a modest rate of radon removal could be effective in reducing radon levels. If we assume that only 60% of the air within the cave needs to be treated every five days, the volume of air is 420 cubic feet per minute. This assumes that the filtration is 100% effective. However, activated charcoal will also remove water from the air and this will reduce the effectiveness in removing radon. It will not completely stop radon adsorption

because activated charcoal is also used to remove radon from water supplies. If we assume an effectiveness of 25%, then approximately 1700 cubic feet of air would need to be treated every minute. This rate of air treatment would theoretically lower the radon levels by 50%. Two removal devices could be located in different areas of the cave such as the Throne Room and the Big Room. Each would treat 800 to 1000 cubic feet per minute.

The major drawback of removing radon in this way is that the radon gas is collected in the activated charcoal and undergoes radioactive decay within the container. The envisioned rate of treatment would result in an equilibrium activity of 9.42×10^9 pCi of radon (0.01 Ci) being contained in the device. This amount of radon would have, through its decay products, a high gamma ray activity and require extensive shielding. This could be mitigated to some extent by having two chambers of activated charcoal which are alternately used. The level of activity in the unused chamber will decay to less than 1% within 28 days.

While radon removal appears to be a possible approach for reducing levels, the cost, efficiency and safety of such a device are unknown.

Removal of radon from the cave by ventilation. Radon levels within the cave can be lowered by removing the radon by exchanging cave air for surface air. Ventilation is widely used in the mining industry to reduce alpha radiation levels. The air within the mine is diluted with outside air which has essentially zero radon. The radon decay products are also flushed out of the mine. To accomplish this in the cave would require that the air within the cave be exchanged several times within the half life of $Radon^{222}$ (3.82 days). If the air exchange rate is less than this, the radon and daughter products will still increase to high levels within the new air. A simple model of the amount of ventilation necessary to lower the radon concentration by ventilation has been constructed. This shows that ventilation does not significantly decrease radon levels until the air in the cave is exchanged once every 10 days. This would theoretically reduce radon to 64% of the unventilated concentration. By increasing the rate of air exchange, the radon level can be further reduced. At a rate of one complete air exchange per day, the radon level should be reduced to 15%. A 50% reduction could be accomplished by exchanging air once every 5.5 days,which is approximately 6 times greater than occurs naturally. This would require a continuous ventilation rate of 700 cubic feet per minute. The effect on the alpha radiation reduction would also be uneven throughout the cave. The greatest reduction would be where outside air is introduced and the smallest reduction would be at the exhaust point. Depending on how this altered the airflow pattern within each room, there could still be "hot spots" where cave air was not completely mixed with the outside air.

The chief objection to this approach is the damage that dry outside air can do to the features of the cave. In order to maintain the existing moisture balance of the cave, the relative humidity must remain well above 99% and the temperature must closely match that of the cave. It does not appear to be feasible to control incoming air to this level of humidity. There are only a few times of a year, chiefly at night during summer months, when outside air contains more moisture than cave air. At these times, outside air would be least damaging to the cave features. Unfortunately this happens at irregular intervals and in 1989 occurred on only one night.The greatest disadvantage to induced airflow even within the cave is its impact on the evaporation rate, stable cave temperature, and on speleothem growth and stability. Airflow can have a great impact on speleogenesis as a high level of CO_2 versus a low level of CO_2 can induce

variability in speleothem formation or even cause them to dissolve. Preliminary estimates indicate that the minimum amount of energy required to condition surface air to cave conditions is several times greater than the power needed to light the cave. Such a system would therefore be expensive to run and maintain. Artificial ventilation of the cave has the greatest potential for creating the conditions which will destroy the beautiful features of the cave.

Control of Radon Daughters

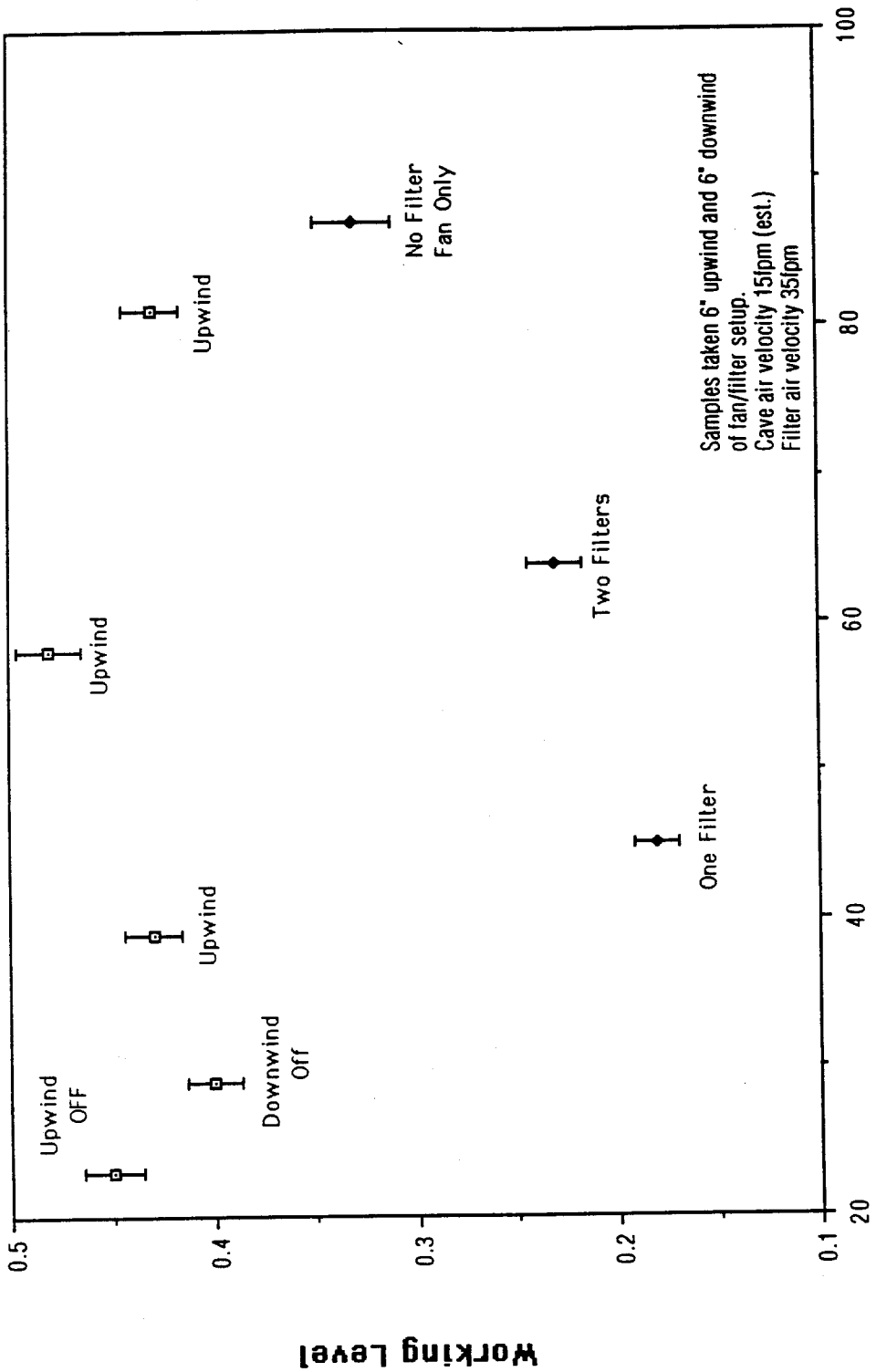
Filtering the air to remove the attached and unattached radon decay products is another method of mitigating the radon levels. Relatively simple air filter systems have been shown to be effective in reducing the alpha radiation levels in experiments (Appendix F). As can be seen in Figure 61, typical reductions of 30% to 50% in working levels can be obtained by filtering air through a simple furnace filter. The amount of reduction is a function of the number of times the air is "cleaned" in respect to the half life of the decay products. The half life of the radon daughters can be assumed to be about 30 minutes for approximate calculations. Therefore, the air would need to be filtered at least once every 30 to 45 minutes in order to obtain a significant reduction. Filtering this volume of air may disturb the natural air circulation (or stratification) in the cave and lead to increased evaporation. However, the advantage of in-cave filtration is that no dry outside air is introduced into the cave. It should also be possible to use filtration as a spot solution to reduce alpha radiation levels in a restricted area. The area immediately downstream from the filter would have the greatest benefit. A requirement of any filtration system is that it would have to operate at fairly low velocities, below 100 feet per minute, in order to prevent setting up strong airflow patterns within the cave. This would make the filter size quite large, on the order of 15 to 20 feet square, to filter all the air in the Big Room. If a series of filters were used, then the size of the individual filters would be reduced accordingly. The impact on the evaporation within the cave is difficult to predict but such a system is almost certainly going to increase the evaporation rate.

An alternate approach to filtration may be to use electrostatic precipitators or ion generators (Hopke, 1987). These would remove the attached decay products from the air. However, removing the particles to which the decay products attach may merely serve to increase the amount of unattached radon daughters.

A final suggested solution would be the use of a humidifier or misting system to remove the radon daughters. Radon daughters which become attached to particles in the air are naturally removed by the slow settling out of these particles. In the case of charged particles, they may also be attracted to solid surfaces. Once attached to a solid surface, they become harmless to people. Since the air in the cave is presently at almost 100% relative humidity, the addition of even a slight amount of additional moisture would cause condensation. Condensation droplets would become additional particles for radon daughters to become attached to. As the size of the drop increased, it would fall faster and remove the decay products quicker. Such a mechanism may already be operating within the cave during the winter months. This may be the predominant removal mechanism within the cave, considering the low airflow volumes observed. The principal advantage of such a system is that it would counteract the evaporation in the cave. The drawbacks are that the effectiveness of such an approach is unknown and that creating condensation is equivalent to heating the cave. The amount of water necessary to bring all the air in the Big Room to 100% relative humidity is less than 100 gallons.

FIGURE 61

Radon WL with Furnace Filter
April 18, 1991 at Mud Flats



Passive filtering of air by convective light fixtures. The heat given off by a light fixture will induce a pattern of rising air over the light fixture. Air will be drawn into the rising plume from around the base of the light fixture. If a suitable screen were placed around the light fixture, it would filter out the radon daughters. Such a screen could also serve as a diffuser for the lights. The most useful location for this type of light would be along the trail as low level trail lights. This would result in the majority of the treated air being produced in the area where people are. Other benefits are that servicing of filters would be easier and the filters would also collect lint before it became attached to the cave surfaces.

Protection of the Individual

Personal protection. It must be remembered that the only health risk to individuals is from the inhalation of radon daughters. There is no known health risk associated with radon daughters being in contact with the outside of the body. Preventing radon daughters from being inhaled will eliminate any adverse health effects. The radon daughters which are harmful can be relatively easily filtered from the air by face masks with high efficiency filters. There are a number of face masks which can reduce the exposure to a minimal level. These are not likely to be practical for use by guides or others who have contact with the visiting public. They should be used or made available during construction to anyone who is likely to have a prolonged exposure to the cave air in excess of 700 hours per year. There are other types of filters available which would likely greatly reduce the exposure. Unfortunately these are not certified as effective. One possibility would be small nose filters such as are used by some allergic people. These are inserted into the nostril and are unobtrusive. The effectiveness is unknown and they would not be a recognized way of reducing the exposure. However, they would reduce an individual's exposure by some extent.

Manage Employee Exposure. The important factor to consider in assessing the employee exposure is that the exposure is the product of the length of exposure and the radon daughter concentration expressed in Working Levels (WL). The length of time in which an employee is exposed to a given concentration is the most easily managed variable. The National Park Service has begun to establish a policy on permissible exposure to alpha radiation in caves. Although the present NPS standard is 4 Working Level Months, a new standard of 3.5 Working Level Months with a total lifetime exposure limit of 105 WLM is now being proposed. The average alpha radiation level in Kartchner is presently estimated to be 0.8 working level. Based on the existing NPS and private cave standards of 4.0 WLM an employee could spend a total of 865 hours underground. Based on a more stringent standard of 3.5 WLM which may be adopted in the future, a total of 757 hours may be spent underground. A study by the National Caves Association showed that in privately owned caves, the average amount of time spent underground by employees was 586 hours per year. At this time, a maximum of 750 hours appears to be a reasonable recommendation as to the number of hours that an employee could spend underground. Alpha radiation levels will need to be monitored after the cave is developed in order to determine the actual exposure of guides. It is anticipated that alpha radiation levels will experience a slight decrease as a result of the development. In that case, a greater number of hours may be spent underground by employees.

Reducing exposure time. This is the approach used by most agencies managing caves which have significantly elevated alpha radiation levels. This can be done by either stationing employees in areas that have lower levels of alpha radiation or

designing a tour route to follow areas of lower levels. Employees may also be rotated to surface assignments on a regular basis. The number of hours spent by each individual can also be limited. Part-time or seasonal guides can be utilized and underground personnel can be rotated with those above ground. These methods would probably require a continuing monitoring program. Approaches such as these appear to offer the greatest management flexibility with the least possible detrimental impact to the cave.

There are several strategies that can be used to manage employee exposure.

One is to maintain a minimum group size for tours. This will reduce the number of trips where there are only a few visitors on a tour. This can be accomplished by reducing the number of tours during slack periods. A less satisfactory method would be to mandate a minimum group size for a tour and cancel tours with fewer visitors available.

Another is to manage the number of guides to match the visitor load. This would involve hiring part-time help during peak seasons. This would distribute the exposure over a larger number of employees.

Recommendations

- Adopt NPS-14 employee exposure guidelines of 3.5 WLM per year and 105 WLM career. (See Appendix F for NPS guidelines).
- Ban smoking from the cave and hire non-smoking employees.
- Monitor alpha radiation levels during construction and require contractor to submit employee exposure records.
- Monitor alpha radiation levels along the trails after the cave is in operation for a minimum of two years to determine employee exposure.
- Maintain records of employee exposure.
- Investigate the use of alpha radiation badges to monitor employee exposure.

DRIP WATER MEASUREMENT

Water which percolates into the cave directly from precipitation falling on the limestone surface of the hill is an important source of moisture for the cave. Understanding the moisture balance of the cave requires that we make a reasonable estimate of the quantity of water which enters the cave in this manner. Additionally, we need to understand how various patterns of precipitation affect the amount and rate of water percolating into the cave. In order to understand these processes, a program of collecting and analyzing drip water was established. A compilation of all drip water measurements is in Appendix H and the data has been summarized in Table 19.

A series of 8 drip water monitoring locations were established by ACPI throughout the cave, although only 5 stations are required by the contract. At each site, drip water was collected during the monthly round of data collection at the environmental stations. Additional samples were also frequently taken during other trips into the cave for a total of 292 measurements. The rate of flow is determined by measuring the volume of water collected in a known length of time. Where samples were taken directly from a pitcher that has collected drip water over an extended period of time, they were noted as 'bulk' samples. All other samples were from water collected directly from the drip over a relatively short period of time. Samples of the drip water were later measured to determine the conductivity of the water. The conductivity of the water is related to the total dissolved solids. During the last half of the study, pH of the drip water was measured at the time of collection. Measurement of pH is not specified under the contract but ACPI feels that it aids in understanding the drip water.

Grand Central Station - A slow drip from a crack in the ceiling. Typically this will drip once every four minutes. Drip water collects so slowly that it takes over a week to fill a one-liter container. There is no evidence of mineral deposition taking place either on the ceiling or on the floor. As this station is so conveniently located near the entrance to the cave, samples were taken much more frequently. A total of 75 measurements were taken at this station from 10/15/89 to 6/5/91.

Maximum observed flow rate	3.7 ml/hr on 10/15/89
Minimum observed flow rate	2.0 ml/hr on 5/17/91
Average of 68 measurements	2.85 ml/hr S.D. ±0.33
Maximum observed conductivity	245 uMHOS/cm on 9/18/90
Minimum observed conductivity	115 uMHOS/cm on 12/27/89
Average of 74 measurements	166 ±33 uMHOS/cm

Bishop Drip - Located on the top of a flat-topped stalagmite near the Bishop formation in the Big Room. This drip originates in a cluster of small stalactites on the ceiling approximately 20 feet overhead. This drip shows marked variability in drip rate over periods of several minutes. The location of the drip is also not constant. This is probably an indication that the drip is actually coming from several adjacent stalactites. A total of 57 measurements were taken at this station from 12/19/89 to 5/21/91.

Maximum observed flow rate	109.6 ml/hr on 8/26/90
Minimum observed flow rate	10.8 ml/hr on 5/13/90
Average of 55 measurements	52 ml/hr S.D. ±26
Maximum observed conductivity	442 uMHOS/cm on 7/17/90

Minimum observed conductivity	266 uMHOS/cm on 12/21/89
Average of 56 measurements	343 ±30 uMHOS/cm

Water Room Drip - Located on the north side of the pool depression adjacent to the trail. Drip water originates in a stalactite approximately 10 feet overhead. There is no deposition taking place on the floor of the cave. A total of 30 measurements were taken at this location during the period 10/15/89 to 2/14/91. Flooding in the Water Room prevented us from continuing to take measurements during the last four months of the study.

Maximum observed flow rate	37.9 ml/hr on 8/26/90
Minimum observed flow rate	5.5 ml/hr on 3/14/90
Average of 18 measurements	17.7 ml/hr S.D. ±11.2
Maximum observed conductivity	383 uMHOS/cm on 10/18/90
Minimum observed conductivity	228 uMHOS/cm on 12/21/89
Average of 29 measurements	322 ±41 uMHOS/cm

Mud Trench Drip - Located on the left side of the Mud Trench at the first bend in the trench. The drip comes from a cluster of small draperies. These drips are presently forming flowstone and small gours; there is no corresponding stalagmite below the drip. This drip has coated all of the measuring equipment with a thin layer of calcite. Usually the drip is from the end of a single stalactite but in periods of high flow may come from several adjacent stalactites. This is the highest flow rate drip measured in the cave. A total of 45 measurements were taken at this station from 9/23/89 to 5/29/91.

Maximum observed flow rate	6000 ml/hr on 7/18/90
Minimum observed flow rate	68 ml/hr on 6/17/90
Average of 36 measurements	1497 ml/hr S.D. ±1277
Maximum observed conductivity	657 uMHOS/cm on 5/29/91
Minimum observed conductivity	325 uMHOS/cm on 2/17/90
Average of 44 measurements	471 ±68 uMHOS/cm

Upper Throne Room Drip - Located on the Throne Room Overlook approximately 6 feet past EMS 18 in the middle of the trail. The drip originates on the edge of a ceiling crack approximately 4" wide. This crack can be seen to extend upward for an unknown distance. There is no deposition taking place on the ceiling or the floor. This is a very slow steady drip; it normally takes several days to collect sufficient water for a sample. A one-liter pitcher will not completely fill in a month's time. A total of 26 measurements were taken at this station from 11/10/89 to 5/29/91.

Maximum observed flow rate	1.55 ml/hr on 9/4/90
Minimum observed flow rate	0.38 ml/hr on 5/29/91
Average of 26 measurements	1.10 ml/hr S.D. ±0.25
Maximum observed conductivity	370 uMHOS/cm on 7/17/90
Minimum observed conductivity	215 uMHOS/cm on 12/23/89
Average of 26 measurements	300 ±35 uMHOS/cm

Lower Throne Room - Located approximately 4 feet to the right of the long soda straw. Water is collected on top of a flat stalagmite. A pitcher on a 5-foot length of PVC pipe is used to collect drip water. This is one of the highest flow rate drips in the cave. The drip originates at a large stalactite and falls approximately 8 feet to the stalagmite below. A total of 25 measurements were taken at this station from 10/16/89 to 5/29/91.

Maximum observed flow rate	2304 ml/hr on 8/26/90
Minimum observed flow rate	150 ml/hr on 6/17/90
Average of 24 measurements	690 ml/hr S.D. ±552
Maximum observed conductivity	580 uMHOS/cm on 7/18/90
Minimum observed conductivity	330 uMHOS/cm on 12/13/89
Average of 25 measurements	446 ±52 uMHOS/cm

Mushroom Drip - Located on the right side of the passage approximately 10 feet past the Mushroom and adjacent to the trail. The drip is centered over a one-foot high white stalagmite. The floor surrounding the stalagmite is actively forming flowstone and gours. The drip originates in a small helictite on the side of a stalactite approximately 5 feet above the floor. A tripod of PVC pipe supports a one-liter pitcher over the stalagmite. A total of 20 measurements were taken at this station from 10/16/89 to 3/10/91.

Maximum observed flow rate	1178 ml/hr on 8/26/90
Minimum observed flow rate	19.8 ml/hr on 4/23/90
Average of 15 measurements	279 ml/hr S.D. ±334
Maximum observed conductivity	620 uMHOS/cm on 8/30/90
Minimum observed conductivity	171 uMHOS/cm on 12/13/89
Average of 20 measurements	489 ±135 uMHOS/cm

Cul-de-Sac Drip - Located on the left side of EMS #7, approximately halfway along the horizontal PVC pipe stand. The drip lands on a large flat stalactite. A one-liter pitcher is placed on the flat top to collect drips. The origin of the drip in the ceiling is not visible. Because the drips fall a considerable distance and land with great force, much of the water collected is splashed out of the container. This has led to serious overestimations of the flow rate. For this reason, the station has been abandoned. A total of 14 measurements were taken at this station from 9/27/90 to 5/21/91.

Maximum observed conductivity	512 uMHOS/cm on 9/27/90
Minimum observed conductivity	329 uMHOS/cm on 2/12/91
Average of 14 measurements	364 ±45 uMHOS/cm

Carbon Dioxide and Drip Water Conductivity.

When the measured conductivity of drip water samples is plotted by date, a consistent pattern emerges. Conductivity is slightly higher during the summer and early fall than at other times of the year. During the winter, the conductivity is at its lowest values. The most obvious interpretation for this seasonal variation is that it is a reflection of the level of biologic activity in the soil. Carbon dioxide is produced by biologic activity in the soil. Higher concentrations of carbon dioxide in the soil allow rain water to dissolve greater amounts of limestone which increases the conductivity of the drip water. During the summer months, the biologic activity in the soil is at its highest level

TABLE 19
Summary of Drip Water Measurements

Period of Measurements			Conductivity (uMHOS/cm)							Drip Flow Rate (ml/hr)						
Drip Station	Start Date	End Date	Avg.	S.D.	No. of Samples	High	Date	Low	Date	Avg.	S.D.	No. of Samples	High	Date	Low	Date
Grand Central	10/15/89	06/05/91	166	33	74	245	09/18/90	115	12/27/89	2.85	0.32	68	3.67	10/15/89	1.98	05/17/91
Upper Throne	11/10/89	05/29/91	300	35	26	370	07/17/90	215	12/23/89	1.1	0.25	26	1.55	09/04/90	0.38	05/29/91
Water Room	10/15/89	02/14/91	322	41	29	383	10/18/90	228	12/21/89	17.7	11	18	37.9	08/26/90	5.5	03/14/90
Bishop	12/19/89	05/21/91	343	30	56	442	07/17/90	266	12/21/89	52.2	26	55	109.6	08/26/90	10.8	05/13/90
Cul-de-Sac	09/27/90	05/21/91	364	45	14	512	09/27/90	329	02/12/91	-	-	-	-	-	-	-
Lower Throne	10/16/89	05/29/91	446	52	25	580	07/18/90	330	12/13/89	690	552	24	2300	08/26/90	150	06/17/90
Mud Trench	09/23/89	05/29/91	471	68	44	656	05/29/91	325	02/17/90	1497	1277	36	6000	07/18/90	68	06/17/90
Mushroom	10/16/89	03/10/91	489	135	20	620	08/30/90	171	12/13/89	279	334	15	1178	08/26/90	19.8	04/23/90

due to the ample supply of moisture and resultant plant growth. During the winter, low levels of moisture and low temperatures inhibit biologic activity in the soil.

Levels of carbon dioxide in cave air have been periodically measured. When drip water conductivity is plotted against carbon dioxide levels it is apparent that the two are related. For each of four drip water stations in areas where CO_2 has been measured, drip water conductivity increases at a rate proportional to the increase in CO_2. Straight lines have been eye fit to each data set. Appendix H shows the graphs.

Drip Station	Proportionality Constant
Lower Throne	11.0 uMHOS per 1000 ppm CO_2
Upper Throne	10.8 uMHOS per 1000 ppm CO_2
Bishop	8.4 uMHOS per 1000 ppm CO_2
Grand Central	24.0 uMHOS per 1000 ppm CO_2
Average	13.6 uMHOS per 1000 ppm CO_2

From a nomograph in Palmer's "Origin and morphology of limestone caves" (Palmer, 1991), it is possible to estimate the change in conductivity due to a change in CO_2. This relationship is 18 uMHOS per 1000 ppm CO_2, only slightly higher than the observed. From the nomograph, it is also possible to estimate the conductivity of water which would be in equilibrium with a given CO_2 concentration. For CO_2 concentrations of 1000 ppm to 6000 ppm, the estimated conductivity is 120 uMHOS/cm to 210 uMHOS/cm. This is lower than any station except the drip in Grand Central Station. The Grand Central drip water conductivity ranges from 115 to 245 uMHOS/cm. This drip has a remarkably constant drip rate and comes from a small crack in the ceiling. All of these facts indicate that the Grand Central drip water is most probably not of surface origin. The water is most likely due to condensation forming on the ceiling of Grand Central Station. This may also indicate that most of the variation in conductivity observed in the other drips is due to changes in CO_2 concentrations within the cave rather than changes in CO_2 production in the soil. While the concentration in CO_2 within the soil undoubtedly increases during the summer, the amount of water percolating through the soil also increases. The increased flow appears to maintain a relatively uniform concentration of CO_2 while it is moving within the limestone. The increase in CO_2 observed within the cave during summer months is due more to increased drip water flow than to changes in CO_2 concentrations in the soil.

Deposition of Calcite by Drip Water

The formations in the cave have been created by the slow deposition of calcite from the water dripping into the cave. Observations at the drip water monitoring stations show that deposition is still taking place at some of the stations. At several stations, the drip water lands on what appear to be actively growing calcite formations. Equipment left at these locations is covered by a very thin layer of calcite within a few months. There are also several stations which do not appear to be depositing calcite. At these stations, the drip water falls onto bare bedrock or other cave sediments.

A rough idea of the minimum specific conductivity needed to deposit calcite can be found by looking at the average conductivity of those stations which deposit and those which do not.

TABLE 20
Drip Water Deposition of Calcite

Station	Calcite Deposition	Average Specific Conductivity
Grand Central	No	166μMHOS/cm
Upper Throne	No	300μMHOS/cm
Water Room	No	322μMHOS/cm
Bishop	Yes	343μMHOS/cm
Cul-de-Sac	Yes	364μMHOS/cm
Lower Throne	Yes	446μMHOS/cm
Mud Trench	Yes	471μMHOS/cm
Mushroom	Yes	489μMHOS/cm

From this table, it appears that water must have a specific conductivity of at least 330μMHOS/cm in order to deposit calcite in Kartchner Caverns.

Monitoring of drip water should continue after the cave is developed in order to verify that the equilibrium of drip water has not radically changed.

Direct Measurement of Water Entering the Cave.

Water which enters the cave from the surface drips from the ceilings and creates the numerous formations in the cave. A significant amount of water enters the cave in this way. Unfortunately, the amount of water entering the cave as drips is difficult to estimate. Drips are randomly spaced throughout the cave and many are inaccessible. The flow rate is also highly variable and dependent upon surface precipitation. Several approaches have been devised to estimate the quantity of water entering the cave as drips.

Percolation of Surface Precipitation into the Cave

The source of drip water is precipitation which falls on the surface of the limestone hill above the cave. Water which is not lost to evapotranspiration and direct runoff percolates down into the limestone. The quantity of water which does reach the cave can be estimated by determining the excess moisture available after accounting for evapotranspiration. A general approach for determining the excess soil moisture is the Thornthwaite Method. In this method, excess soil moisture is determined from the mean daily temperature, precipitation, time of year, geographic location and soil moisture capacity. Soil moisture and excess soil moisture have been calculated on a daily basis for the 24 months of the study. The results of these calculations are given in Appendix A. During the first 12 months of the study, June 1989 to May 1990, the excess soil moisture totalled 1.42" and the annual precipitation was 11.34". During the last 12 months of the study, June 1990 to May 1991, the excess soil moisture totalled 5.43" and the precipitation was 23.90".

We can estimate what the long-term excess soil moisture is by assuming that Sierra Vista is similar to Kartchner Caverns State Park. Both sites have the same elevation, mean temperature and average yearly precipitation. Based on an analysis of weather records for Sierra Vista from 1955 to 1990, the average excess soil moisture is 1.70" per year. For the 36 years of record, annual excess soil moisture ranged from 5.34" to 0.00". During 8 years, the excess soil moisture was less than half of the long-term average 22% of the time.

On average, the area above the cave receives 15" of precipitation every year. Of this amount only 1.70" (11%) is excess moisture. The excess moisture is partitioned between direct surface runoff and water which percolates into the limestone bedrock. Because the limestone hill is quite rocky with only a thin layer of soil we can assume that most of the excess water will run off the hill before percolating into the limestone. A rough guess is that only one-third will percolate into the cave, or approximately 0.60" per year.

The amount of water which actually reaches the cave has been measured by several methods. Two of these methods involve directly measuring the amount of drip water reaching the cave. These methods rely on several assumptions and can only provide an approximate answer. The third method estimates the amount of water percolating into the cave by determining how much evaporation is needed to dry out portions of the cave. These three methods, in conjunction with the available moisture supply from surface percolation, can provide a reliable estimate of the water which reaches the cave.

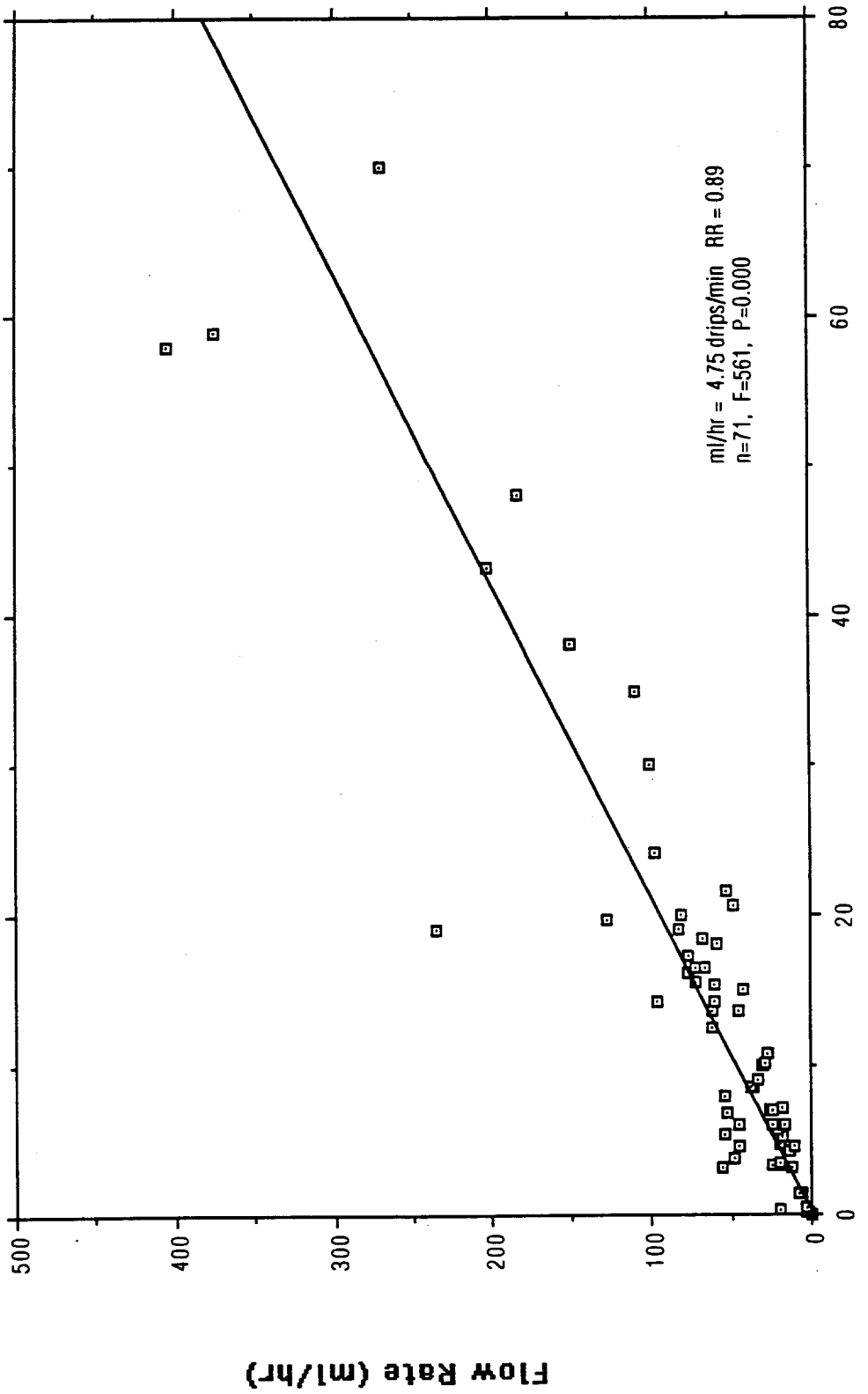
1) By Drip Counts. Frequently, when drip water samples were collected, the rate of dripping was also recorded. From this data, a general correlation has been found between the number of drips per minute and the flow rate for stalactites in Kartchner Caverns. The flow rate in ml per hour is found to be 4.75 times the number of drips per minute (Figure 62). Therefore, by counting the number of drips per minute in a given area, it is possible to estimate the quantity of water entering that area of the cave. The number of drips can easily be counted. The area from which the sound of dripping water can be heard can only be roughly approximated and is the greatest source of error. In order to correct for the variations caused by different precipitation, the observed count rates have been indexed to the flow rate of the Bishop drip at the time of the observation. When there were no simultaneous measurements at the Bishop drip, the flow rate was interpolated from the closest measurements. This method yields an estimated 0.17" of water that enters the cave each year per square foot.

2) By Collection in Pans. A set of 10 empty, 9" evaporation pans were placed randomly about the Big Room. These were originally placed on Dec. 5, 1990 and removed on April 29, 1991. During this period (145 days), the volume of water, if any, was measured and the pan emptied. After each measurement, the pan was moved to a new location. This experiment yielded estimates of the water reaching the cave of 0.07 to 0.13 inches per year. This rate is the excess left after a portion has evaporated. The amount of evaporation which occurs is estimated to be the same as at EMS #22, Kartchner Towers, for the same months. At Kartchner Towers, the evaporation rate is 0.46 ml per day which is equivalent to 0.17 inches per year. Adding this to the amounts collected in the pans gives an estimated 0.24" to 0.30" of water reaching the floor of the cave.

The sample size is relatively small. Pans were placed within easy reach of the trail and, since the trail avoids areas of active formation growth, the pans likely under-estimate the true drip rate.

3) By Evaporation Rates in Dry Areas. There are very few areas that can be found in the cave where the floor and walls are actually dry. Portions of the entrance passages up to EMS #14 in Main Corridor and the Tarantula Room have a dry floor during winter months. The evaporation rate at these areas must exceed the moisture supply. By comparing the evaporation records of monitoring stations in this area, we can determine the minimum evaporation rate that will just cause drying of the cave.

FIGURE 62
Correlation of Drip Rate to Flow Rate
(for drip rates less than 70 drips per minute)



Since the majority of the cave remains moist year-round, the rate at which water enters the cave must exceed the amount lost by evaporation.

Data from the following stations near the natural entrance were examined to determine average evaporation rates during those months when drying is known to occur.

At EMS # 15 in the Scorpion Passages, the average evaporation rate from December to March is 1.36 ml per day. This area of the cave does not dry out but does have numerous formations which are actively dripping.

At EMS #16 in Grand Central Station, the average evaporation for the months of November to May is 2.75 ml per day. This area becomes quite dry.

At EMS #14 in Main Corridor, the average evaporation rate from December to May is 0.95 ml per day. The floor in this area becomes quite dry. The evaporation rate may be underestimating the amount occurring at floor level because the pan is set approximately two feet above the floor. This area also frequently has a condensation fog at approximately the level of the evaporation pan.

At EMS #12 in Mud Flats, the average evaporation for the months of December to May is 0.70 ml per day. This area of the cave does not dry out but does have numerous formations which are actively dripping.

At EMS #11, in the Tarantula Room, the average evaporation for the months of December to May is 1.03 ml per day. This area of the cave becomes quite dry and has few active drips.

The results can be summarized as:

TABLE 21

Evaporation Rates and Dry/Moist Conditions at Selected Stations

Station	Evaporation Rate	Conditions	Comments
EMS #12	0.70 ml/day	Moist	Active drip
EMS #14	0.95 ml/day	Dry	Evap underestimated
EMS #11	1.03 ml/day	Dry	
EMS #15	1.36 ml/day	Moist	Active Drips
EMS #16	2.75 ml/day	Dry	

Based on these measurements, we can estimate that at 1.3 ml per day of evaporation, an area of the cave would dry out within a few months. This corresponds to 0.49 inches of evaporation per year. Since these areas do dry out, the moisture supplied must be supplied at a rate less than 0.49" per year. This sets an upper bound on the moisture influx into the cave by percolating surface water of 0.49" per year.

The estimates of the annual drip water influx are:

Drip estimates 0.17" per year.
Random pans 0.24" to 0.30" per year
Dry areas 0.49" per year.

The average of these estimates is 0.3" of water per year entering the cave in the form of drips (60,000 gallons per year).

Only a small portion of the precipitation which falls on the surface reaches the cave. This water is first held in the soil and then slowly percolates into the limestone along small cracks, bedding planes and permeable beds of limestone. The vertical distances from the surface to many of the drip measuring stations vary from only 50 feet at the Bishop drip to 265 feet at the Mushroom drip. The average vertical flow path is 130 feet.

Direct vertical percolation appears to be unlikely. There is little evidence of enlarged joints or faults on the surface which would allow for rapid vertical percolation. Surface water is more likely to percolate along the bedding planes. Within the cave, active dripping formations are predominantly found along walls where permeable beds intersect the cave. The measured drip stations continue to drip for an extended time without appreciable precipitation. The distances from the drip measuring stations to the surface measured along the dip of the bedding plane ranges from 200 feet for the Grand Central drip to 550 feet for the Mud Trench drip. The average flow path along bedding planes is 360 feet. Flow path lengths are summarized in Table 22.

TABLE 22
Drip Water Flow Path Characteristics

Drip Station	Avg. Flow (ml/hr)	Avg. Conductivity (uMHOS/cm)	Distance Along Bedding Plane
Grand Central	2.85	166	200
Bishop	52	343	250
Water Room	17.7	322	350
Upper Throne	1.1	300	220
Lower Throne	690	446	400
Cul-de-Sac	----	364	500
Mud Trench	1497	471	550
Mushroom	279	489	400

The long flow paths allow time for percolating water to become saturated with dissolved limestone. This is shown in Figure 63, which plots specific conductivity as a function of flow path length. After 250 to 350 feet, the conductivity has reached a plateau of 450 uMHOS/cm. Increased length of flow path beyond 350 feet does not result in an increase in conductivity. The Grand Central station is an anomalous case. This drip appears to be from water condensing on the ceiling of the cave rather than from surface water percolating into the cave.

The flow rate may decline at a steady rate for many months as it did from October 1989 to July 1990 (Figures 64 and 65). The slow steady decline is indicative of considerable storage and a long flow path. Figure 66 shows a plot of flow rates as a function of flow path length. This indicates that longer flow paths tend to have higher flow rates. This appears to be reasonable, as a longer flow path will contain a larger volume.

The time for surface water to percolate along the bedding planes is another useful indication of the flow geometry. The overall correspondence of the drip flow rates and soil moisture shows that most of the drips respond within a month to changes in surface soil moisture. The drip in Grand Central is the only exception. This drip does not appear to change flow rate in response to surface precipitation despite the fact that the flow path is relatively short. This drip also has the greatest number of measurements and any changes should have been detected.

Frequent measurements are needed to determine the time lag for water to percolate into the cave. Unfortunately, drip water samples were taken only every few weeks and this does not allow us to determine the length of time for individual drips to respond. A few general observations can be made, however. The Bishop drip

responded in less than 4 days to 0.44" of precipitation in April 1990. The Mud Trench and Lower Throne Room drips responded to the October 1989 storm in less than 14 days. These drips also responded to the storms of early July 1990 within 10 days. These observations are consistent with travel times of approximately 50 feet per day (Ford and Williams, 1989). If this is correct, then the cave will respond to excess surface precipitation within 4 to 12 days, depending on the length of flow path.

Results of Drip Water Study

- The annual amount of drip water entering the cave is estimated to be 0.3 inches per year. This is equivalent to 60,000 gallons of water per year entering the cave.
- Drip water rates are highly variable, being dependent on precipitation patterns and flow path length. Typically, flow rates will vary by a factor of 10 to 50 over the course of a year.
- Drips respond to storms on the surface within 4 to 12 days. Water appears to move through the limestone at approximately 50 feet per day.
- Water seeps into the cave only when there is a surplus of soil moisture on the surface.
- There is considerable storage of water in the limestone, enough to supply most drips with water for six months or longer.
- Water appears to move along the dip of the limestone beds rather than by direct vertical percolation along joints.
- Specific conductivity and flow rate appear to increase with increased flow path length.
- The rate of dripping is a good estimate of the volume of water. The number of drips per minute times 4.75 gives the volume in milliliters per hour.
- Variations in specific conductivity throughout the year are most likely due to changes in the concentration of carbon dioxide in the cave atmosphere.
- Deposition of calcite does not occur in drip water with a specific conductivity of less than 330 µMHOS/cm.

Monitoring Recommendations

The present study of monitoring drip water shows that important information on the amount of moisture reaching the cave can be obtained. Drip water monitoring should be continued on a monthly basis for at least three stations: the Bishop drip station in the Big Room, Lower Throne Room drip and Mud Trench drip. Measurements should include drip rate, flow rate determined from time taken to collect a known volume and specific conductivity.

Additional samples could be taken at more frequent intervals (daily) after an isolated rainstorm to determine the time for precipitation to percolate into the cave. The present study has estimated that it may take 4 to 12 days for surface water to reach the cave. This is based on an assumed flow path along the sloping bedrock rather than by vertical percolation along joints and fissures. Determining the time lag would help to resolve how water percolates into the cave. Flow rates may also be determined by some sort of data recording device.

A study could also be performed to determine the flow path by dye tracing from suspected recharge areas on the surface. This work should be performed if surface facilities are likely to be built in areas that are suspected of being recharge areas for the cave.

FIGURE 63

Drip Water Measurements - Conductivity & Flow Path Length

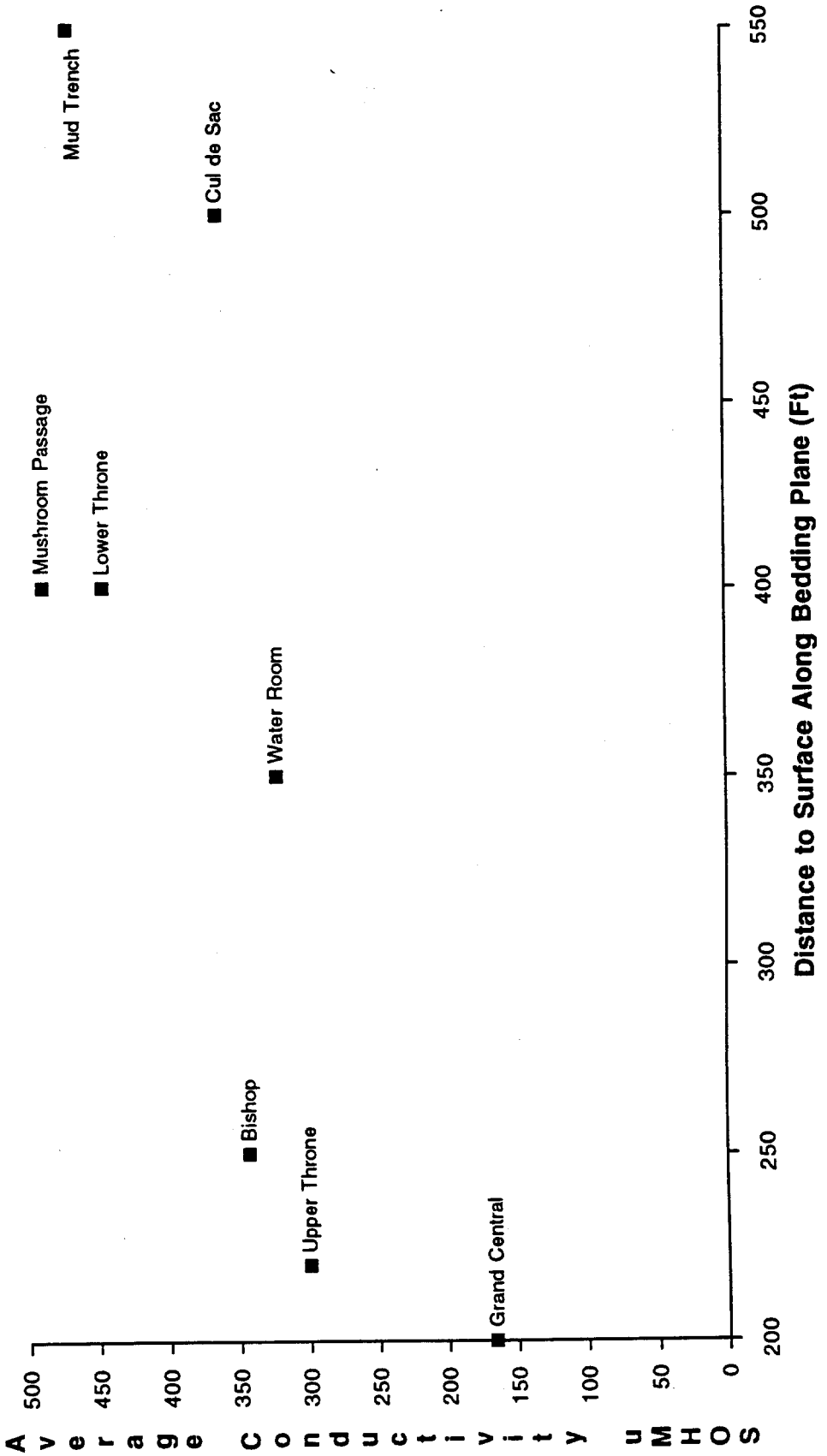


FIGURE 64

Combined Drip Rates & Excess Soil Moisture

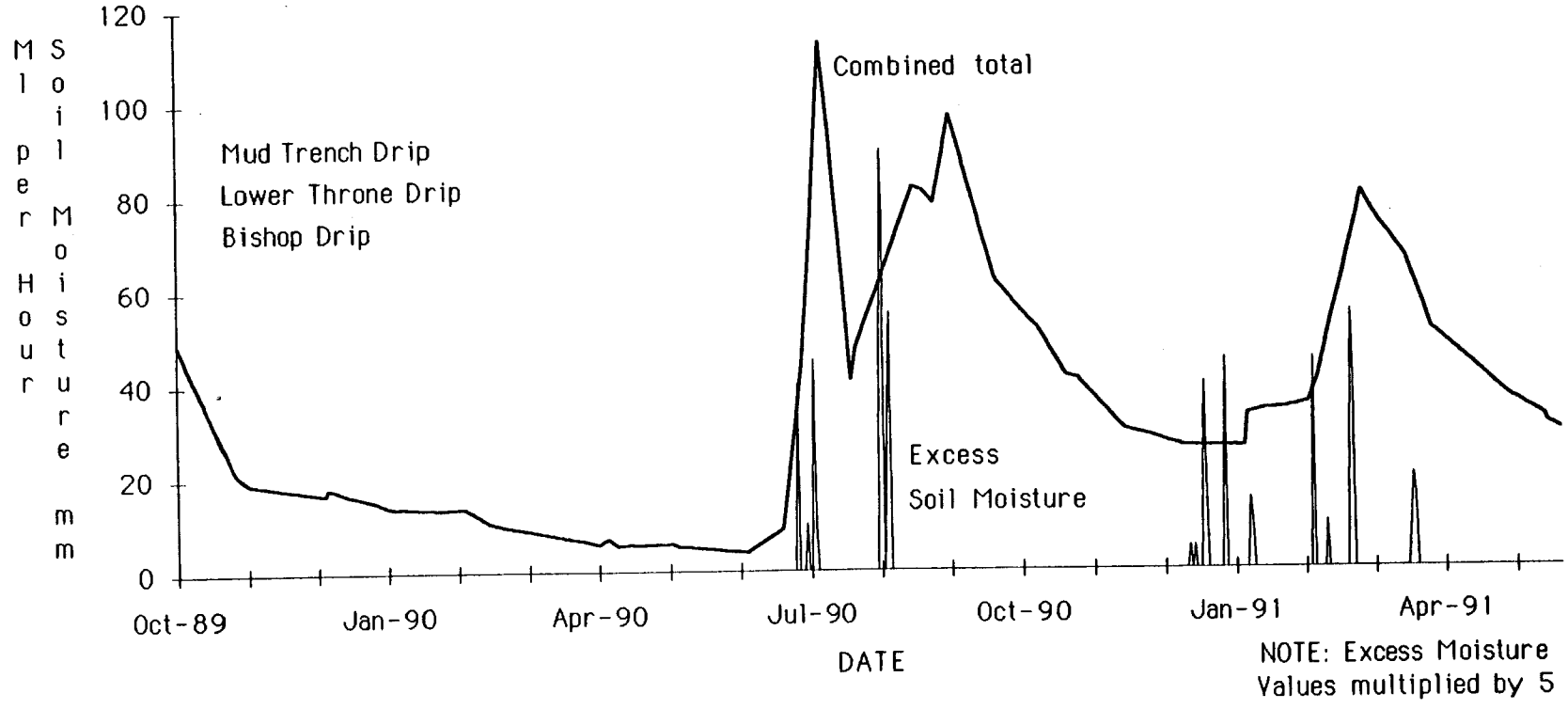


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FIGURE 65

Combined Drip Rates & Soil Moisture

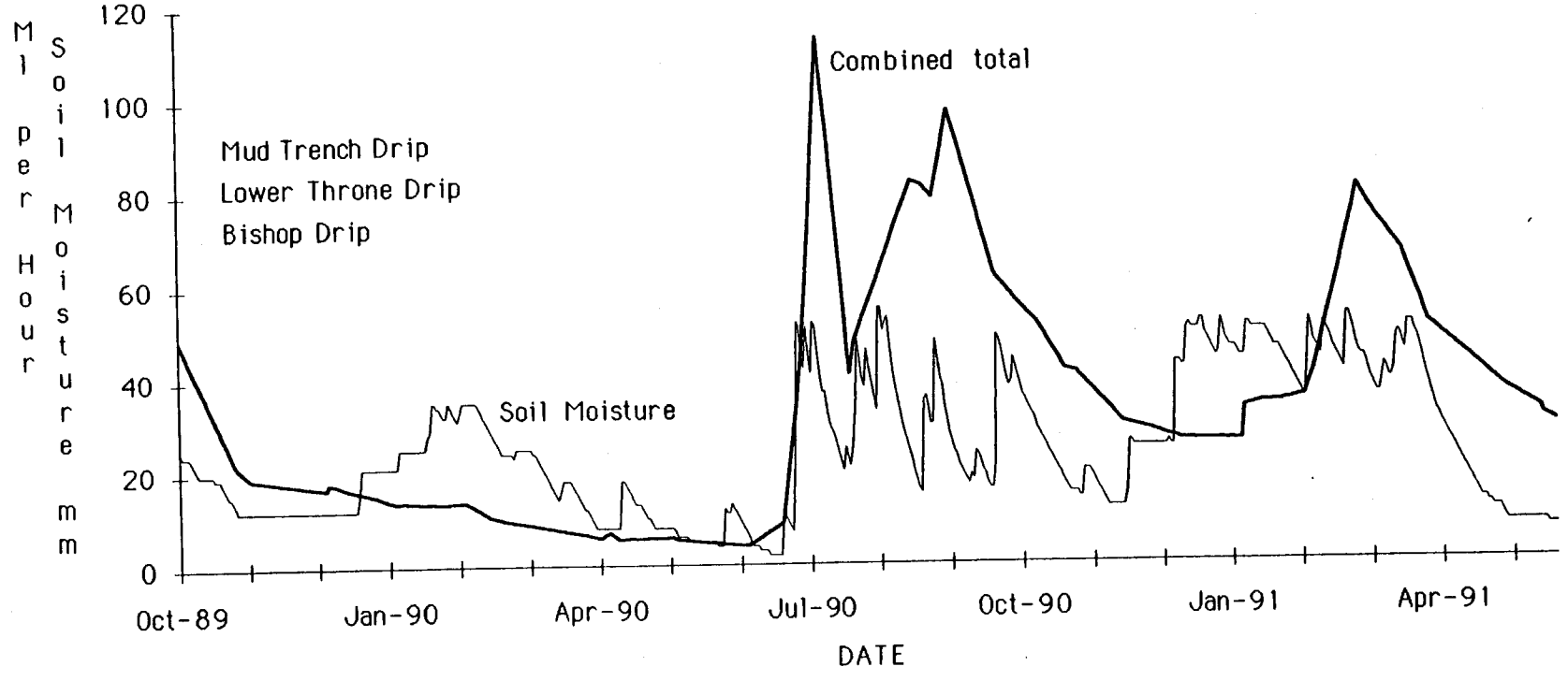

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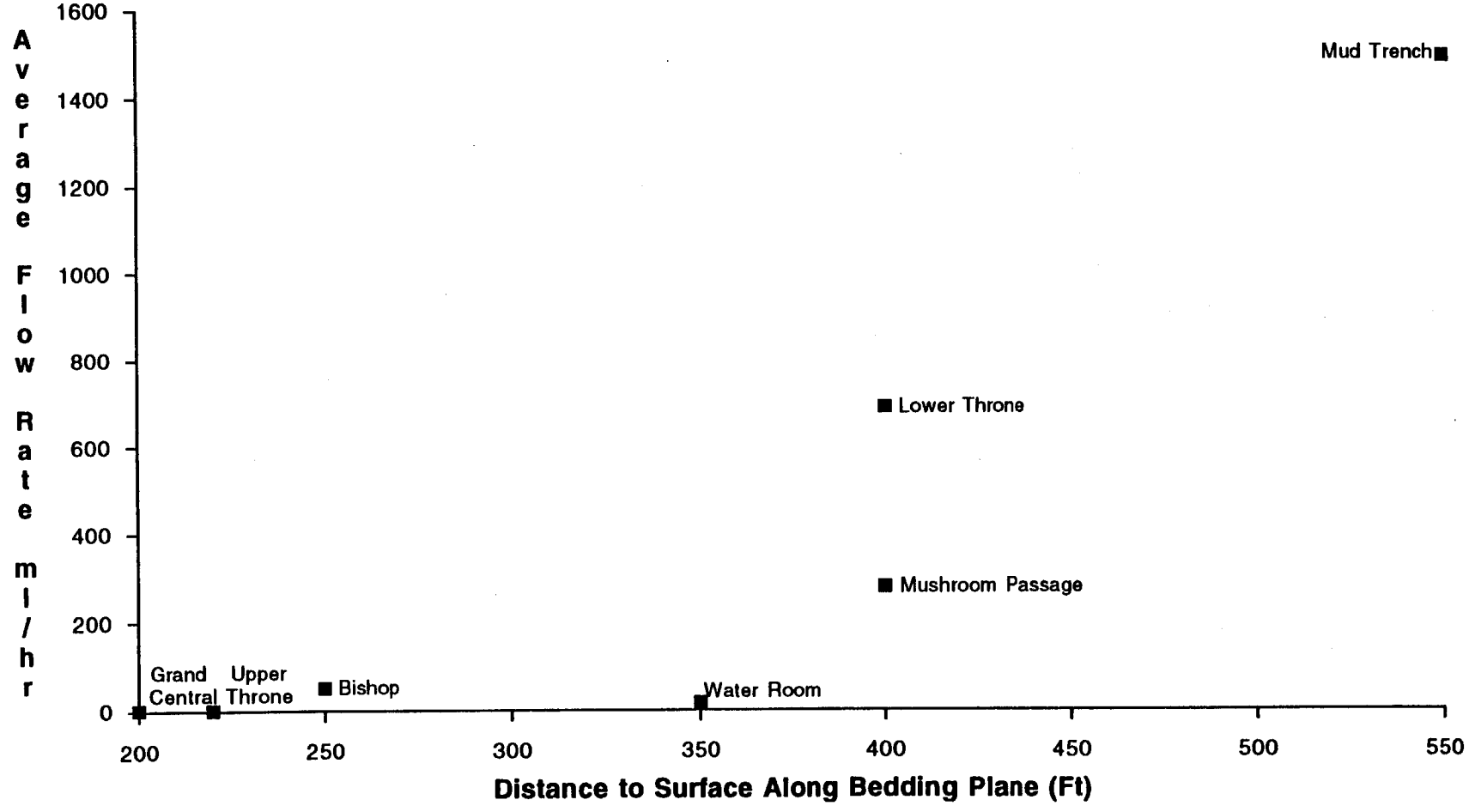
FIGURE 66

Drip Water Measurements - Flow Rates & Flow Path Length



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CAVE FLOODING

Portions of the back sections of Kartchner Caverns have been known to slowly fill with water on several occasions. The flooding has been associated with periods of above average precipitation. Flooding is only known to occur in the back sections of the cave and includes Granite Dells, Water Room, Subway Tunnel, Hill Room, Mud Trench, Triangle Passage, Grand Canyon, Rotunda Room, North Passage and Thunder Room.

A small stream has been observed in the Front portion of the cave in 1985. This stream entered the cave at the Crinoid Room, flowed through Grand Central Station, under portions of Main Corridor and re-emerged in the Red River Passage.

The occasional flooding of the cave is important for several reasons.

- Areas that are subject to frequent flooding are likely to be unsuitable for development. Flooding would disrupt tours and damage the trails and electrical system.
- The large amount of water brought into the cave during flooding events may be very important in maintaining the overall moisture balance of the cave.
- If the flooding occurs rapidly, it may pose safety concerns. The rate at which flooding and draining occur offers insight into the general hydrology of the cave.
- The source of the flood water may impact the surface management of the park. Small changes in cave passages can also potentially increase flooding and cause flooding in other areas of the cave.

In order to answer these questions, a number of different approaches were used. As the flooding was known to occur on a relatively infrequent basis, we could not depend on having a flood occur during the 24-month study. The first approach was to obtain as much information as possible from the previous floods. These were then correlated with surface weather records.

Surface streams were monitored during the study period. This included marking stream beds in order to determine if runoff had occurred between visits to the site. When surface streams were actively flowing, water temperature, specific conductivity and flow rates were measured.

During the study two flooding events occurred, the first in the summer of 1990 and the second in the winter of 1991. The results and interpretation of these floods is presented below. Measurements and observations are contained in Appendix J.

Within the cave, a series of measurements were taken of flood events. Water levels were marked with plastic stakes. Subsequent changes in water level could be measured and the volume of water entering the cave estimated. Temperatures and specific conductance of flood waters were measured on a frequent basis. Four crest gauges were installed in the cave. These were placed in areas which could become inaccessible due to high water. They were placed in the Mushroom Passage, Subway Passage, Rotunda Room and Water Room. Each gauge consists of a nylon screen tube approximately 4" in diameter and 3 feet long. Inside the tube, styrofoam pellets will be floated up and stick at the high water mark. The tube is suspended from the wall or from a PVC pipe. When a stream was observed flowing in the cave, the volume of flow was estimated. This was usually done by timing a small, floating plastic bottle partially filled with water a known distance along a uniform section of the stream.

In order to confirm the sources of flood water, two series of dye traces were also carried out (Figure 67). This involved dumping strong dyes into surface streams and recovering dye within the cave with activated charcoal dye traps. Dye, dye traps and analysis of samples were supplied by OUL. Methods used by OUL allow the dye to be detected at levels below one part per billion. Dye injection, setting and recovering traps were performed by ACPI.

Summer Flood, August 1990

The summer flood of August 1990 was quite unexpected. Historic reports of previous flooding by the original explorers indicated that flooding occurred during the winter. The back sections of the cave were visited on August 3 and no evidence of flooding was observed. On exiting the cave, it was found that Guindani Wash had begun to flow while we were in the cave. The wash continued to flow for several weeks with peak rates estimated to be over 100cfs. The next trip into the back section was on August 26. The Water Room, Triangle Passage and much of the Subway was flooded. In the Mushroom Passage, a small stream, estimated to be flowing at 10 gpm, was found to originate along the north wall of Sue's Room. Measurements over the next few days showed that water levels were declining and had probably peaked only a day or two before August 26. The maximum water elevation reached was 4624.4 feet. Figure 68 shows the extent of flooding observed on August 26, 1990. Initially, it was thought that the stream from Sue's Room was the source of the flood water. However, since the Water Room and Triangle Passage were also flooded, water must have entered from this part of the cave also. From the amount of scouring observed in the Mud Trench channel, it could be determined that the flooding was gradual and must have occurred over several days' time. A check of conditions on the surface showed that Guindani Wash had ceased to flow but that a small trickle was still flowing in Saddle Wash. The water in Saddle Wash sank into the streambed near Sue's Room. On August 30, fluorescein dye was placed in Saddle Wash. On September 4, positive dye results were obtained in the Mushroom Passage. The point at which the surface stream disappeared is 800 feet from Sue's Room and 70 feet higher.

Water levels continued to decline in the back sections of the cave. Water in the Triangle Pit and Water Room drained within a few weeks. The Subway Passage took over two months for all of the pools of water to drain. From the rate at which water levels declined, the average rate of draining could be determined. The Subway Passage drains at a maximum of 20 gallons per minute. As the depth of water decreased, the rate of draining slowed. When only a few small pools remained in the Subway Passage, a small crack along the left wall of the Subway just past the Angel Wing junction was discovered. This crack was quite small but very likely could account for a large percentage of the water leaving the cave. The Triangle Pit was estimated to drain at 0.1 gallons per minute. The total volume of water which flooded the cave is estimated at 500,000 gallons.

Measurements at the environmental stations allowed us to determine the effect of the flooding on temperature and evaporation rates. Several evaporation pans in the back section showed large amounts of condensation rather than evaporation. At first, this was thought to have been the result of splashing from the large amounts of drip water entering the cave. However, several pans showed no evidence of unusual amounts of dripping. We now believe that the excess water was in fact condensation. The surface water flooding the cave was slightly warmer than the temperature of the cave. This resulted in moisture being given off by the water. The warmer water set up

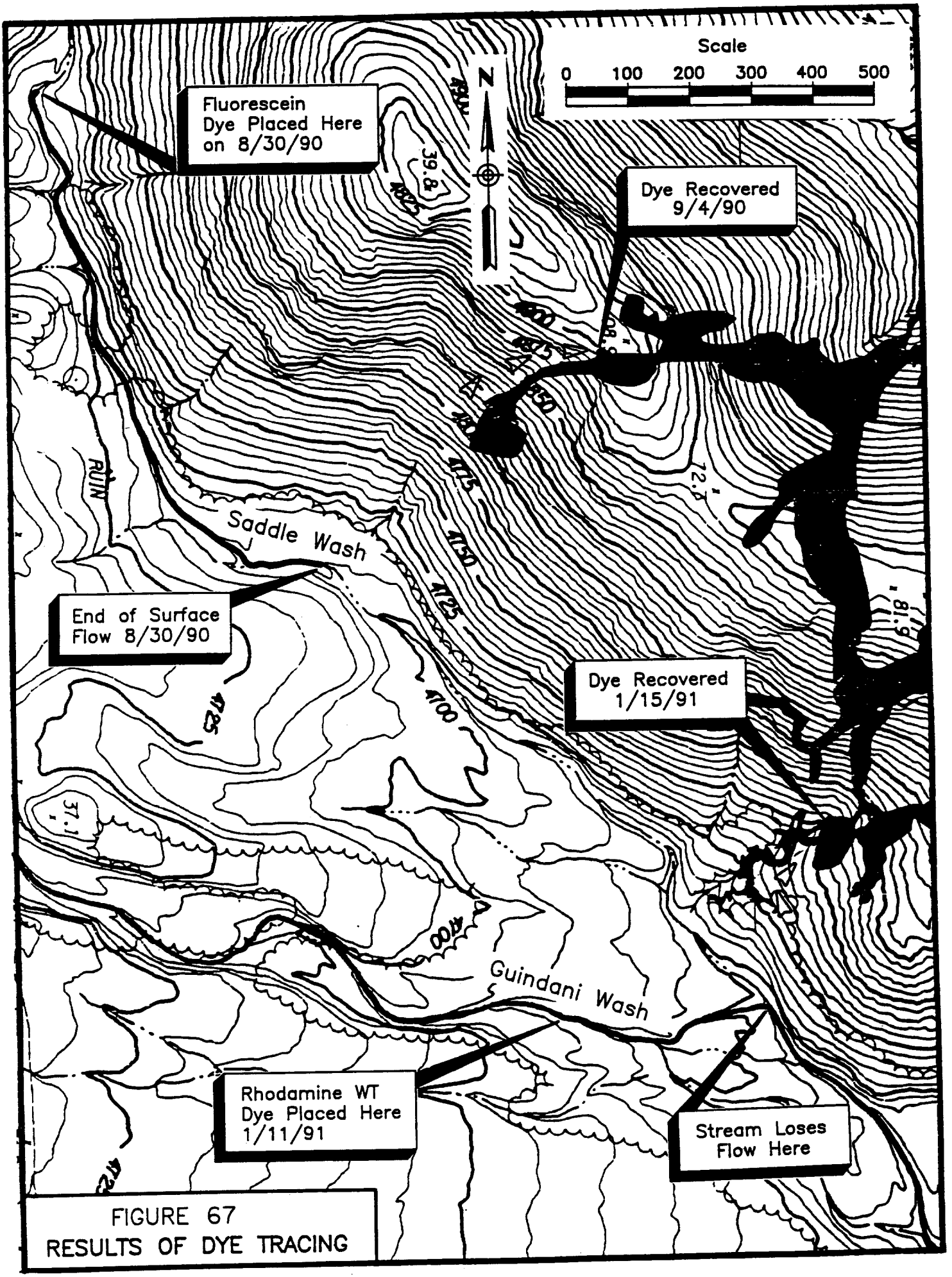


FIGURE 67
RESULTS OF DYE TRACING

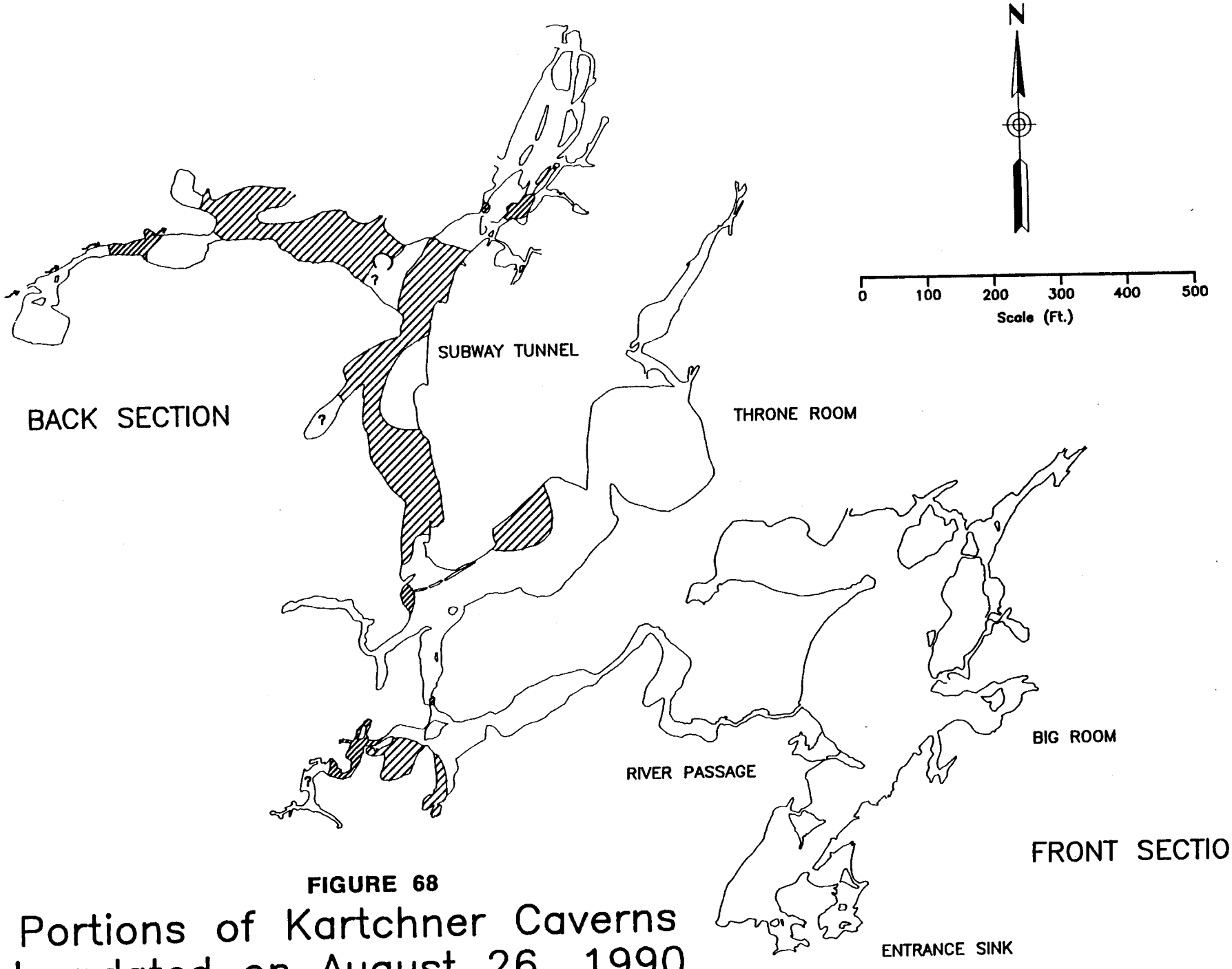


FIGURE 68

Portions of Kartchner Caverns Inundated on August 26, 1990

a convective airflow pattern which transported the warm moist air throughout the back section of the cave. When this warm air come into contact with the colder walls and ceiling of the cave, the excess moisture would condense out. The rate of condensation was estimated to be 1.2 ml per day. The air, soil and water temperatures also showed a slight rise of 0.2°F.

The summer flooding showed that the source of water was the adjacent surface streams. Specific conductivity of the flood waters most closely matched that of the surface waters. Dye tracing confirmed that Saddle Wash was the source of the water entering at Sue's Room. It was unresolved as to the location where water in the Water Room and Triangle Passage originated. The rate at which flooding occurred was not determined but appeared to be slow and require several days. Draining of the cave was also quite slow and required approximately two months.

Winter Flood, 1991

A second flooding event occurred during the winter of 1991. During this event, the rise of water was observed from the very earliest stages. On January 11, the Water Room was found to be half full of water. Markers placed at the water level showed that the level was still rising. Guindani Wash had begun to flow on the surface several days previously, but Saddle Wash was not flowing and had not flowed. On January 11, Rhodamine WT dye was placed in Guindani Wash. Dye traps were placed in the cave at the Water Room and Granite Dells. A flowing stream was found in Granite Dells. This stream also had the coldest temperature, indicating that it was close to the source of the water. Dye was detected from the Water Room on January 21. Dye traps from Granite Dells could not be recovered due to high water levels. The long amount of time that it took dye to reach the cave was apparently due to decreasing flow in Guindani Wash. Flow increased after 0.42" of rain was received on January 16 and 17. Water levels continued to rise with several fluctuations which correlated with precipitation on the surface. Three episodes of flooding occurred, separated by periods of limited draining. The first flooding occurred from January 8 to January 31. The maximum flood water elevation reached was 4624.3 feet. The second period of flooding was from February 11 to February 28. The final flooding occurred from March 1 to April 10. The maximum water elevation reached was 4629.2 feet.

Measurements of the flow in Guindani Wash indicate that 0.5 to 0.8 cfs is lost from the dye injection point to the junction with Saddle Wash. A majority of this loss occurs at the junction. Measurements made inside the cave show that about 2/3 of the water lost in Guindani Wash reappears in the cave. The junction of Saddle Wash and Guindani Wash is 150 feet from Granite Dells and 45 feet higher.

In early March, the back section of the cave, which had been inaccessible due to high water, was visited by rubber rafts. It was found that no water had entered the cave from Sue's Room. Measurements were also made at each of the environmental stations in the back section. These and subsequent measurements at the more accessible stations show the changes in evaporation and temperature caused by the flooding.

The summer flood had been by water that was slightly warmer than cave temperature. The winter flood was of water that was much colder than cave temperature. This caused a general lowering of temperatures throughout the back of the cave. Temperatures dropped an average of 1°F and had not recovered to the pre-flood temperatures by the end of the study in June. The evaporation rates increased slightly (0.08 ml per day, an increase of 24%).

The winter flooding produced increased evaporation because moisture in the air condensed on the colder surface of the water. This produced a net moisture gradient with the lowest concentration of moisture over the flood water. A larger horizontal moisture gradient caused a general increase in the amount of evaporation at adjacent stations. Since the flood water was colder than the cave and collected in the lowest areas of the cave, it formed a stable layer of cool air over the water. This prevented any large scale convective airflow pattern from developing. The stratified air means that the increased evaporation can only be due to the increase in diffusion caused by the moisture gradient rather than large scale air motion.

The maximum amount of flooding occurred in early April when the water level reached a maximum elevation of 4629.2 feet. At this level, it was almost impossible to reach the Rotunda Room, as there was only one foot of air space at the Mud Trench. Figure 69 shows the maximum extent of the floodwaters.

Changes in the elevation of the flood water confirmed the drainage rates determined from the August flooding. Several trips were taken on the surface in order to locate any resurgence of the water draining out of the cave. No evidence of this water could be found on the surface. It may be that the volume of water, 20 gallons per minute, is too small to be noticed and is quickly soaked up by vegetation. It is also possible that the water draining out of the cave never appears again on the surface but instead sinks deeper into the limestone.

During the winter flood, we observed a stream flowing in the Pyramid Room which would flow out into the end of Grand Canyon and then turn and flow back into the Pyramid Room and then into the Triangle Passage. The end of Grand Canyon is a drainage divide in the cave. A lowering of the elevation at this point would radically change the pattern of flooding. Presently it appears that the Subway Passage and back section must fill up with water to an elevation of 4632 feet before water will begin to flow into the Grand Canyon Passage. This was observed in 1985 when the Triangle Passage was completely filled with water, making the back section of the cave totally inaccessible.

Prior Flooding Events and Estimated Frequency

Kartchner Caverns was discovered in 1974. Since that time, portions of the cave have been observed to flood approximately 4 times. Because the trips were infrequent during the early years, other floods may have occurred between trips and gone unobserved. The known flooding events are:

- December 1978 - Water flowing into Triangle Passage from Pyramid Room.
- April 1979 - Water flowing into Triangle Passage from Pyramid Room.
- May 1979 - Pool of water remaining in North Passage.
- June 1979 - Pool of water remaining in Subway near Angel Wing Junction.
- January 1985 - Water flowing in Crinoid Room.
- February 1985 - Water flowing into Thunder Room from Shelf Passage.
- March 1985 - Triangle Passage is flooded to ceiling. Back of cave is inaccessible.
- August 1990 - Back of cave flooded to an elevation of 4624.5 feet. Slowly recedes, mostly gone by the end of October 1990.
- January to August 1991 - Back of cave flooded by water entering from Pyramid Room. Maximum flood elevation of 4629.2 feet reached in early April 1991.

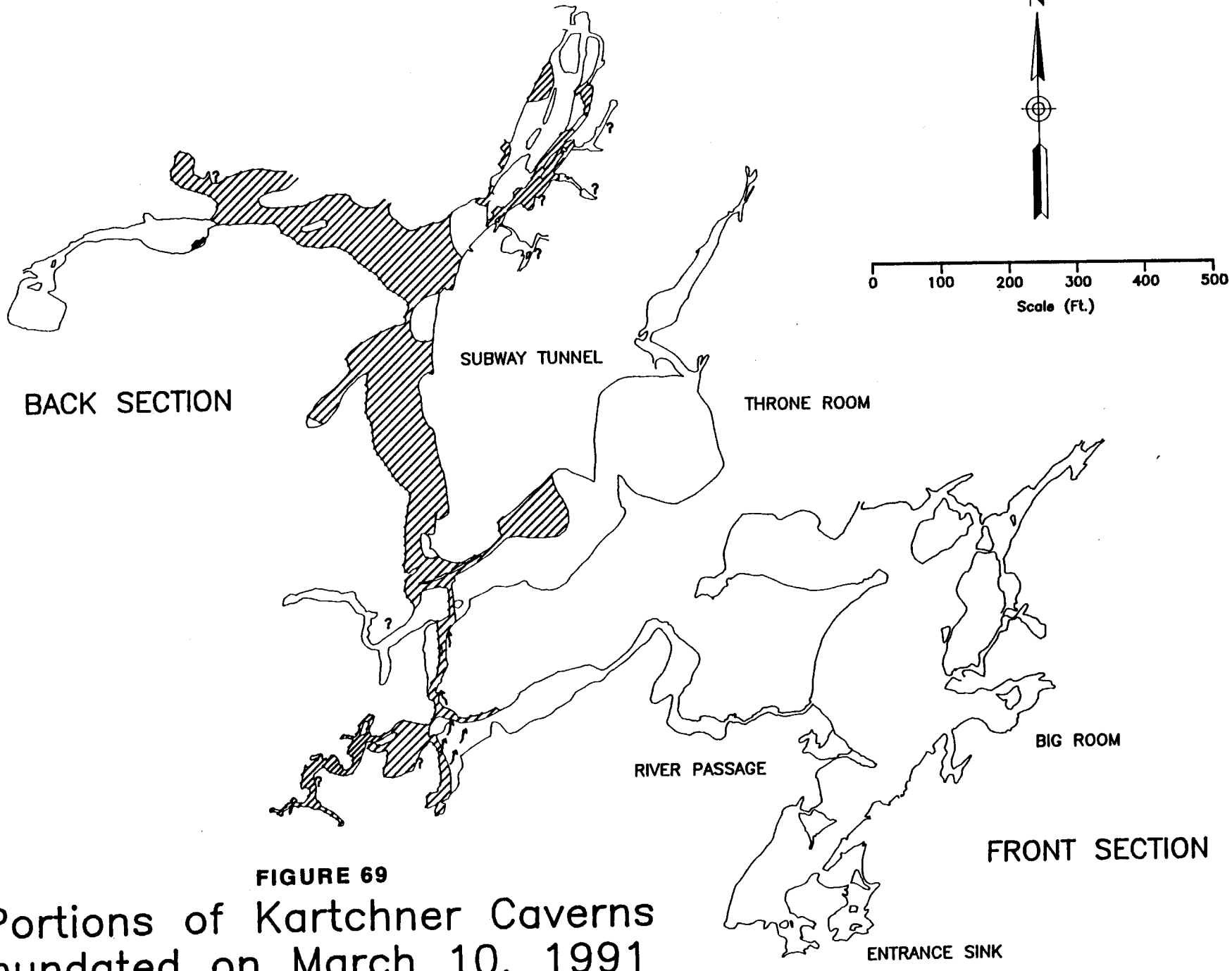


FIGURE 69

Portions of Kartchner Caverns Inundated on March 10, 1991

Observations of the two flooding events has shown that in order for the cave to flood, water must enter from the surface stream. This only happens when there is sufficient excess moisture available to produce the runoff in Guindani and Saddle Washes.

In order to determine how frequently the flooding events are, we have extended the Kartchner surface weather records by comparing them to other nearby weather stations. By determining the excess moisture available at other stations with the known flooding events at Kartchner Caverns, a predictive relationship can be developed. This can be used to infer the likely dates of past floods prior to the discovery of the cave. The weather records for Fort Huachuca/Sierra Vista will be used to develop the relationship. The records for this station span the period from September 1954 to February 1991, a total of 37 years and 5 months of record. The Sierra Vista station has been chosen because the elevation and proximity to mountains is the most similar to Kartchner Caverns of all the nearby weather stations.

Excess moisture is determined by the Thornthwaite method for determining potential evapotranspiration (Thornthwaite and Mather, 1957). This method requires a knowledge of the mean monthly temperature and precipitation for a given geographic location. Excess moisture is the amount by which precipitation exceeds the potential evapotranspiration. The excess moisture was calculated for each month of record. Additionally, because flooding events are dependent not only on the excess moisture for that month but also on the previous soil moisture conditions, the total excess moisture for each month and the preceding month was determined. See Appendix A.

A comparison of monthly excess moisture at Sierra Vista with known flood events at Kartchner Caverns indicates that two criteria must be met to predict a flood event. The excess moisture in the month of the flooding must exceed 0.7 inches and the total excess moisture for the current and preceding month must be greater than 1.3". However, this criteria does not predict all of the known flood events. It does not predict the Summer 1990 flood. This appears to be due to the difference between winter and summer flooding events.

Winter floods are caused by large area storms of low intensity. Flooding of the cave is most likely the result of several storms occurring over a period of a month or two. Summer flooding is apparently caused by a single intense thunderstorm on the watershed of the cave. Because these storms cover a small, localized area, there is little correspondence between precipitation at Kartchner Caverns and Sierra Vista. Therefore, exact times of predicted summer flooding events from Sierra Vista weather records are not likely to be correct. However, the number of summer events predicted is likely to be similar for the two sites.

Based on the above criteria, 25 flooding events were identified in the 37 years of Sierra Vista weather records. Of these, 15 probable flooding events occurred during the winter months, one during the fall and 9 during summer months. In total, 21 years out of 37 are thought to have experienced a flooding episode in either the summer, winter or both. The dates of prior probable flooding events are tabulated in Table 23.

The winter flood of 1985 was caused by one of the greatest amounts of excess moisture. During this flood, a small stream entered the cave at the Crinoid Room, flowed through Grand Central Station and out of the cave at Red River. If we assume that such flooding requires a minimum of 4" of excess moisture, then streams flowing into the front part of the cave have occurred on only 5 occasions in the last 37 years.

Flooding of the back sections of the cave and actively flowing streams have only been observed on four occasions from 1974 to the present. This has led to the belief

TABLE 23
Dates of Probable Flooding Inferred from Sierra Vista Weather Records
September 1954 to February 1991

Date	Mean Monthly Temperature	Precipitation (inches)	Surplus Moisture (inches)	Two Month total Surplus Moisture	
Jan-55	42.1	2.74	2.43	2.43	Probable Flood
Aug-55	74.3	7.67	2.78	2.78	Probable Flood
Mar-58	48.2	2.43	1.62	1.63	Probable Flood
Jan-60	41.8	1.49	1.20	1.89	Probable Flood
Aug-61	74.2	6.98	2.11	2.11	Probable Flood
Jul-64	77.9	8.90	2.96	2.96	Probable Flood
Sep-64	69.4	5.82	2.27	2.27	Probable Flood
Dec-65	46.4	4.09	3.53	3.53	Probable Flood
Jan-66	42.4	1.11	0.79	4.31	Probable Flood
Feb-66	42.6	1.87	1.55	2.33	Probable Flood
Jul-67	76.2	7.32	1.76	1.76	Probable Flood
Dec-67	43.2	4.78	4.42	4.42	Probable Flood
Aug-70	75.4	8.06	2.95	2.95	Probable Flood
Dec-71	44.1	2.45	2.04	2.04	Probable Flood
Feb-73	48.1	2.10	1.42	1.79	Probable Flood
Mar-73	47.4	1.55	0.81	2.23	Probable Flood
Jul-74	75.8	7.33	1.86	1.86	Probable Flood
Oct-77	64.6	5.48	2.83	2.83	Probable Flood
Jan-78	48.6	2.31	1.57	1.57	Probable Flood
Feb-78	48.1	1.49	0.81	2.38	Probable Flood
Dec-78	43.7	3.50	3.11	4.08	Probable Flood
Jan-79	43.5	2.59	2.20	5.31	Probable Flood
Dec-82	44.6	3.12	2.67	2.67	Probable Flood
Jan-83	44.8	1.25	0.78	3.46	Probable Flood
Mar-83	51.0	1.99	0.91	1.54	Probable Flood
Sep-83	74.1	6.67	2.29	2.29	Probable Flood
Jan-84	45.6	2.20	1.68	1.68	Probable Flood
Dec-84	45.9	3.89	3.36	3.36	Probable Flood
Jan-85	43.6	1.83	1.44	4.80	Probable Flood
Dec-86	45.9	2.45	1.92	1.92	Probable Flood
Aug-87	75.1	7.13	2.08	2.08	Probable Flood
Dec-87	45.8	2.57	2.05	2.05	Probable Flood
Jan-88	45.9	1.58	1.04	3.09	Probable Flood
Aug-88	76.0	6.19	0.95	1.77	Probable Flood
Jan-91	45.8	1.46	0.93	1.39	Probable Flood

Floods assumed to take place when Surplus Moisture
exceeds 0.7" for one month AND exceeds 1.3" for two months.

that such flooding is an uncommon occurrence in the cave. However, a comparison of excess moisture at Kartchner Caverns with a longer record at Sierra Vista indicates that flooding is a relatively common occurrence. From past records, it appears that there is a 67% chance of a flooding event in any year. Larger floods which may cause normally dry streams in the front sections of the cave to run have a 14% chance of occurring in any given year.

A similar approach can be used to determine the conditions necessary for flooding of the cave to occur based on the two years of surface climate data gathered at Kartchner Caverns. Monthly excess soil moisture was computed by the Thornthwaite Method. A comparison of the monthly excess moisture with known flooding events leads to the following indications that flooding is occurring in the cave.

- Guindani Wash or Saddle Wash flowing for several days.
- Excess soil moisture of >1.2 inches for a single month.
- Total excess soil moisture of >1.5 inches in 2 consecutive months.

A continuous flooding of the cave probably occurred during the early formation of the cave thousands of years ago. Much of the cave was formed when the present cave was below the watertable. This may have occurred when the San Pedro valley was filled with sediments and the watertable was a thousand feet higher. The other possibility is that during the past, higher amounts of precipitation created an elevated watertable within the limestone hills. By using the method for estimating times of cave flooding, it is also possible to estimate the yearly precipitation that would support year-round inflow of surface water into the cave. Using the Thornthwaite method, the monthly potential evapotranspiration can be calculated based on mean monthly temperatures. It has already been shown that a month with an excess moisture of 0.7" will cause water to enter the cave. Therefore, adding 0.7" to the potential monthly evapotranspiration gives an estimate of the precipitation required to maintain a steady water flow into the cave all year. Calculations indicate that a total yearly precipitation of 42 inches is required, which is approximately four times the present precipitation. These calculations show that it is not necessary to raise the regional watertable in order for the cave to form. A period of time when the average annual precipitation was several times greater than the present would create a local watertable high enough to explain the formation of the cave.

Moisture Stored in Mud

The back sections of the cave; the Subway Passage, Pirate's Den, Hill Room, Mushroom Passage, Sue's Room and Rotunda Room all have floors covered with mud. The thickness of the mud appears to vary from about one foot to several feet thick in the area of the Mud Trench.

In all areas, the surface of the mud is covered by a pattern of cracks caused by an extended period of drying at some time in the past. The mud cracks have been partially refilled by subsequent flooding that has deposited a thin layer of mud that softens the edges of the cracks. Based on our present knowledge of the cave, it would take many years of little moisture for this area of the cave to dry out to this extent. It is also possible that the cracks date from a time when there was a second entrance into the back section of the cave. Ancient deposits of bat guano in the Throne Room indicate that, about 40,000 years ago, bats utilized this part of the cave, presumably from a now-collapsed entrance.

The mud is thought to act as an important reservoir of moisture for the cave. Episodes of flooding recharge the reservoir of moisture held in the mud. The mud

slowly releases moisture as it dries, a process that appears to take several years. Therefore, the mud acts as a buffer, maintaining the moist conditions even through several years of drought.

A series of samples were taken to estimate the amount of moisture stored in the mud (Table 24). Moisture content of the mud from the back section of the cave is surprisingly high. In the winter of 1989 the average was 114.9%. A year later, the average was 114.2%, only a very slight decrease.

A rough estimate of the total amount of water stored in the mud can be made from the moisture content and area of the mud. If we assume that only the water in the top 8" is available, then, at 115% moisture content, each square foot will contain approximately 28 pounds of water. The total area of the mud-covered back section is 122,767 square feet. The water stored in the top 8" is therefore approximately 412,000 gallons of water. This is equivalent to a depth of water of about 5.38". At the current rates of evaporation (0.08"/year), it would take 65 years to completely dry out the mud. A more realistic estimate would be half of this, as the rate of drying would speed up as the cave dried out, or about 30 years.

TABLE 24
Soil Moisture Content
(% of Dry Weight)

LOCATION	Dec-Jan 1989	Dec-Jan 1990	% Change
Grand Central Station	28.8	13.2	-15.6
Mud Flats	32.7	21.4	-11.3
Babbitt Gate	8.0	-	-
Bath Tub Room	5.4	-	-
Mud Trench	122.4	112.3	-10.1
Hill Room	107.2	111.8	+4.6
Subway Tunnel	115.1	118.4	+3.3

Conclusions

The following facts are now known about the flooding of the cave.

- Flooding is a major source of moisture for the cave. More water may enter the cave during one flooding episode than normally enters the cave from percolating rainwater in several years. The effect that flooding has on the microclimate of the cave is dependent upon the temperature of the water. Flood water is stored in the mud and this acts as a reservoir of moisture during dry years.
- Flooding events should be monitored. This should include keeping records of the times that surface streams are flowing and temperature of the water. The elevations of flood water should be monitored within the cave. Simple crest gauges at one or two locations would be sufficient.
- The highest flood elevation observed in the Subway Passage was 4629.2 feet. Prior flooding events in 1985 may have reached elevations of 4632 feet. No development in the Throne or Rotunda Room should be below the 4632 foot elevation. Development in other areas of the cave which are not hydraulically connected to the Back Section may be at elevations below 4632 feet.

- Flooding occurs on a relatively frequent basis; flooding is likely to occur in two years out of three. Flooding during the winter is most common (40% chance for any year) and is caused by extended periods of above-average precipitation. Flooding during the summer is most likely caused by a localized, intense rainfall typical of thunderstorms. Summer flooding has a 24% chance of occurring in any year. It is also possible to have both winter and summer flooding in the same year.
- Flooding is quite gradual and takes a week or more. Flooding does not occur unless Guindani Wash has been flowing in the intake area for at least several days.
- Guindani Wash at the junction with Saddle Wash is the principal infiltration point. Additional water infiltrates into the cave along Saddle Wash. The drainage basins for Guindani Wash and Saddle Wash are important in maintaining the present input of water to the cave.
- The flooding of the cave proceeds in a stair-step fashion. As water enters the cave, it must fill a series of hydraulically compartments separated by impermeable fault zones. As each compartment fills to capacity, the excess begins overflowing into the next compartment. Flood levels are highest in those compartments closest to the points of inflow.
- The draining of the cave is much slower than the flooding and has a maximum rate of about 20 to 30 gallons per minute. The draining proceeds in the same order as the flooding with the first compartments to flood also being the first to drain. Water appears to drain out of the cave through several very small cracks. These could easily be inadvertently sealed, resulting in greatly prolonged flooding of the back areas. Water which drains out of the cave apparently does not reappear on the surface but appears to sink to a greater depth.
- Small changes in the elevation of the drainage divide at the end of the Grand Canyon at the crawl into the Pyramid Room could produce major changes in the pattern of flooding. A lowering of this area would divert water into the River Passage and Thunder Room on a more frequent basis. The effect that this would have on the front section of the cave is unknown.
- A stream has been observed to enter the cave at the Crinoid Room, flow through Grand Central Station, under the floor of Main Corridor and presumably into Red River Passage and out of the cave. This has not occurred during our study period and the conditions necessary for its occurrence are not known. An estimate based on the 1985 flood indicates that streams may flow once every seven years in the front of the cave. A likely source for this water is the point where the fault which crosses the entrance sink would intersect Guindani Wash, about 400 feet upstream from the trail crossing. As Guindani Wash dries up, the stream will often sink into the streambed at this location for many days.
- Conditions Which Indicate the Cave is Flooding:
    1. Guindani Wash or Saddle Wash is flowing on the surface. Prolonged flow of a week or more appears to be necessary before water begins to enter the cave. If the preceding weather has been dry for a long period of time, then a longer period of surface flow is needed before water enters the cave.
    2. Excess of soil moisture for a single month exceeds 1.2".
    3. Excess of soil moisture for two consecutive months totals more than 1.5"
    4. Water elevation in the North Well is above 4699 feet for a month or more.

CAVE MOISTURE BALANCE

Under present conditions, the interior of the cave is damp; there are very few areas of the cave where surfaces are either completely dry or very wet. This indicates that the cave is roughly in balance with the supply of water to the cave. Only during very wet periods are there standing pools of water to be found in the cave. This indicates that the supply of moisture is sufficient to keep the cave damp but not enough for excess water to accumulate in pools. We also observe that only a few areas of the cave are ever dry. These dry areas are found near the entrance passages and two small areas in the Tarantula Room and Granite Dells. This indicates that, under present conditions, the cave does not dry out to any great extent. The amount of moisture the cave presently receives must slightly exceed the losses due to evaporation and percolation.

These observations place a rough limit on the moisture balance in the cave. Since the cave is moist but not wet, we know that the available moisture entering the cave is slightly in excess of what is needed to keep the cave moist. Also, since the cave does not become dry to any great extent, we know that there is no great excess of moisture in the cave.

Based on the studies of surface precipitation, drip water, evaporation, relative humidity and airflow, a rough moisture balance will be calculated for the cave. Knowledge of how the cave gains and loses moisture will allow us to determine which, if any, of these processes are critical to maintaining the existing conditions.

SOURCES OF MOISTURE

Water enters the cave by three methods.

1. Direct percolation of surface precipitation on the hillside above the cave.
2. Infiltration of surface water into the cave from Guindani and Saddle Washes.
3. Moisture carried in by air exchange.

Direct Infiltration of Precipitation. The amount of precipitation the park receives has been measured since August 1988. Based on precipitation measurements and a comparison with adjacent weather stations, Kartchner Caverns State Park is expected to receive an average of 16.5" of precipitation per year.

Not all of the precipitation which falls enters the ground. In fact, the majority of the water is lost to runoff, evaporation and evapotranspiration. A 1954 USDA publication, "Arizona Heat and Moisture Indexes for Use in Land Capability Classification", using the Thornthwaite Method, has estimated the amount of moisture entering the ground. The estimated amount in the area of Kartchner Caverns is 1.0" per year of excess moisture. The majority of this excess precipitation occurs during the winter months, December to February.

This is in agreement with the results of a daily soil moisture balance calculated for the Park. Based on two years of temperature and precipitation records were compared with Sierra Vista weather records to determine that the average excess moisture 1.7" per year. The amount of excess moisture is quite variable; in some years there may be no excess, in others the excess may amount to over 5". Of this excess, only 0.3" is estimated to actually reach the cave.

Infiltration from Washes. The back sections of the cave are known to slowly flood during years with abnormally high precipitation. This has been observed to happen in 1978, 1985, 1990 and 1991.

By releasing dye into the surface washes and recovering the dye within the cave, it has been possible to determine the origin of the floodwaters. Water enters the cave along certain portions of Guindani Wash and Saddle Wash adjacent to the limestone hill.

In August 1990, the pattern of flooding was observed in sufficient detail to make an estimate of the volume of water which entered the cave. At the peak, the cave contained 600,000 gallons of water. The floodwaters took approximately six weeks to recede. Figure 68 shows the maximum extent of the August floodwaters. A larger flood occurred during the winter of 1991. A total of 3,700,000 gallons of water is estimated to have entered the cave during this flood (Figure 69).

Moisture Transported by Airflow. Air inside the cave contains approximately 17.3 grams per cubic meter (g/m^3) of water vapor. The moisture content of outside air, averaged over the whole year, is approximately 6 g/m^3 of water vapor. Therefore, air entering the cave already contains approximately 1/3 of the necessary moisture. The remaining 2/3 is picked up within the cave by evaporation. Air which enters the cave will eventually leave the cave and when it does, it takes more moisture away from the cave than it brought in. The amount of moisture leaving the cave as water vapor varies throughout the year. During the winter, outside air is generally much drier than cave air and because of increased airflow, there is a greater drying of the cave during the winter. In the summer, the outside air can be quite humid and may at certain times of the day have a greater moisture content than the cave air. However, even during the summer, the average daily moisture content does not equal the moisture content of the cave air. Summer is also a time when the annual pattern of air exchange is at its lowest. For these reasons, summer is a time of less moisture loss by air exchange.

Total moisture input by the three methods is estimated to be: (1) 60,000 gallons/year (percolation), (2) 600,000 gallons of flood water approximately once every five years (large flooding events) and (3) 13,000 gallons/year of water vapor brought into the cave. The total average yearly input ranges from 213,000 to 813,000 gallons/year. In drought years, the input would be considerably less than 200,000 gallons.

MOISTURE LOSS

Moisture is also lost from the cave by several mechanisms.

- Percolation through the floor of the cave.
- An internal drainage system and outlet drains.
- Evaporation and subsequent transport out by air exchange.

Percolation Through the Floor of the Cave. The fact that water seldom collects in standing pools of water indicates that it is somehow being removed. During wet periods, water may collect in small rimstone pools. These pools last only a few weeks before disappearing. The measured rates of evaporation within the cave are much too small to explain why these pools dry up. The remaining possibilities are drains or direct percolation. Many of these rimstone pools have no observable outlet. It is thought that the water is percolating out the bottom of the pools. The fact that pools several inches deep can disappear within a month indicates that potentially all of the

water entering the cave could be lost in this way. A rough estimate of the percolation rate is 3" per month.

Internal Drainage System and Outlet Drains. Within the cave, there is a system of small stream channels. During very wet years, these channels may carry light flows of water. Most of these channels lead to small drains in the floor of the cave. These drains appear to act independently from each other. Based on observations of the rate of recession of the August 1990 and winter 1991 floodwaters, the capacity of these drains in the back of the cave can be estimated. The drains in the Subway Tunnel have a capacity of at least 25 gallons per minute (gpm). This is equivalent to draining 66 inches of water throughout the whole cave per year. It is only during very wet periods that the capacity of the drains is exceeded.

It is important to understand that the effectiveness of the drains and percolation is a function of the depth of water. The rate at which water leaves the cave increases as the depth of water increases. Under normal conditions, cave surfaces are moist and there is only a very thin film of moisture. Percolation and the drainage system are much less effective at removing this film of water which adheres to the surfaces and flows very slowly. As soon as there is sufficient free water, however, percolation and drains quickly remove it.

Moisture lost by evaporation. The amount of moisture lost by evaporation inside the cave can be estimated from the measurements of the evaporation pans . However, it must be remembered that the evaporation pans are not a true reflection of the rate to be expected from the cave surfaces for the following reasons. 1) The rate of evaporation is dependent on the difference in relative humidity (more properly, it is the humidity gradient). 2) The water surface in the pan can be considered as being at 100% relative humidity. Cave surfaces, however, are at a slightly lower humidity and should therefore evaporate slightly less water. At a constant temperature, air, which is more humid, is lighter and will rise to the ceilings. We would expect that the humidity near the ceilings is greater than near the floor for this reason and also because water percolating in from the surface first reaches the ceiling. Since the evaporation pans are all located on the floor, we would expect that they will overestimate the evaporation rate on the upper walls and ceilings. 3) The distribution of evaporation pans is not uniform and is skewed toward potential entrances in drier parts of the cave. This would result in the amount of evaporation being overestimated. Also, while each evaporation pan has a cover to prevent water from dripping into the pan, drips hitting the floor nearby can still splash into the pan. If the air is supersaturated, then condensation can form on the pan. Both of these would cause the pans to show less evaporation.

Any attempt to estimate the true evaporation from cave surfaces must take into account the above differences. The distribution of the evaporation pans can be accounted for by determining which represent "deep-cave conditions" and which reflect "entrance influences". By examining the variability of a number of parameters at each environmental station, the "deep-cave" and "entrance-influenced" stations can be divided out. The "deep-cave" evaporation pans lose an average of 0.22 ml/day. The "entrance-influenced" pans lose an average of 0.91 ml/day. The amount of evaporation is computed for each section. The walls and ceiling areas are not considered as being effective evaporation surfaces because of higher humidity levels near these surfaces. "Deep-cave" evaporation is estimated to be 13,500 gallons per year. "Entrance-influenced" areas are estimated to evaporate 7,500 gallons per year.

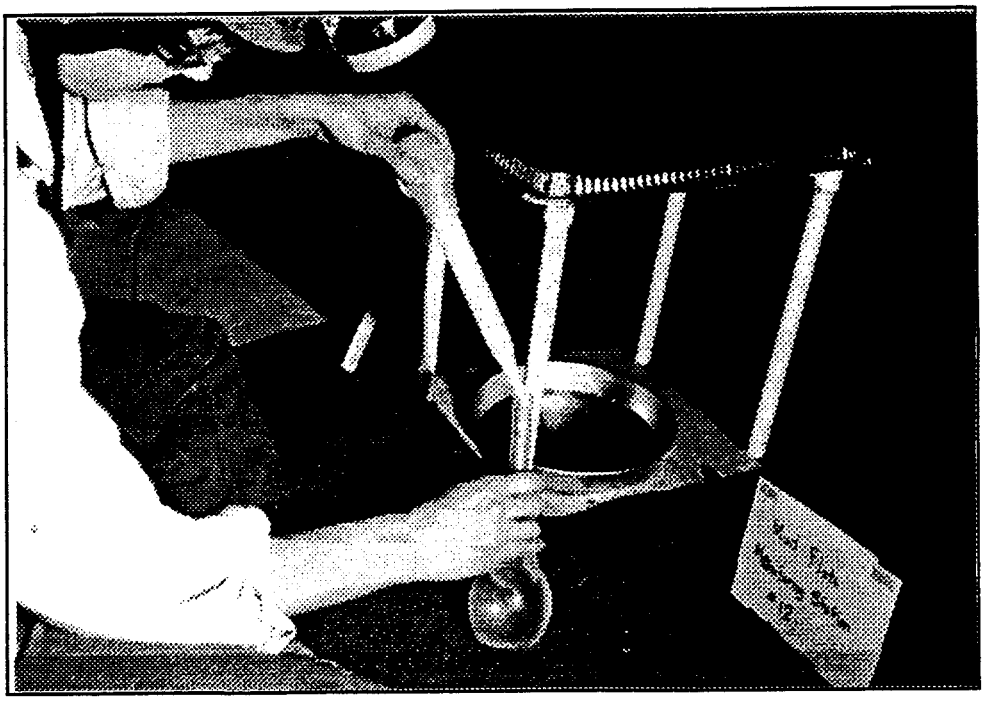


Figure 70. Debbie Buecher measuring evaporation water loss at the Mud Flats Environmental Monitoring Station.

It should not be surprising that "entrance-influenced" areas, which comprise a small fraction of the total cave area, have almost the same total evaporation as the rest of the cave. Surface air entering the cave is very dry and will quickly evaporate moisture off cave surfaces. Total evaporation from the cave is therefore estimated to be 21,000 gallons per year.

The amount of evaporation can also be independently checked by calculating the amount of moisture that the observed airflow can remove from the cave. Measurements of airflow at the Blow Hole and start of the River Passage consistently show a volume of 140,000 cubic feet per day entering the cave. If we assume that this represents only one-third of the total airflow, then 420,000 cubic feet may be exchanged each day. During the months from October to June, the outside air contains approximately 4 grams of moisture per cubic meter. Outside air entering the cave will evaporate 13.3 grams of water per cubic meter of air. Total moisture lost in these months is estimated to be 14,130 gallons. During the summer months, July through September, the outside air contains an average of 11 grams of moisture per cubic meter. It will evaporate an additional 6.3 grams of moisture when it enters the cave. Evaporation from airflow in the summer months is estimated to be 2,254 gallons. Total evaporation from the cave based on airflow measurements is estimated to be 16,384 gallons per year. This is less than the 21,000 gallons estimated from the evaporation pan data but is not an unreasonable difference, considering the possible errors of the different techniques.

The amount of moisture lost from the cave by evaporation is estimated to be the mean of the two estimates or approximately 20,000 gallons per year. This is only an

estimate and the true moisture loss may be as low as 16,000 gallons or as high as 35,000 gallons per year.

ANNUAL WATER BALANCE

A rough water balance for the cave can now be constructed. There is a large amount of uncertainty in each of the estimates but it is useful to compare the various amounts of water entering and leaving the cave.

The following assumptions are made. Variations in annual precipitation are estimated to be ±35%. Evaporative losses are less in a wet year because cool flood water causes water to condense out of the air rather than evaporate. The capacity of drains and percolation greatly exceeds the present moisture inputs to the cave. The amount of water leaving the cave by percolation and drains is used to balance the moisture equation.

TABLE 25
Tentative Cave Water Balance

Moisture Inputs:	Dry Year	Average Year	Wet Year
Direct Percolation	30,000 gal/yr.	60,000 gal/yr.	120,000 gal/yr.
Wash Infiltration	0 gal/yr.	0 gal/yr.	600,000 gal/yr.
Total Input	30,000 gal/yr.	60,000 gal/yr.	720,000 gal/yr.

Moisture Losses:	Dry Year	Average Year	Wet Year
Drains & Percolation	9,000 gal/yr.	39,000 gal/yr.	704,000 gal/yr.
Evaporation	21,000 gal/yr.	21,000 gal/yr.	16,000 gal/yr.
Total Losses	30,000 gal/yr.	60,000 gal/yr.	720,000 gal/yr.

IMPORTANT WATER RECHARGE AREAS TO THE CAVE

Areas which are important in maintaining the supply of moisture to the cave can be broken down into two categories based on the source of the water. Studies of the two flooding events has shown that the largest volume of water enters the cave from Guindani and Saddle washes when these streams are running. A smaller but important amount of water percolated directly down to the cave from surface precipitation. The areas which contribute percolating water to the cave can be delineated based on the drip water and geologic mapping.

Figure 71 is a map of the area surrounding the cave and shows the locations of important water recharge points. These areas should be protected from any changes which would reduce the amount of water that reaches the cave. The most vulnerable area is along Guindani and Saddle Washes. Very small changes in these washes could result in water being diverted away from the cave.

The area from which water directly percolates into the cave is shown as two shaded areas. The darker shading corresponds to areas for which surface water would percolate into the cave along the dipping beds of limestone. This is the most likely route for surface percolating water to follow and is consistent with the drip water measurements. The lighter-shaded area corresponds to areas where water may

percolate into the cave along more vertical flow paths. In all cases, this zone is placed at a point where a 45° line from the cave would intersect the surface. From a management point of view, both of these areas are equally significant and should be protected.

PROTECTION OF SURFACE RECHARGE AREAS

Maintaining the moisture balance of the cave is an important component of managing and preserving the cave resource. One aspect of maintaining the moisture balance is the protection of the sources of water which ultimately reach the cave. This water comes from two sources. One is direct precipitation which falls on the limestone hill above the cave and percolates into the cave. Additional water occasionally floods the cave from streams along the south side of the hill when these streams are flowing. Both of these areas should be protected from adverse impacts which would decrease the amount of water reaching the cave or degrade the quality of the water.

Portions of the hill overlying the cave contribute drainage which eventually finds its way into the cave in the form of drip water and diffuse flow through the bedrock. This area is entirely within the park boundaries (Figure 71) and is particularly important because it is the quantity and quality of the water which percolates into the cave and continues to create the cave formations. Any surface construction which could result in the altering of surface drainage patterns should be avoided. This includes the management of silt and other sediments which could clog the small cracks where water enters. The condition of the natural vegetation and soil cover is probably important to the chemical equilibrium of the waters which reach the cave. The existing plant communities and amount of cover vegetation should be maintained. Potentially a change in surface vegetation could cause the water entering the cave to shift from depositing calcite to one which would dissolve and erode the cave formations. Additionally, the color imparted to the formations is frequently the result of small amounts of impurities picked up in the soil. Changes in soil or vegetation may result in changes in the color of subsequently deposited calcite.

Both Guindani Wash and Saddle Wash, where they flow adjacent to the hillside, have been identified as areas where large amounts of water sink into the streambed and enter the cave. The majority of the Guindani and Saddle Wash drainage basins lie to the west of the park on Coronado National Forest lands (Figure 72). Changes in land use within these drainage basins may have adverse impacts on the quantity and quality of water reaching the cave. The application of chemicals to these basins for vegetation or insect control could damage the resources of the cave. The present quality of water which enters the cave from these streams is very high (Appendix M). Surface runoff from these areas is the source of the water which floods the back sections of the cave. The wash bottom is an area of critical recharge for the cave. Disturbance or alteration of the stream channel may significantly affect the amount of flooding and duration of flooding.

MANAGEMENT IMPLICATIONS OF AIRFLOW AND MOISTURE

The cave is in a delicate balance with the existing supply of moisture. The cave receives moisture through percolation of precipitation on the limestone hills and also through periodic infiltration from the adjacent washes. The cave loses moisture by infiltration down through the floor of the cave and also by evaporation. At the present time, evaporation plays a small role in transporting moisture out of the cave.

AREA OF DIRECT PERCOLATION TO CAVE

AREAS WHERE SURFACE STREAMS INFILTRATE INTO THE CAVE

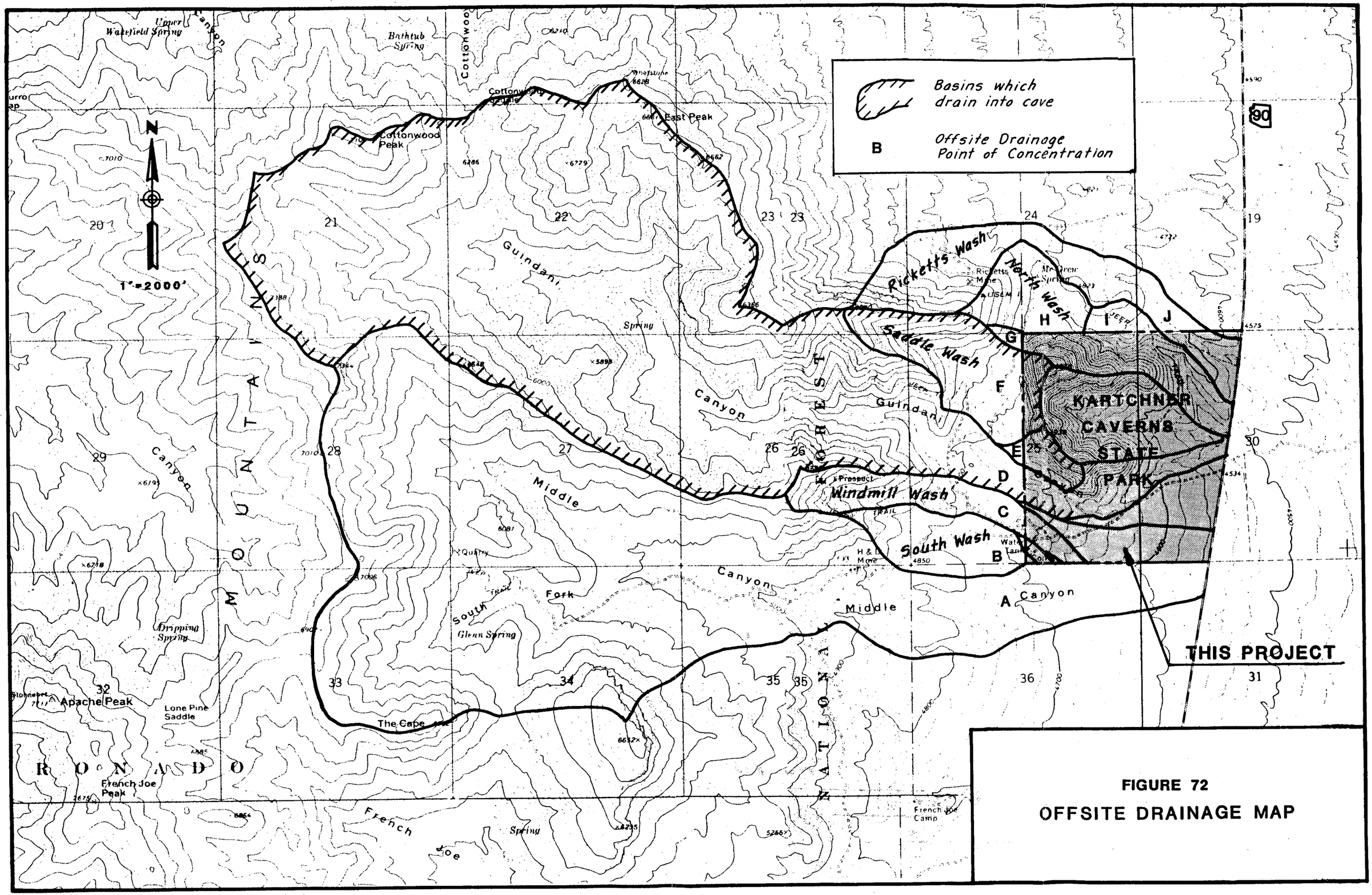
AREAS THAT MAY CONTRIBUTE WATER TO THE CAVE

Scale (Ft.)

0 100 200 300 400 500

FIGURE 71

IMPORTANT AREAS OF WATER RECHARGE FOR KARTCHNER CAVERNS


Basins which drain into cave
B Offsite Drainage Point of Concentration
N
1"=2000'
Upper Wakefield Spring
Bathtub Spring
Cottonwood Canyon
Cottonwood Peak
East Peak
Guindani Spring
Ricketts Wash
North Wash
Saddle Wash
Guindani Canyon
Windmill Wash
South Wash
Middle Canyon
South Fork Middle Canyon
Dripping Spring
South Glenn Spring
Apache Peak
Lone Pine Saddle
The Cape
French Joe Peak
French Joe Spring
French Joe Camp
KARTCHNER CAVERNS STATE PARK
THIS PROJECT
SANTA CRUZ
ROMERO
ATLONA
A
B
C
D
E
F
G
H
I
J
FIGURE 72
OFFSITE DRAINAGE MAP

How the park is managed can effect the amount of moisture entering and leaving the cave.

- Under present conditions, evaporation plays a minor role in removing moisture from the cave. This is because the present entrance is quite small and there is relatively little air exchange with the surface. Development of the cave for public viewing can greatly increase the amount of air exchange and moisture loss by evaporation. Poorly located or constructed entrances can potentially induce a strong airflow pattern which in turn will greatly increase the moisture lost by evaporation. This has been observed in many other developed caves. These problems can be lessened by care in locating or enlarging entrances and connecting tunnels. Steps can also be taken to control the airflow entering the cave. Entryway doors can be constructed to act as airlocks and prevent the entry of outside air. Developing the cave so as to prevent increased airflow and evaporation is the most controllable part of the moisture balance. It is the one variable that we are most confident of the effects on the cave.
- Changes on the hills overlying the cave can reduce or increase the amount of water entering the cave. Examples of man-made changes are: construction of roads, parking areas, buildings, or diversion of drainage. We do know that there are specific areas which are more important than others in recharging the cave (Figure 71). Changes in the type and amount of vegetation on the hillsides are likely to cause changes in the amount of moisture reaching the cave. Man-made changes are less likely to affect the cave unless they occur in a critical recharge area.
- The amount of moisture lost by infiltration down through the floor of the cave and through small drains appears to be the most significant mechanism for water loss. Man can change this by disturbing the existing drainage patterns in the cave. Presently the internal drainage pattern of the cave is only partially understood. In the rear of the cave, several specific drains have been identified. In the front of the cave, it appears that much of the water infiltrates directly into the floor or drains into the Red River. Additional depressions in the floor near Kartchner Towers and the Strawberry Room suggest other drainage patterns. Many of the drainage holes are quite small and could be easily blocked by trail construction. Short of blocking the known drainage patterns and drains, development is unlikely to cause significant changes in the amount of moisture lost through the floor of the cave.
- Several specific areas along Saddle Wash and Guindani Wash have been identified as important recharge areas for the cave (Figure 71). These areas are the source of the water which floods the back portions of the cave occasionally. This periodic flooding recharges the mud in the back of the cave. The moist mud acts as a reservoir for moisture, slowly drying out during extended dry periods. Water which enters from the adjacent washes exerts a major influence on the temperature of the back sections of the cave and on airflow patterns. Changes in surface land use within the Guindani and Saddle Washes watersheds can affect the amount of water entering the cave. Additionally, changes in the alignment of the washes can also change the infiltration into the cave. Any withdrawal of groundwater in these areas may reduce the amount of water in these washes and also that water which would enter the cave.

ACTIVE MANAGEMENT OF THE CAVE MICROCLIMATE

Conditions within the cave appear to be at near equilibrium. To the best of our knowledge, the present conditions within the cave are optimum for preserving the contents of the cave. The wisest approach to managing the cave is to strive to maintain the existing conditions. However, it is also possible to envision a scheme of management where the factors which control the microclimate within the cave are actively managed. One could control the amount of water reaching the cave from Guindani Wash by changing the wash alignment. In dry years, the amount of moisture in the cave could perhaps be increased by sprinkling water on the surface or creating artificial pools within the cave. The amount of airflow through the cave could also be controlled to optimize the moisture loss, carbon dioxide and alpha radiation levels.

While this appears to be a possible approach, it has many unknowns. The microclimate has many interrelated processes and an attempt to manage one aspect of the microclimate is likely to adversely affect the cave in other ways. Other show caves have found it necessary to actively manage the cave resource. Unfortunately, the choice of active management has been forced on many developed caves. Frequently, the attempt to correct a problem by controlling one factor has led to the creation of many other unanticipated problems. For example, we do not know how sprinkling a different type of water on the surface would affect the water chemistry. Would it continue to form deposits so the formations would continue to grow or would it dissolve the existing formations, or change the color of them? Could introducing water in some areas cause stability problems? It is unlikely that these questions could be adequately answered without experimenting on the cave and perhaps finding out too late. At the present time, the cave appears to be a system in equilibrium. If that equilibrium is disturbed, then it may require a much greater effort to restore it. For instance, if the cave begins to dry out, it may be some time before this is noticed. During that time, the moisture reserves stored within the mud and rock may be lost and it may take years to restore the moisture balance. It is also possible that once the present equilibrium is lost, it may not be possible to return to the existing conditions

Active management of the cave also requires an active monitoring program to assess the success of that management. Based on two years of study, we can see how the major elements of the microclimate interact. It would take considerably more study in order to be able to accurately predict the outcome of attempts to manipulate the microclimate.

The most famous example of man's attempts to manage the microclimate of a cave is Lascaux Cave in France. The cave and the greatest collection of prehistoric cave paintings was discovered shortly before World War II. Opened to the public in 1948, Lascaux Cave quickly became a major tourist attraction. Unfortunately, the growing number of visitors upset the microclimate of the cave. Increased condensation, temperature fluctuations and a rise in carbon dioxide levels were destroying the paintings. In 1958, an elaborate system was constructed to control the microclimate of the cave. Outside air was filtered, cooled and brought to the same humidity as that of the cave and carbon dioxide was removed from the air within the cave. This proved to be only a temporary cure. In 1962, patches of bacteria and algae began to appear on the paintings. These rapidly spread and in order to save the prehistoric paintings, the cave was closed to the public in 1963. The cave is still closed and there appears to be no hope of opening to the public without eventually destroying the paintings.

Carlsbad Caverns in New Mexico is one of the greatest caves in the world. It was first open to the public in the 1930s with the installation of trails and elevators. It was

not until the late 1960s that it was determined that Carlsbad was drying out. The drying was produced by the constant airflow out the elevator shafts. The shafts acted like a giant chimney which in conjunction with the desert environment produced extensive drying. Air-tight doors have been installed which partially alleviate the problem.

Colossal Cave near Tucson installed a ventilation fan, apparently to remove the odor of bat guano from the cave. Colossal Cave, like Kartchner Caverns, is located in an arid environment. Operation of the fan has also resulted in the complete drying of the cave features and also the loss of the nectar-feeding bats which once used Colossal Cave. The management of the cave is now attempting to modify the ventilation system to allow bats to return to the cave.

Other caves which are known to have installed ventilation fans include Howe Caverns in New York and Inner Space Caverns in Texas. The reasons why fans were installed in these caves is unknown. Fortunately these caves are located in areas which have much higher rainfall and would be less susceptible to drying from increased airflow.

Active management of the cave is not recommended. It has never been attempted before as a basic management strategy. At other developed caves, it has been used as a tool of last resort to protect the cave resource once problems have arisen. The experiences at other caves indicate that attempting to manage the microclimate is more likely to create than solve problems. A much better approach appears to be the careful maintenance of the current pre-development conditions in the cave.

Impact of Development on the Cave Microclimate

Development of portions of the cave to allow large numbers of visitors to view the cave will unavoidably alter the microclimate of the cave. The cave should be developed with the goal of minimizing those impacts while preserving the conditions which are necessary for maintaining the long-term integrity of cave features. The cave microclimate is in balance with the existing conditions and will change to remain in balance after development. The presence of visitors will alter the cave environment in four ways:

- Additional Heat from lights and body heat of visitors
- Increased Carbon dioxide (CO_2) from respiration
- Oxygen (O_2) consumed by respiration
- Water vapor given off by respiration

The amount of each of these can vary considerably depending on age, sex, weight, level of exertion and manner in which tours are operated. Reasonable estimates for the impact from each visitor are:

- Body heat - 175 watts per hour
- CO_2 - 20 liters per hour
- O_2 - 25 liters per hour
- Water vapor given off - 13 grams per hour

Based on an average of 275 people per day (100,000 visitors/year) and a 1.5 hour tour length, the daily impacts would be:

- Body Heat - 72 Kilowatt hours (250,000 BTU)
- CO_2 - 8.3 cubic meters released (293 cubic feet, 53 ppm)
- O_2 - 12.4 cubic meters consumed (438 cubic feet)
- Water equivalent to 5.4 liters (1.4 gallons) added to cave

These impacts will vary with the number of people who visit the cave on any particular day. On days of high use, the impact may be three times higher; on low-use days, only two thirds as high. The potential for disrupting the microclimate can be estimated by comparing the impacts to the existing conditions. The amount of water that would be added to the cave, 1.4 gallons per day, is quite small in comparison to the 160 gallons of water that percolates into the cave each day and no adverse impacts are anticipated. The amount of oxygen that would be depleted from the cave air (438 cubic feet per day) is also quite small compared to the average amount brought into the cave daily by natural air exchange (6,000 to 80,000 cubic feet of oxygen per day) and no significant change in oxygen content is anticipated. The amount of heat that would be introduced is large compared to the heat budget of the cave and will have a significant impact on temperatures, evaporation rates and internal air circulation. The amount of carbon dioxide that would be exhaled into the cave air by visitors is also quite large and is anticipated to double the concentration of CO_2 in the cave air.

Preventing dry surface air from entering the cave has been identified as the primary concern in developing the cave. However, even if no additional surface air is allowed into the cave, there will still be other changes in the microclimate of the cave. These changes will arise from the introduction of electric lights and the presence of the visitor. Both of these will give off large amounts of excess heat. The increased heat load is estimated to be 72 KW-Hr. per day from lighting and 72 KW-Hr. per day from visitors for a total of 144 KW-Hr spread over an eight hour period. This excess heat will be dissipated within the cave by several processes:

Increased convective airflow
Raising the air temperature
Increased evaporation from cave surfaces
Increased wall temperatures

It is assumed that air exchange with the surface will continue to be quite small, comparable to the natural rate found in the undeveloped cave. This should be the case if new entrance tunnels are properly constructed to reduce air exchange through the use of airlock doors. We can also consider that the air exchange with outside air is a negligible mechanism for exchanging heat inside the cave. The cave can therefore be considered as approximating a closed system. Ultimately, all of the excess heat introduced by the visitors and lighting will be dissipated as heat on the walls of the cave.

Convective airflow, increased air temperature and evaporation are the mechanisms that will transport and distribute the excess heat to the walls of the cave. The problem is how to proportion the excess heat among these mechanisms. One approach is to determine the maximum possible effect for each process by assuming that it is the only mechanism in operation. Internal air circulation will be increased by rising heat from electric lights and visitors. The maximum amount of airflow induced is

estimated to be 4,000,000 to 9,000,000 cubic feet per day produced by a rise in air temperature around light fixtures. The maximum internal air circulation within the cave in its undeveloped state is approximately 1,500,000 cubic feet per day. The increased circulation induced by the development will overwhelm the natural circulation pattern and result in a more uniformly mixed cave air. The existing airflow patterns are produced by slowly varying temperature gradients, typically less than one degree per hundred feet, which cause predominantly horizontal air movements. Heat from electric lights and visitors will cause large thermal gradients over very short distances. These will produce predominantly vertical air motions. The airflow pattern will be dramatically changed by development. Airflow is an inefficient mechanism for dissipating the heat energy as only small amounts are lost by friction with the walls and internal viscose forces. Other mechanisms such as evaporation and condensation are more efficient in transferring heat and will be the predominant means by which the increased heat load will be transferred to the walls of the cave.

A reasonable estimate of the likely increase in air temperature can be made from the amount of extra moisture that will be held in the cave air. The amount of water that can be evaporated by 144 Kw/day is calculated to be 57 gallons per day. This will increase the average air moisture content by 1.5 grams per cubic meter. The air will remain at near saturated conditions and the temperature will rise 2.7°F to enable it to hold the increased moisture. Because the heat produced by lights and visitors will only be produced for part of the day, the temperature will fluctuate on a daily basis over much of the cave.

The expected rate of evaporation, 57 gallons per day, represents a doubling of the natural rate of evaporation in the cave. If the rate of air exchange with the surface were allowed to increase through a faulty airlock, then the rate of moisture loss would greatly exceed the natural rate and drying of the cave would result. However, if properly developed, the cave will continue to act as an essentially closed system and there will be only a small increase in moisture lost to the surface. This occurs because warm air will be able to evaporate and hold greater amounts of water. But this warmer and more humid air will lose moisture by condensation onto cooler walls of the cave. Increased evaporation is most likely to occur on the floor and ceiling of the cave. Walls of the cave are more likely to be areas where increased condensation will occur. Heat from lighting and visitors will be transferred to the walls of the cave by moist air which will alternately condense on these surfaces at night and evaporate during the day. The walls of the cave can increase in temperature a maximum of 0.3°F if the excess heat is uniformly dissipated. If the heat is mainly dissipated on the ceilings (since warm air will rise), then the maximum increase will be 0.9°F.

The above discussion illustrates that the possible changes in airflow and evaporation rates could be quite substantial. Anticipated changes in air and wall temperatures are likely to be 1°F to 3°F and will result in substantial changes in the air circulation and evaporation within the cave. Continued monitoring of temperature and evaporation within the cave will be needed to determine the actual changes.

CAVE MOISTURE CONCLUSIONS

1. Evaporation within the cave is much less than what occurs on the surface. Outside, the annual evaporation is approximately 65" per year. Inside the cave, the average evaporation is 0.08" per year. If exposed to outside air, the entire yearly moisture supply to the cave would be evaporated in less than six days.

2. The largest source of moisture into the cave is the infrequent flooding of the back of the cave. This water drains from the cave within a few months but leaves behind large amounts of moisture stored in the moist mud. Flooding of the back section of the cave also cools this area and exerts a strong influence on the microclimate of the cave. Percolation of precipitation into the cave appears to be the most significant moisture source for the cave. Both of these sources are highly variable and can change from year to year.

3. The cave loses most of its water by percolation out through the floor of the cave and by a system of channels and small drains. These become more effective when there is a lot of water. The cave can lose much more water in this fashion than it receives in even the wettest years. Only a small portion of the water entering the cave is presently lost by evaporation and air exchange.

4. The cave is probably now receiving slightly more moisture than is required to maintain an equilibrium with the supply of moisture.

5. Development of the cave will increase the airflow and evaporation within the cave. These increases can be minimized but cannot be completely eliminated. During dry years, the moisture lost through evaporation and air exchange may equal or exceed the moisture gained through direct percolation.

6. Outside air always contains less moisture than cave air. Air brought into the cave from outside can always be considered as having a drying effect on the cave.

7. Proper development of the cave can avoid disrupting the supply of moisture to the cave. Care in locating trails and disturbing in-cave drainage patterns will preserve drainage capacity of the cave.

MONITORING EXISTING WELLS

INTRODUCTION

The juxtaposition of igneous and metamorphic rocks, carbonate rocks, and alluvial sediments within and around the park has created a complex groundwater system. The key to understanding how Kartchner Caverns formed and why it is so unique rests in large part on elucidating the groundwater hydrology. In addition, knowledge of the hydrogeology is crucial to park planning in two other ways:

- Siting of a park water supply well that will prove dependable over the long term and that will prevent deleterious effects on the cave (for example, drying of the cave caused by reducing streamflow in Guindani Wash and subsequent infiltration into the cave).
- Siting of park improvements (sewage treatment plant, parking lot drainage structures, etc.) in locations that will prevent groundwater contamination and possible adverse cave effects.

One of the basic tasks in studying the occurrence and movement of groundwater is the measurement of water levels in wells. This information will help correlate the surface hydrologic events to subsurface changes in water levels and will provide some understanding of groundwater conditions in the park. The program of water level monitoring and the additional work is outlined below:

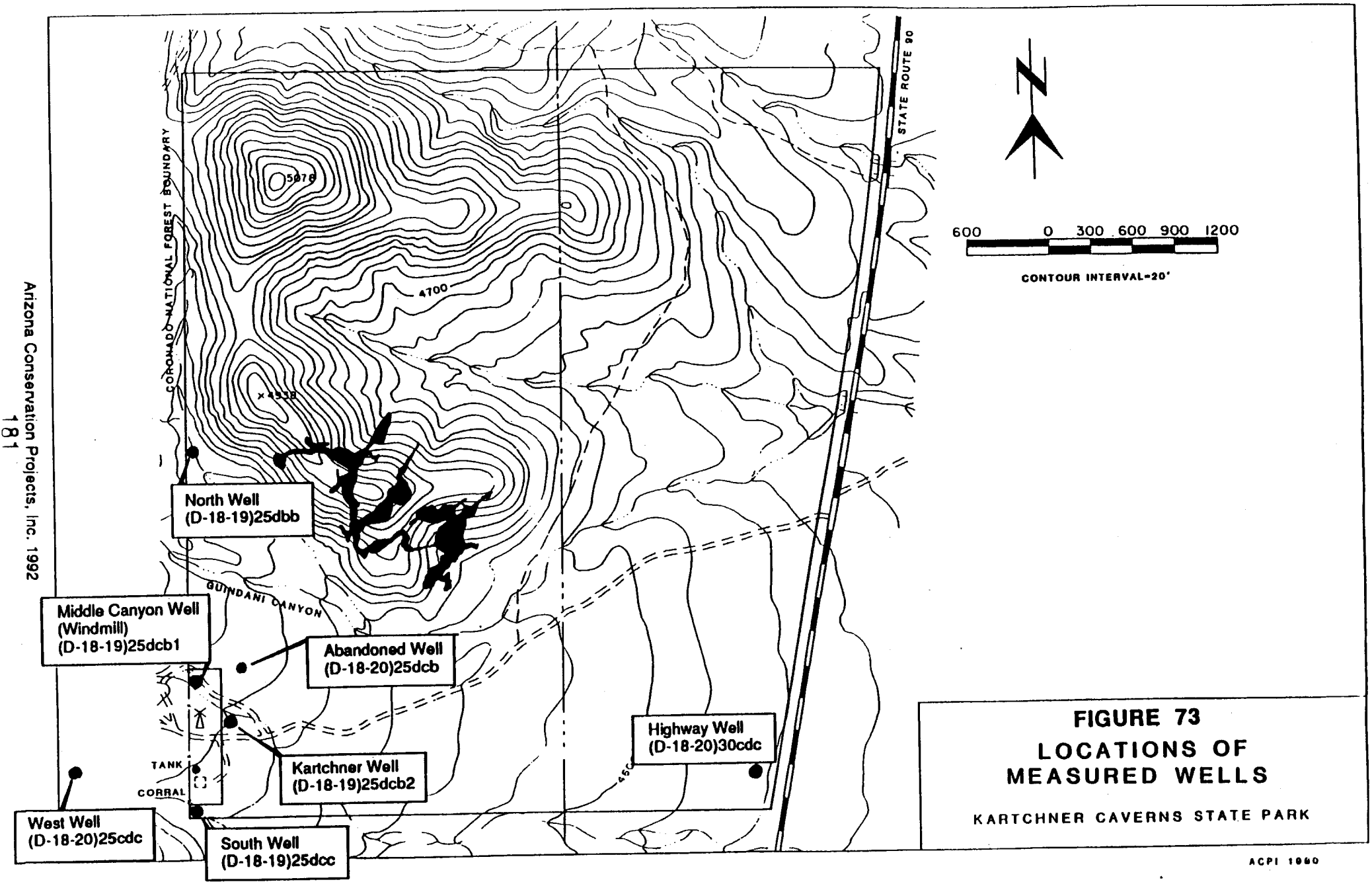
- Records of all active, inactive, and dry wells on the property and in the park vicinity will be compiled from data sources such as the Arizona Department of Water Resources and well drillers. Pertinent data from these records such as depth, diameter, date drilled, lithology, etc., will be tabulated in the Surface Hydrology Report.

- Absolute elevations of all wells and water-level measuring points were determined by spirit leveling in order to relate the position of the water table to cave elevations.

- A continuous water-level recorder was installed in the North well nearest to the limestone bedrock. This will provide a record of very detailed changes in water level that may be more easily correlated with stream flows than weekly water level measurements. The recorder is able to discern changes in water level of less than 0.01 foot.

- As called for in the RFP, water levels in the remaining wells have been measured weekly. Measurement of depth to water was made to the nearest 0.01 feet.

Four wells (North Well, Kartchner Well, South Well and Highway Well) are located on the Park. Figure 73 is a map showing their locations. Two additional wells are adjacent to the west boundary of the Park. (Middle Canyon Well and West Well). Names given to the wells are informal designations used in this report to aid in the discussion of the wells. The contract calls for the monitoring of three wells. ACPI has been monitoring three wells on the park and two wells adjacent to the west property line on a weekly basis. Measurements taken at each well and hydrographs have been compiled in Appendix I.



Arizona Conservation Projects, Inc. 1992

Middle Canyon Well (Windmill)
Actual Cadastral Location (D-18-19)25 dcb1
DWR Registered Cadastral Location: (D-18-19) 25dcc
State Plane Coordinates: 303,972.01N 440,973.58E

ADWR Well Filings
Report of Well Driller: None
Registration: 55-601568

Measuring Point = Top of horizontal plate at hole, north side, 1.1 ft. a.l.s.
Elevation of Measuring Point = 4714.33
Elevation of Land Surface = 4713.3

Depth of Well = 205 feet (reported)
Diameter of Well = 6.0 inches
Date Constructed : 1948
Construction Method: Drilled
Use of Well: Stock water
Pumping Equipment: Windmill

Depth to Water Level Below LS (range): 53-80 feet
Water Temp/Specific Conductivity @ 25°C/Collection Method/Date:
23.0°C, 324 uS/cm, pumped, 6-18-88
24.0°C, 318 uS/cm, pumped, 6-24-89

The Middle Canyon Well is located on private land adjacent to the west park boundary. This well, which supplies water to a cattle tank, is the only well that is currently being pumped within or in the immediate vicinity of the park. No yearly water level pattern is discernible against the fluctuations caused by the pumping, although a general upward trend of 5 feet in the last 2-1/2 years is indicated by water level measurements . This trend may represent a true long-term water level rise or may simply be due to the pump wearing out. If declining pump output is the cause of the water-level rise, then the aquifer being tapped by the pump must be quite small and limited in storage.

This Middle Canyon Well has the greatest depth to water of any of the wells along the west park boundary; the bottom of the adjacent Windmill Wash is about 55 feet above the well water level. The resulting water table elevation is the lowest among the west park boundary wells with the exception of the Kartchner Well. On windy days when the windmill is pumping hard, the water level in the well will drop as much as 20 feet.

A crude estimate of the amount of water which is produced can be estimated from the rate at which the stock tank empties and fills. The stock tank has been drained and refilled which enables us to make some estimate of how much water is being pumped. Measurements of the rate of emptying of the cattle tank give a lower estimate of the capacity of the Middle Canyon Well of approximately 100 gallons per day. This is consistent with the observations that, on windy days when the windmill is pumping hard, the water level will drop considerably. The large drop in water level is indicative of a limited supply of water to this well.

Kartchner Well
Actual Cadastral Location (D-18-19) 25dcb2
(About 380' ESE of the Middle Canyon Well)
DWR Registered Cadastral Location: (D-18-19) 25dcc
State Plane Coordinates: 303,705.08N 441,244.58E

ADWR Well Filings
Report of Well Driller: None
Registration: 55-626887

Measuring Point = Top of 6.5" O.D. Casing, E. side, 1.3' a.l.s.
Elevation Measuring Point = 4699.91
Elevation of Land Surface = 4698.55

Depth of Well = 220 feet (reported)
Diameter of Well = 6.5 inches
Date Constructed: 1977
Construction Method: Drilled
Use of Well: Unused (capped)
Pumping Equipment: None

Depth to Water Level Below LS (range): 52-54.8 feet
Water Temp/Specific Conductivity @ 25°C/Collection Method/Date:
No water sample collected to date.

The water level in the Kartchner Well fluctuates approximately 2 feet over the course of a year. This well is located 30 feet south of Windmill Wash. The water level is 50 feet below the flow line of the wash (4694'). This well does not show an immediate response to precipitation and has the smallest fluctuations in water level of all of the wells. This well was drilled to a depth of approximately 250 feet but apparently did not produce sufficient water for use and was abandoned immediately after being drilled. Reportedly only the top 30 feet of the well is cased.

North Well
Actual Cadastral Location: (D-18-19)25 dbb
DWR Registered Cadastral Location: Not registered
State Plane Coordinates (approximate): 305,450N 441,012E

ADWR Well Filings
Report of Well Driller: None
Registration: None (however, registration needed)

Measuring Point = Sawed slot on top of casing North side, 4.4' a.l.s.
Elevation Measuring Point = 4724.76
Elevation of Land Surface = 4720.7

Depth of Well = 34 feet (measured)
Diameter of Well = 32 inches

Date Constructed: Unknown; 1930's (?)
Construction Method: Dug
Use of Well: Unused
Pumping Equipment: None (formerly windmill)

Depth to Water Level Below LS (range): 18-26 feet
Water Temp/Specific Conductivity @ 25°C/Collection Method/Date:
No water sample collected to date.

The North Well has a continuous chart recorder which was installed in June of 1988. Water fluctuations show an amplitude of about 6 feet over the course of a year. It is located near bedrock outcrop west of park boundary, less than 100 feet south of limestone hill and 50 feet south of Saddle Wash. Does not seem to respond to water flowing in the wash (ground water flow is to north away from well?). Water level is 15 to 20 feet below the flow line (4715') of Saddle wash. This is a hand-dug well that at one time apparently had a windmill. This well is closest to the limestone hill. Surprisingly the elevation of water in the well does not correspond to water levels measured in the cave. Water levels measured in this well are 60 feet above the floor of the cave which is only 550 feet away. This well is also slow to respond to the flow of water in the adjacent Saddle Wash.

Because of the large diameter and remains of the pump rod sticking out of the well this well could present a safety hazard to unsupervised park visitors. The well to should be covered to prevent someone from falling into the well.

South Well
Actual Cadastral Location: (D-18-19)25 dc (South of corral)
DWR Registered Cadastral Location: (D-18-19) 25dcc
State Plane Coordinates (approximate): 303,070N 440,990E

ADWR Well Filings
Report of Well Driller: None
Registration: 55-626886

Measuring Point = Top of 36" corrugated metal pipe, W. side, 0.8 ft. a.l.s.
Elevation Measuring Point = 4684.46
Elevation of Land Surface = 4683.7

Depth of Well = 58 feet (measured), 60 feet (reported)
Diameter of Well = 36 inches
Date Constructed: Prior to 1941
Construction Method: Dug
Use of Well: Unused
Pumping Equipment: None (formerly windmill)

Depth to Water Level Below LS (range): 14.1-23.7 feet
Water Temp/Specific Conductivity @ 25°C/Collection Method/Date:
19.5° C, 918 uS/cm, bailed, 7-10-88
21.0° C, 393 uS/cm, bailed, 6-24-89

This is a hand-dug well. Water fluctuations show an amplitude of approximately 9 feet over the course of this study (Figure 74). It is located within 50 feet of South Wash and does not appear to respond quickly to water running in the wash. Water level is 21 feet below the level of the wash (4682'). This well is supposed to have had a windmill but did not produce enough water so the Middle Canyon well was drilled.

This well is also a safety hazard due to the large diameter and being close to the ground. A secure, locking cover should be placed on this well.

West Well
Actual Cadastral Location: (D18-20)25cdc (750' west of corral)
DWR Registered Cadastral Location: Not registered
State Plane Coordinates: 303,394.75N 440,227.63E

ADWR Well Filings
Report of Well Driller: None
Registration: None

Measuring Point = Top of 6"x 8" post at SE corner, inside well (ST9 engraved on it)
Elevation Measuring Point = 4714.71
Elevation of Land Surface = 4715.0

Depth of Well = ?
Diameter of Well = ?
Date Constructed: Not known
Construction Method: Dug
Use of Well: Unused
Pumping Equipment: None (formerly windmill)

Depth to Water Level Below LS (range): 8.7-19.4 feet
Water Temp/Specific Conductivity @ 25°C/Collection Method/Date:
No water sample collected to date

This is a hand-dug well, of unknown depth, located on National Forest Service land. It is presently unused. Water fluctuations show an amplitude of 6 feet over the course of a year. This well exhibits the quickest response to precipitation, rising as much as a foot in one week. It is located approximately 50 feet north of South Wash. Water level in well is 10 to 15 feet below the level of the wash. At one time this well had a windmill.

This well is also a safety hazard because of the large size of the opening which is at ground level. The well is located on Forest Service land and arrangements should be made to have a secure cover placed over this well by the Forest Service.

Highway Well
Actual Cadastral Location: (D-18-20) 30 cdc
DWR Registered Cadastral Location: Not registered
State Plane Coordinates (approximate): 303,540N 444,905E

ADWR Well Filings

Report of Well Driller: None
Registration: None (however, registration needed)

Measuring Point = Top of Casing, N. side, 0.61' a.l.s.
Elevation Measuring Point = 4568.47
Elevation of Land Surface = 4567.86

Depth of Well = 790 feet (reported)
Diameter of Well = 6.5 inches
Date Constructed: circa 1984
Construction Method: Drilled
Use of Well: Unused (capped)
Pumping Equipment: None

Depth to Water Level Below LS (range): 13.5-19.5 feet
Water Temp/Specific Conductivity @ 25°C/Collection Method/Date:
No water sample collected to date

This is the deepest well on the park. When it was drilled in the late 1970's it did not produce enough water and was never used. The Highway Well, located at the southeast corner of the park, has been measured only twice owing to its great depth. The Highway Well is reportedly in alluvium all the way . Only the top 20 feet is cased. The Highway Well is east of the bounding fault. The water level is consistent with the water table measured in the valley. Because of the great depth to the water, the water table on the east side of the park is thought to be isolated from the cave.

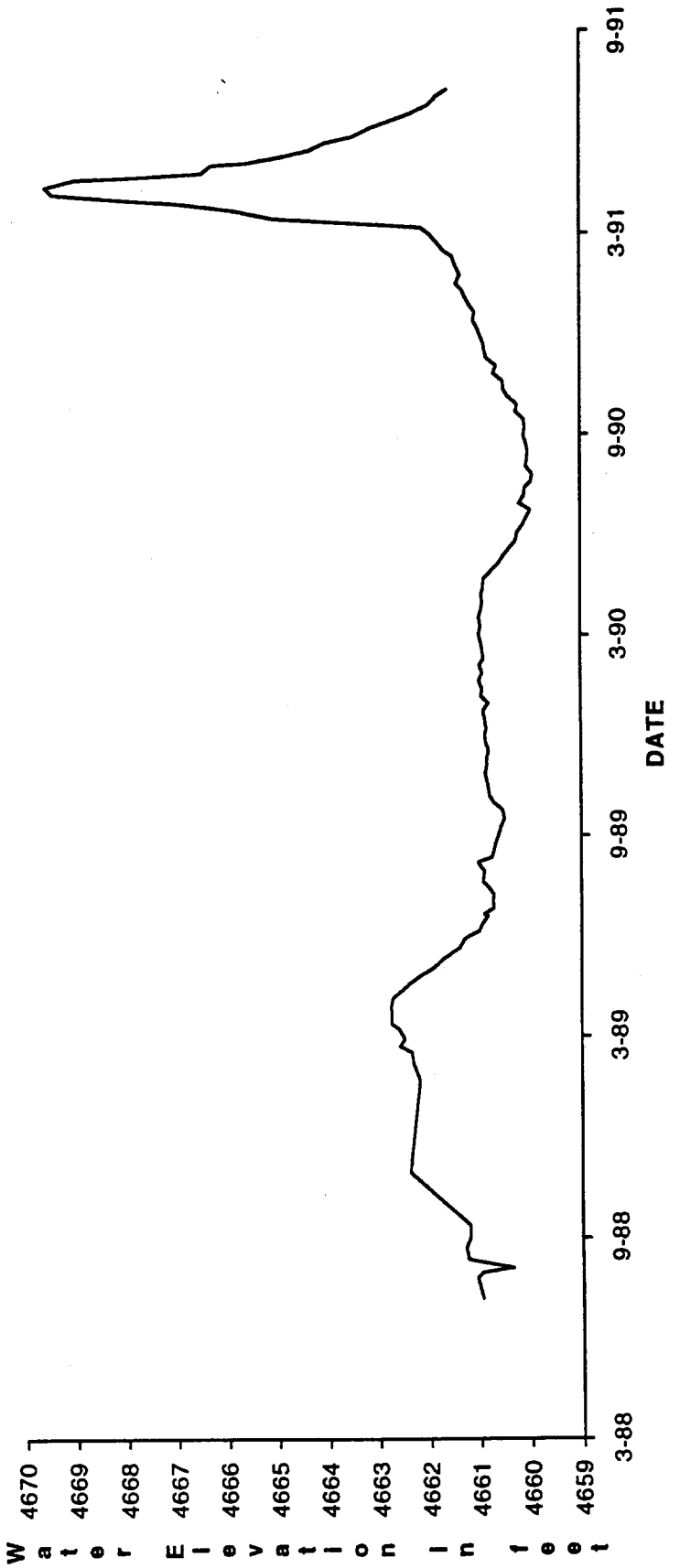
Abandoned Well
Actual Cadastral Location: (D18-19) 25dcb2(450' NE of Windmill)
DWR Registered Cadastral Location: Not registered
State Plane Coordinates (approximate): 305,100N 441,365E

ADWR Well Filings
Report of Well Driller: None
Registration: None

Depth of Hole: Not known
Diameter of Hole: Not known
Date Constructed: 1977?
Construction Method: Drilled

This hole was probably drilled in 1977 immediately prior to the drilling of the Kartchner Well as a substitute for the Middle Canyon Well, which was sold by the Kartchners. It is likely that this well failed to produce water and was abandoned as an open hole, which has since filled in or collapsed. The exact point at which the well was drilled is not know, but may be marked by a small depression near the edge of a mound of drill cuttings. The rig was then likely moved to the location of the Kartchner Well, which after drilling was capped because of little or no yield. The depth of the abandoned well is reportedly 250 feet.

FIGURE 74
Hydrograph
South Well (D-18-19)25dc



McGrew Spring
(D-18-20)24dbc

The spring is located approximately 1500' north of the northwest corner of the park. Overflow from the spring flows down North Wash. At the present time the spring is developed and water is stored in a stock tank.

CONCLUSIONS

Near the western boundary of the park, the North and South Wells (dug) and Middle Canyon and Kartchner Wells (drilled) penetrate a blanket of alluvium (termed "granite wash" in geologic reports published on the Whetstones - San Pedro Valley area which overlies bedrock. The depth to water in these wells ranges from 10 to 55 feet below land surface. Examination of drill cuttings and dug material deposited next to the wells indicates that bedrock was encountered at relatively shallow depth (probably in the same range of depths as the measured water levels) and consists of Pinal Schist. The gravity geophysical survey indicates the bedrock surface slopes (or may be stepped downward by faults) at a relatively steep angle to the southeast (Lange, 1990). SeeGeophysical Interpretive Map in a back pocket, Figure 75. The depth of alluvium overlying bedrock may be greater than 800 feet at the southeast corner of the park.

In southwestern alluvial fan settings, the groundwater piezometric surface typically mimics the land surface, with recharge occurring near the mountain front and groundwater flowing downgradient toward the alluvial basin. Beneath the Kartchner alluvial fan groundwater definitely moves from mountain front to basin, but because of the configuration of the underlying bedrock surface, this movement is not as straightforward as might be expected. Groundwater table elevations (calculated from water level measurements obtained in the park wells) indicate that the water table is probably not continuous in the alluvial fan in the western part of the park. The water table at the North Well is approximately 50 feet higher -- at the South Well about 12 feet higher -- than at the Middle Canyon and Kartchner Wells. The Kartchner and Abandoned Wells, drilled east of the Middle Canyon Well, did not produce appreciable water and therefore were never used as water supply wells. Based on this information, it appears that groundwater occupies low areas (erosion channels?) in the bedrock surface; the groundwater probably occurs as individual bodies or shoe-string aquifers that lack significant continuity over the area. Beneath the alluvium, some groundwater probably also exists in fractured or weathered zones in the Pinal Schist.

Groundwater flow within the alluvial fan is probably to the southwest down the bedrock surface. As interpreted from the geophysical data, flowing groundwater may converge into a shallow trough in the bedrock east of the South Well and into a broad deep trough underlying the southeast corner of the park. At the Highway Well, which is located at the east edge of the park, east of the buried fault scarp, the static water level was measured at a depth of 741 feet below land surface (3827 feet above sea level). The water level at the Black Well, located $2\frac{1}{2}$ miles east, was measured at 518 feet below land surface (3704 feet above sea level). These two water level measurements define a water table in valley fill deposits that probably represents the unconfined distal extension of the artesian aquifer underlying the San Pedro River near Saint David. Thus, based on a synthesis of all information collected to date, groundwater within the granite wash likely flows to the southeast supported on the surface of Pinal Schist, then descends the buried fault scarp to recharge the regional

aquifer penetrated by the Highway and Black Wells. This regional water level lies about 765 feet below the lowest measured point in Kartchner Caverns.

In the vicinity of the North Well, geophysics indicates a trough of alluvium depressed into the bedrock surface. North Well was dug less than 100 feet from the limestone hill containing Kartchner Caverns, yet the water level within the well is 60 feet higher in elevation than the bottom of the passage leading into Sue's Room only 700 feet away. In this area, groundwater may drain through the alluvium into the limestone to a depth below the present level of the cave. Flooding of the cave occurs when more water enters the limestone block at a rate faster than it can descend. The manner in which the cave floods and drains indicates that water is moving steeply down into the limestone. The general direction of floodwater within the cave is to the northeast.

The location of the water table within the Paleozoic sedimentary sequence remains unknown. The water table may lie at great depth, occurring as the continuation of the regional water table encountered in the Highway and Black Wells. If this hypothesis is correct, the water table would probably lie at a depth greater than 700 feet below land surface. However, because of the complex structure and presence of dipping beds within the limestone block, the possibility of a perched water table lying significantly above the level of the regional water table should not be ruled out.

The present study has monitored the wells on and near the park on a weekly basis for two years. The data collected has allowed us to determine the general nature of the groundwater in the vicinity of the cave. It has also shown that monitoring the wells provides insight into the general moisture conditions in the subsurface. While the water table monitored by the wells does not appear to be directly connected to the cave they do reflect the general ground moisture conditions which the cave is also experiencing. Continued monitoring of the wells provides an easy way of tracking the subsurface moisture conditions. A continued program of well monitoring will also provide information on long term changes in the surrounding water table. A general decline in the elevation of the water table may signal a corresponding drying trend in the cave. It will be important to be able to determine if changes in the cave microclimate are caused by external conditions or if they are caused by the development of the cave. It is recommended that wells be monitored on a monthly basis as more frequent monitoring appears to be unwarranted at this time. The continuous chart recorder installed on the North Well should be kept in operation.

The park should also take steps to reduce the hazard presented by several of the wells; i.e., the North Well, South Well and West Well. These wells have a large diameter and are close to ground level. Unsupervised children could easily fall into one and be unable to climb back out. It is recommended that secure, locked covers be installed on these wells.

RECOMMENDED ADDITIONAL WORK

ACPI recommends that a comprehensive groundwater investigation be undertaken to gain additional knowledge about the groundwater conditions on the park. This will be necessary if an on-site source of water is to be developed.

1. Contract with a qualified groundwater hydrologist to perform the following work. Each of the hydrogeologic units should be examined -- surficial alluvium, valley-fill

alluvium, Pinal Schist, and limestone sequence. For each unit, the following topics should be discussed:

- Lithology
- Groundwater flow: Occurrence, lateral extent, depth to piezometric surface, saturated thickness, direction of flow, hydraulic gradient.
- Aquifer parameters (hydraulic conductivity, transmissivity, storage coefficient), yield of wells.
- Recharge and discharge, relationship to adjacent hydrogeologic units.
- Water quality, susceptibility to contamination.
- Water supply well targets.

2. Register the North and Highway Wells with the Department of Water Resources.

3. Perform a pump test on the South Well. It is unlikely that this well would provide a sustainable yield, but if so, it would greatly simplify and lessen the cost of finding a park water supply.

4. Drill a monitor well into the limestone block. Depending on the results, drill a production well nearby and conduct a pump test to determine well yield and aquifer properties. The monitor well could be drilled on the south bank of Guindani Wash about 200-300 feet east of the trailer. This would test Lange's suggestion that the limestone fault block may extend south and southeast under the alluvium. If the well reaches the water table in limestone, a test production well could probably be drilled 100-200 feet further east along the south bank. If the monitor well hits schist, other possible limestone targets include a location just east of the exposed limestone bedrock north of Guindani Wash and a location centered in the weak trough (indicated by the 600' depth to bedrock contour on the geophysics interpretive map) near the highway - entrance road junction.

5. Drill a test well into the weak trough mentioned earlier about 1000 feet east of the South Well.

6. Deepen the Highway Well and test.

7. Drill a test well closer to the center of the trough near the 800' depth to bedrock contour, about 1000 feet northwest of the Highway Well.

SURFACE HYDROLOGY

Surface drainage bears an important relationship to maintaining the conditions within the cave. Kartchner Caverns is a moist cave where the unique formations are still actively forming. The moist interior of the cave is in marked contrast to the present arid surface environment. Moisture in the cave is in delicate balance with the input of water from the surface and natural drainage out of the cave.

Providing all-weather, year-round access to the park and cave is also an important consideration. Several washes cross the park and knowledge of the flow characteristics of these washes is important in locating park visitor facilities. Surface facilities built to serve visitors to the park should be located so as to minimize the damage potential from flooding and erosion.

The surface drainage study focuses on the identification of those surface drainage basins that discharge floodwaters onto the park, drainage basins on the park and the drainage that leaves the park. Once the drainage basins were identified, the peak runoff was estimated for a variety of return periods ranging from 2 years to 500 years. The ability of the existing structures and drainage channels to convey the 100-year flood was also investigated. The 100-year floodplain has been delineated for Guindani Wash, the major wash bisecting the park (Buecher, 1991).

DESCRIPTION OF SITE

The park is located on the east flanks of the Whetstone Mountains in Cochise County. The land slopes from the Whetstone Mountains to the west toward the San Pedro River, which is several miles to the east of the park. Much of the park is located on ancient alluvial fan terraces that slope to the east at 3% to 4%. Several low hills of limestone bedrock occupy the northwestern portion of the park. Kartchner Caverns is located in the southeastern-most hill. These hills have approximately 400 feet of vertical relief. The limestone hills are steep and sparsely vegetated. A significant portion of the surface is bare bedrock. The surface drainages impacting Kartchner Caverns State Park have their origins in the heart of the Whetstone Mountains.

The park is roughly bisected by a large wash, Guindani Canyon, which flows from west to east and is the largest drainage to enter the park. This wash appears to have remained close to the south side of the limestone hill with no meandering outside of a 500-foot-wide floodplain. Of particular importance to the cave is the location of the junction of Saddle Wash and Guindani Wash. The location of this junction appears to have shifted both upstream and downstream of its present location. Interestingly, the land to the south of Guindani slopes away from the wash.

Another large wash, Middle Canyon, flows parallel to the south boundary of the park, approximately 300 feet south of the southern park boundary. Middle Canyon exhibits a more pronounced meandering stream pattern than Guindani Canyon.

Drainage within the park can be divided into three categories: major washes that convey off-site drainage through the park, drainages on uniform alluvial fan terraces and drainages on steep limestone hills. Each of these categories has different physical and hydraulic characteristics.

Five major washes cross the park and convey off-site runoff through the park and collect runoff from the on-site drainage basins. These washes have well defined channels and, with the exception of Windmill Wash, exhibit little meandering or braided channels. Channel slopes are quite steep, generally between 3% and 4%.

These five washes are, from south to north, South Wash, Windmill Wash, Guindani Wash, North Wash, and Ricketts Wash.

DETERMINATION OF RUNOFF

Peak runoff rates for various return periods for each drainage area were evaluated by assessing the controlling parameters of each watershed, such as acreage, soil types, overall slope, impervious area and vegetative type and density (Table 26). The anticipated runoff from each watershed was determined by a modified Soil Conservation Service hydrologic procedure. This analytic approach has been accepted and is presently required in the analysis of all watersheds over two square miles in Pima County, Arizona. The modified version was designed by the Pima County Flood Control District but calibrated on watersheds near Tombstone, Arizona. This makes the modified version ideally suited to Kartchner Caverns State Park as the two sites are within the same major river valley. This process will calculate the quantity of water one can expect to flow in the drainageway in a 100-year event.

The peak discharges as estimated by the Pima County Method were used as the basis for all subsequent analysis. The 100-year flood was then used in the HEC-2 (Hydrologic Engineering Center) water surface profile computer program. This program can analyze the flow in any particular natural channel and model the runoff by use of cross-sections. This allows the 100-year floodplain to be delineated on a map for future guidance in the planning of the surface facilities of Kartchner Caverns State Park.

Detailed results of the HEC-2 computer program may be found in the Surface Drainage Report. The limits of the 100-year floodplain for Guindani Wash are shown in Figure 76 (in a back pocket). Average depth of flow is approximately six feet, increasing to over fifteen feet in the backwater pool of the highway box culvert. The average channel velocities are quite high, generally between 15 and 20 feet per second. Except for the box culvert backwater pool and Saddle Wash junction, the water surface slope is 3.82% with little deviation.

CAPACITIES OF EXISTING DRAINAGE STRUCTURES

Highway 90 was constructed along the present east boundary of the park in the late 1950's. Seven drainage structures were built adjacent to the park as part of the highway improvements. The capacities of these structures was investigated to determine both the impact on access to the park and possible flooding within the park due to water ponding at the inlets.

EROSION POTENTIAL

Several areas along the banks of Guindani Wash have been identified as having a significant bank erosion potential. These include channel sections where the banks are nearly vertical and show evidence of recent erosion. Typically, these sections are also located on the outside of stream meander bends. These areas should be avoided for any use; i.e., roads, trails etc. unless adequate bank protection is constructed.

EROSION SETBACKS FOR STRUCTURES

Erosion setbacks from major washes and drainages are recommended for the siting of permanent structures. Other improvements such as roadways, parking areas or trails may be placed within these areas if an adequate assessment of the erosion

TABLE 26
Summary of On-Site and Off-Site Runoff

POC*	Description	Area (Acres)	Lc** (ft)	Lca (ft)	Sc (ft/ft)	Nbw	Q2 (cfs)	Q10 (cfs)	Q100 (cfs)
A	Middle Canyon at Highway	2428.2	24500	13800	.061	.041	736.5	2493.5	5885.3
B	Adjacent to South Well	105.9	4600	2200	.091	.036	58.7	210.1	504.9
C1	At Post Windmill	104.6	6200	3200	.123	.038	70.3	220.7	497.3
D	Guindani Cyn at W. Boundary	2157.0	20250	12200	.106	.045	895.6	2704.5	6366.8
D1	Guindani Cyn + Cave Creek	2374.8	21500	12825	.099	.044	912.2	2866.8	6723.8
D2	Guindani entering box culvert	2473.0	26650	13500	.077	.042	787.5	2378.5	6104.5
D3	Guindani Cyn etc.at Highway	2822.8	27000	13500	.075	.042	870.6	2892.7	6932.6
E	Entering Park at W.Boundary	3.8	600	200	.083	.035	2.9	9.3	20.3
F	Entering Park at W.Boundary	172.4	5900	3000	.150	.038	115.7	366.7	851.2
G1	Entering Park at NW Corner	6.2	900	350	.414	.038	6.3	17.1	35.2
G2	Leaving Park along N.Bound.	15.8	1100	500	.496	.038	15.0	42.4	88.3
H1	Entering Park at N.Boundary	113.2	3300	1700	.177	.040	102.1	304.9	666.4
H2	Leaving Park at Guindani Box Clvrt	207.2	8100	4800	.055	.037	101.0	334.8	778.1
I	Entering Park at N.Boundary	29.9	900	500	.167	.040	42.0	96.2	183.6
J1	Entering Park along N.Boundary	205.4	10000	5900	.078	.040	102.8	333.7	779.1
J2	Leaving Park at Hwy 90	231.3	11700	6100	.065	.039	101.0	345.9	822.6
C2	Leaving Park at S.Prop.Line	119.4	7700	4200	.097	.037	65.7	222.1	524.3
a	Leaves Park in SW Corner	3.7	850	350	.040	.035	2.4	9.2	20.0
b	Leaves Park along S.Boundary	7.2	1550	730	.041	.035	3.8	15.9	38.4
c	Leaves Park along S.Boundary	2.9	800	250	.048	.035	2.1	7.0	15.3
d1	Leaves Park along S.Boundary	17.6	1950	950	.045	.035	9.1	37.2	90.1
d2	Extends from W.Bound.to Road	12.2	2250	1050	.035	.035	5.6	23.2	59.1
e	Leaves Park along S.Boundary	5.0	1150	400	.036	.035	2.9	11.7	26.8
f	Leaves Pk along Hw90 at Pipe Clvrt	29.0	3200	1450	.035	.035	11.6	49.9	126.8
g	Leaves Park along Hwy 90	0.9	300	100	.047	.035	0.7	2.2	4.8
h	Leaves Pk along Hw90 at Pipe Clvrt	13.1	1700	600	.039	.035	7.2	29.2	70.3
i	Leaves Pk along Hw90 at Pipe Clvrt	21.5	2800	1450	.035	.035	8.8	38.2	94.0
j	Leaves Pk along Hw90 at Pipe Clvrt	14.9	2200	1000	.039	.035	7.0	28.3	72.0
k	Drainage between N.Hill & Cave Hill	143.2	5650	2400	.053	.038	95.5	284.0	649.8
l	Leaves Pk at Hwy90 at Pipe Clvrt	3.6	770	250	.065	.035	2.7	8.9	19.3
m	Leaves Park at Hwy 90	4.8	750	250	.044	.035	3.5	11.9	25.9
n	Leaves Park at extreme NE Corner	2.1	850	350	.047	.035	1.4	5.2	11.3
o	Leaves Park along N.Boundary	5.4	800	350	.393	.040	7.6	17.5	33.4
p	Leaves Pk along W.Bound(#of Places	16.6	670	300	.372	.040	24.4	55.2	104.3
q	Comb. of Area E & F(Offsite Areas)	200.1	7250	3800	.111	.038	117.8	391.8	898.3
d2+f	Comb. of Area d2 and Area f	41.2	5050	2400	.036	.035	27.5	81.0	157.9
d1+d2	Comb. of Area d1 and Area d2	29.8	3500	1550	.040	.035	9.1	37.2	121.8

*Capital letters designate off-site drainage areas. Lower case letters designate on-site drainage areas.

**Lc = Length of drainage flow path.

Lca = Length to center of gravity of drainage area.

Sc = Equivalent slope of drainage area.

Nbw = Drainage basin Manning's Number weighted by area.

risk is made. Structures may be placed closer to the channels, if adequate bank protection is provided. These setbacks are recommended for the smaller washes on the park based on single point channel capacity. The recommended erosion setbacks are also illustrated in Figure 76. For other drainages that are not specifically delineated, a 50-foot setback is recommended.

SURFACE DRAINAGE IMPACTS ON THE CAVE

Water from two surface washes, Guindani Wash and Saddle Wash, have been found to be the source of the water which floods the back portions of the cave. Dye which has been injected into short segments of these streams reappears a short time later inside the cave. Any changes in land use within the Guindani Wash and Saddle Wash watersheds that would change the runoff characteristics will have an impact on the conditions within the cave. See Figure 72 for a map of the off-site drainage areas which impact the park.

Saddle Wash flows east along the south side of the limestone hills for 1800 feet until it joins with Guindani Wash. Upstream from the junction with Saddle Wash, Guindani has begun to shift its channel to the north and overflows into Saddle Wash in larger events. This will eventually move the confluence with Saddle Wash further to the west. As this section of Saddle Wash is a known water recharge area for the cave, a channel shift that brings more water from Guindani Wash closer to the limestone hill may have considerable impact on the periodic flooding of portions of the cave.

CONCLUSIONS

The size and hydraulic characteristics of both off-site and on-site drainage have been determined. Based on these parameters, the runoff for various return periods has been estimated. Hydraulic calculations using the estimated 100-year discharges were made to determine the flood-prone areas within the park and the adequacy of existing drainage structures at Highway 90. Field inspection of washes within the park, in conjunction with hydraulic calculations, were used to identify potential erosion areas and realistic setbacks for structures. The results of the analysis are summarized in Figure 76.

Additional recommendations are broken down into the following categories:

Conditions Which Affect the Caverns

- Two of the off-site drainage areas, Guindani Wash and Saddle Wash, are known to be hydraulically linked to portions of Kartchner Caverns. Portions of the runoff in these streams are diverted into the cave. Changes in the land use within these drainage areas that affect the quantity and quality of runoff will have an adverse impact on conditions within Kartchner Caverns. Increased amounts of runoff may result in more frequent and extensive flooding of the cave. Reduced amounts of runoff may decrease the moisture entering the cave and cause drying of the cave formations.
- The main Guindani Wash channel is shifting in the vicinity of the junction with Saddle Wash. This shift will move the junction further to the west. This may increase the amount of water entering the cave and the frequency of flooding.
- There is an old abandoned channel of Guindani Wash at the west property line, just north of the present-day channel. In large runoff events, this channel may act as an overflow channel. Potentially the overflow channel could recapture the

majority of the runoff. This would also have a significant impact on the frequency and severity of flooding in the cave.

Erosion Setbacks

- Bank erosion has been noted at several locations along Guindani Wash. Usually this erosion occurs on the south bank. The north bank of the wash adjacent to the limestone hills should experience little if any erosion. The south banks are more susceptible to erosion, particularly on the outsides of stream meander bends. However, it appears that Guindani Wash has not significantly meandered to the south in perhaps thousands of years. A geomorphology study should be performed to confirm this.
- Erosion setbacks from the larger washes are shown in Figure 76. Structures may be built closer to the wash if a detailed engineering study is performed to determine the need for bank protection. Additionally,there should be a 50-foot setback for any building from all drainages. Detailed hydrologic studies should be included in the design phase of the surface facilities.
- The alluvial terraces are susceptible to erosion where the surface has been disturbed and runoff is concentrated. Roadway alignments that are perpendicular to the slope of the land should be avoided wherever possible. Care should be taken in the discharging of roadway runoff without adequately reducing the velocity and dispersing the flow.

Flood Prone Areas

- The 100-year flood prone area along Guindani Wash has been delineated. The flow during the 100-year event is supercritical and the channel velocities are high.

- Windmill Wash. The whole drainage area C2 and "b" through the park should be considered as a flood-prone area due to the meandering nature of this wash. Shifts in the existing channel are likely and unpredictable. With adequate erosion protection and sufficiently high floor elevation, structures could be constructed in this area. A detailed hydrology study would be needed in conjunction with any buildings placed in this area. Roadways may be constructed in this area as long as sufficient protection is built to protect the road, such as cutoff walls. Care should be taken in designing any roadway to minimize the impact on the existing drainage pattern and diverting runoff along the road.
- Structures and entryways to the cave should have finished floor elevations at least one foot above the 100-year flood water surface elevation.
- For facilities located south of it, Guindani Wash is a major barrier, limiting all-weather access to the cave. Depending on the degree of access desired to the cave entrance, an expensive drainage structure may be required.

Existing Drainage Structures

- The existing drainage structures under Highway 90 generally do not affect conditions within the park to a significant extent with two exceptions.
- The box culvert at Highway 90 and Guindani Wash is undersized for the 100-year storm. During a 100-year storm, water will overtop the highway. Potentially the embankment at the box culvert could fail during the 100-year flood.

- The small 18 inch CMP culvert located just south of the dirt road onto the site has insufficient capacity for all but the smallest storms. If this road is developed as the primary access point for the park, the capacity of this pipe will need to be upgraded. The frequent local flooding of Highway 90 at this point will be a nuisance and safety hazard to vehicles entering and leaving the park.

Middle Canyon.

- This drainage falls outside the park boundaries but is adjacent to the south boundary of the park. There is insufficient topographic data available to adequately investigate the impact it will have on the park. However, this wash appears to have a meandering channel and shifts in the channel could result in flooding on the park. An additional study of Middle Canyon may be necessary if facilities or roads are constructed along the south boundary of the park.

BIOLOGICAL INVENTORY OF KARTCHNER CAVERNS

The results of the biological inventory of life in the cave is provided under this section. The inventory includes an identification of the species and population estimates of the bats that inhabit the cave in the summer and other small vertebrates and invertebrates that can use the cave throughout the year. The ecological role of each species has been investigated before development begins. The ecology of the cave approaches that of a closed system. With development may come alterations in the types and quantities of food available, the cave microclimate, and potential competition with outside species. **Changes in the population of cave species may indicate possible changes in other aspects of the cave environment; cave biota constitute a sensitive, indigenous monitoring system.** The four groups of organisms which are a management concern during cave development are:

A) Bats
B) Invertebrates
C) Plant and algae growth in the cave
D) Other small vertebrates

A BASELINE STUDY OF BATS AT KARTCHNER CAVERNS

INTRODUCTION

The purpose of this study was to obtain a biological inventory of bats at baseline level prior to the development of Kartchner Caverns. The acquisition of such data before the population has been impacted by much major disturbance provides a vehicle to study the effects of future activities on the population. This purpose has been paramount in the activities carried out thus far concerning bats at Kartchner Caverns State Park.

Among its many other values, Kartchner Caverns is important because it is a natural refuge for a large colony of bats. From May to mid-September of each year, the cave is home to 1000 to 2000 Myotis velifer, a species of insectivorous bat. These bats, primarily pregnant females , return each year to Kartchner Caverns to rear their young. These bats provide an important link between the ecosystem of the cave and the surface. The bat guano introduces a rich food source for Kartchner's cave limited organisms. During the summer, bats are usually found roosting together in a small cluster on the ceiling of the Big Room. Accumulations of bat guano in other parts of the Big Room indicate that they may occasionally use different parts of the room. There is no indication that bats presently use any other part of the cave.

The importance of the bats to Kartchner Caverns State Park is three-fold. For Arizona State Parks, they are an exciting educational experience for the park visitor. The public has become increasingly aware of the many benefits provided by this often misunderstood animal. Cave parks such as Carlsbad Caverns fill an amphitheater on summer evenings for a natural history talk about bats during the bats' nightly emergence. The bats also act as a natural insecticide for the park property. A conservative estimate indicates that the bats roosting in Kartchner devour approximately one-half ton of insects every summer. The third benefit of a healthy bat roost within Kartchner Caverns is its introduction of excrement (guano) below the

roost. This bat guano is the primary source of food for the permanent organisms in the cave and is an unusually rich source of food for those obligate residents. These invertebrates are sensitive indicators of the conditions in the cave. The uniquely cave-adapted organisms utilize the bat guano in different ways but all depend on it for their survival. A loss of the bat roost would cause a collapse in the entire cave ecosystem and the destruction of a healthy cave environment.

All activities which take place within the vicinity of the Big Room when bats are present are potential sources of disturbance to the bats. Bats are extremely sensitive to disturbance and will abandon a roost if they feel threatened there. Variation between populations of the same species makes it difficult to predict just how much disturbance a colony will tolerate before abandoning a site. A period during which there is no question that the population will suffer reproductive loss is during the parturition (birth) event. It is essential that females have a time of non-disturbance following birth during which they imprint on the smell and sounds of their own young. If disturbed prior to this bonding, the female will not even know her offspring and therefore will not attempt to care for it. Another danger is disturbance in the maternity roost before the young can fly. Female bats will attempt to move their young to safer areas and higher mortality can result. The temperature, humidity and other conditions on the ceiling of the Big Room are, for some reason, important enough to the females that they will fly through small tortuous passages to reach it.

Bats have particularly good hearing and can sense intrusion into their roost just from the sound of movement through the cave. As a result, tours will have to be carefully designed to avoid driving the bats from Kartchner Caverns. Options for maintaining the bat population after development are to restrict visitor use of the Big Room while bats are present or attempt to entice the bats to use another portion of the cave. It should be noted, however, that the literature does not support the second option. We do not totally understand what conditions bats need in their roost and relocation has not been generally successful in the past. In Arizona there are very few known bat roosts in caves, especially with this many individuals. The bats are a valuable resource to be protected because serious bat populations declines have been documented throughout Arizona during the last twenty years. Arizona State Parks has a wonderful opportunity to utilize this facet of a unique cave. The interpretive possibilities of incorporating the bats into the whole cave development outweigh the problems of working around the bats.

METHODS

At this point, we have garnered information about the bats with minimal disturbance to the population and only little disturbance to some individuals. Our goal of minimal disturbance to the bats at Kartchner Cavern State Park has been paramount in the activities carried out thus far, in order to obtain information as close as possible to baseline. For species of bat which are readily identifiable at a distance, low-disturbance techniques achieve identification with high confidence. This has been the case with our observations of Plecotus townsendii and Choeronycteris mexicana which occur in small numbers in outer areas of the cavern. On the other hand, a species of Myotis is not so easily identified, and other measures must be employed. We have not attempted to net bats within the cavern because of the potential risks that disturbance within a roost can cause. Fortunately, it has been possible to patiently

gather much evidence with other low-disturbance techniques to identify the bats in residence. During the study, trips into the cave during the summer were greatly reduced or taken during the night while the bats were out of the cave feeding. Head lamps, with red filters, were used whenever work was performed near the bat roost.

Additional low-disturbance techniques have included examination of bone material and carcasses inside the cavern for species identification. Only a couple of isolated bats have been handled within the cavern for species identification. Information on the areas of the cave used by the bats can be determined by noting changes in the guano piles after bats have exited at night . The presence and number of non-volant juveniles has been determined by photographing the juvenile cluster after adults have exited at night. Bats have been netted outside of the cave and away from the roost in order to determine events in the reproductive cycle of the population. Captured animals have been banded and reflective tape placed over the tag. Subsequent observations of reflective tags on bats flying from the entrance during the evening exit flight confirms that these animals come from Kartchner Caverns. Using these techniques a number of bat species have been identified from the interior of Kartchner Caverns. These identifications are based upon observations of live bats and collection of preserved material.

The number of bats using the cave has been estimated by careful counts of individuals during the exit flight. Due to the constricted passages near the entrance, bats are forced to leave in small groups which are easily counted. The results of numerous counts made in past four years is shown in Figures 77 to 80, individual counts are found in Appendix O. The counts of exiting bats are our best estimate of the population size of bats using the interior cavern. For various reasons, we assume these are Myotis velifer. The entrance sinkhole forms an ideal location to observe the exit flight. An observer in the bottom of the sinkhole, sitting against the north wall, is out of the direct flight path of the bats but has an excellent view of them silhouetted against the sky. Most of the counts of exiting bats were recorded with a computer counting system (graphs of individual counts are included in Appendix O). The time at which each bat leaves the sinkhole is recorded to the nearest second. Bats which re-enter the sinkhole can similarly be subtracted from the total. These counts were primarily taken by Debbie Buecher, Bob Buecher, and Ronnie Sidner, along with various volunteers. Some training and experience is needed to acquire the observational skills that result in the most precise counts under the conditions within the sinkhole.

In addition, in 1990 and 1991 infrared light goggles with an external source of infrared light were used while sitting inside the Blockade Room to observe bats exiting through the small opening named the "bat window." The use of infrared light and goggles to watch bats departing through the small "bat window" provided an opportunity to count the bats one at a time without repeating counts of individuals. An observer counting in the sinkhole can repeatedly make this error under poor light or inclement weather conditions when bats circle unseen or return into the cave. The sinkhole opening is large enough that individual bats can occasionally miss detection by the observer when they do not pass through the line of sight or are not backlit well. Continued use of artificial optical devices should increase the accuracy of bat counts.

Nets were set at the cattle tank located just outside the southwest corner of Park property, and nets also were set south of the opening to the cavern sinkhole within the

fenced enclosure. We banded all Myotis velifer that were captured, and initiated the use of different colors of reflective tape on bands to denote sex of these bats.

Much information can be gained about the areas of the cave being utilized by the bats by simply examining the piles of bat droppings (guano) below the bat roost. The locations of guano piles provide information on the areas of the cave which have been inhabited by the bats. The size and condition of the piles give qualitative information about the population size or length of use. The amount of activity can be found by draping a fine mesh nylon netting over the guano piles. Fresh bat droppings remain on top of the netting and allow active roost sites to be identified and a rough estimate of the bat population to be made. The advantage of this system is the ability to inventory the guano piles after the evening bat flight. It indicates which sites are active without entering the roost when the bats are present. The open weave of the netting allows the guano pile to "breath" and should not impact the invertebrates living in the bat guano. As larger numbers of bats congregate over a single pile, the amount and types of visible mold changes. Studies of the invertebrates living in the guano pile also provide an indication as to the frequency of use by the bats.

OBSERVATIONS OF BATS

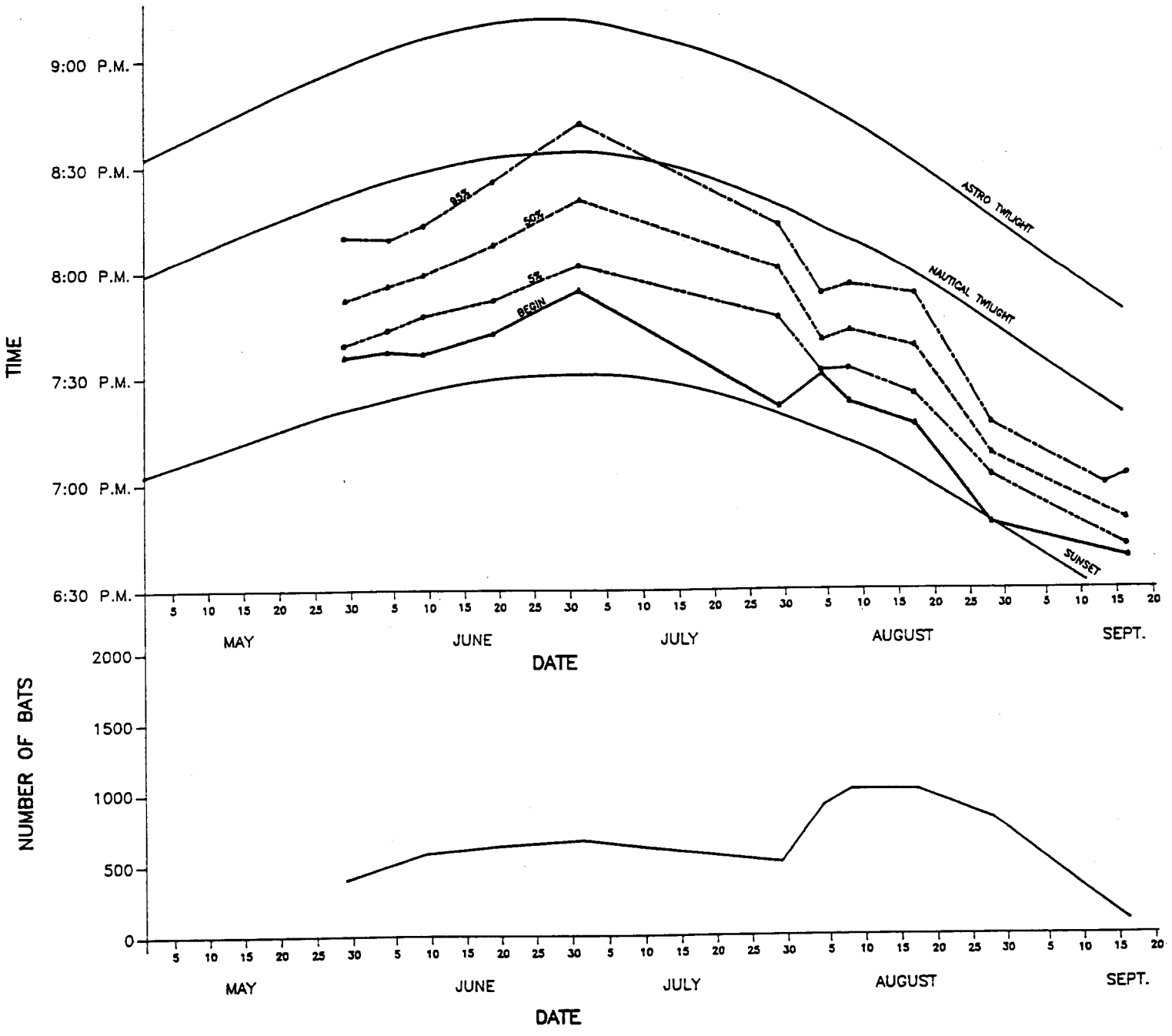
1988 Fieldwork

Studies of the bats were carried out by volunteers in 1988, and the information collected has been made available for the present study. No work was conducted inside the cave during this year. A program of monitoring the number of bats exiting the cave in the evening was started in 1988. Bat counts were made on 12 nights through the summer. The first count was on May 28, when 393 bats were counted. Apparently bats had returned to the cave at an earlier date but had gone unnoticed because of a ban on trips into the cave during the summer of 1988. The number of bats remained relatively stable at approximately 600 bats until the end of July. During the first week of August the number of bats increase sharply. The peak number of bats counted was 1303 on August 6. The number of bats remained high for about two weeks and then began to decline during the last week of August. The last count was 21 bats on September 16. Information on the numbers of bats observed and characteristics of the bats flights are presented in Figure 77.

Bats were netted at the southwest cattle tank adjacent to the park. A total of 21 Myotis velifer bats were captured and banded. These consisted of 3 males and 18 females. Reflective tape was placed on some of the bands. This allows banded bats to be identified when a light reflects off the tape. During the evening exit flight on 2 August 1988, we observed five reflective tags on the bands of exiting bats which we had placed on Myotis velifer netted at the cattle tank on 30 July 1988. This confirmed that at least some of the bats using Kartchner Caverns were Myotis velifer.

1989 Fieldwork

Initial contract work on the bats in Kartchner Caverns began during the winter of 1989. Several trips were taken into the cave to search and collect bat bones. These bones have been identified and the bat species are listed in Table 28. The locations and general condition of bat guano piles in the front section of the cave were noted. Netting was placed over guano piles which appeared to have been active in the past.



ASTRO TWILIGHT = 6.0×10^{-5} FOOT-CANDLES
NAUTICAL TWILIGHT = 7.7×10^{-4} FOOT-CANDLES
SUNSET = 42 FOOT-CANDLES

KARTCHNER CAVERNS BAT FLIGHT

1988

FIGURE 77

Few bats were observed during this time. A single Plecotus townsendii was repeatedly observed hanging in the Crinoid, Anticipation and Blockade Rooms from March until July. Plecotus townsendii were also observed in the Archeo Site Cave by Dick Ferdon in February. The five Plecotus were seen a few days later roosting in the small, south cave near Guindani Wash.

Bats were first observed in the Big Room of the cave on April 23, 1989 when six were seen near the Bacon Rind Trail. Initially bats roosted near the Bacon Rind trail in the Big Room. By early May the numbers had increased to 400 and then dropped off to less than 100 during the middle of May. At the end of May the numbers again began to increase, reaching approximately 900 by the middle of June. The bat population remained relatively stable through the middle of July and then began rising once again. The peak number of bats counted was 1804 on August 11 and again on August 13. After the brief peak, the number of bats declined at a steady rate. The last exit flight count was on September 6 when 43 bats were observed. A total of 35 bat exit flight counts were made in 1989. Information on the numbers of bats observed and characteristics of the bats flights are presented in Figure 78.

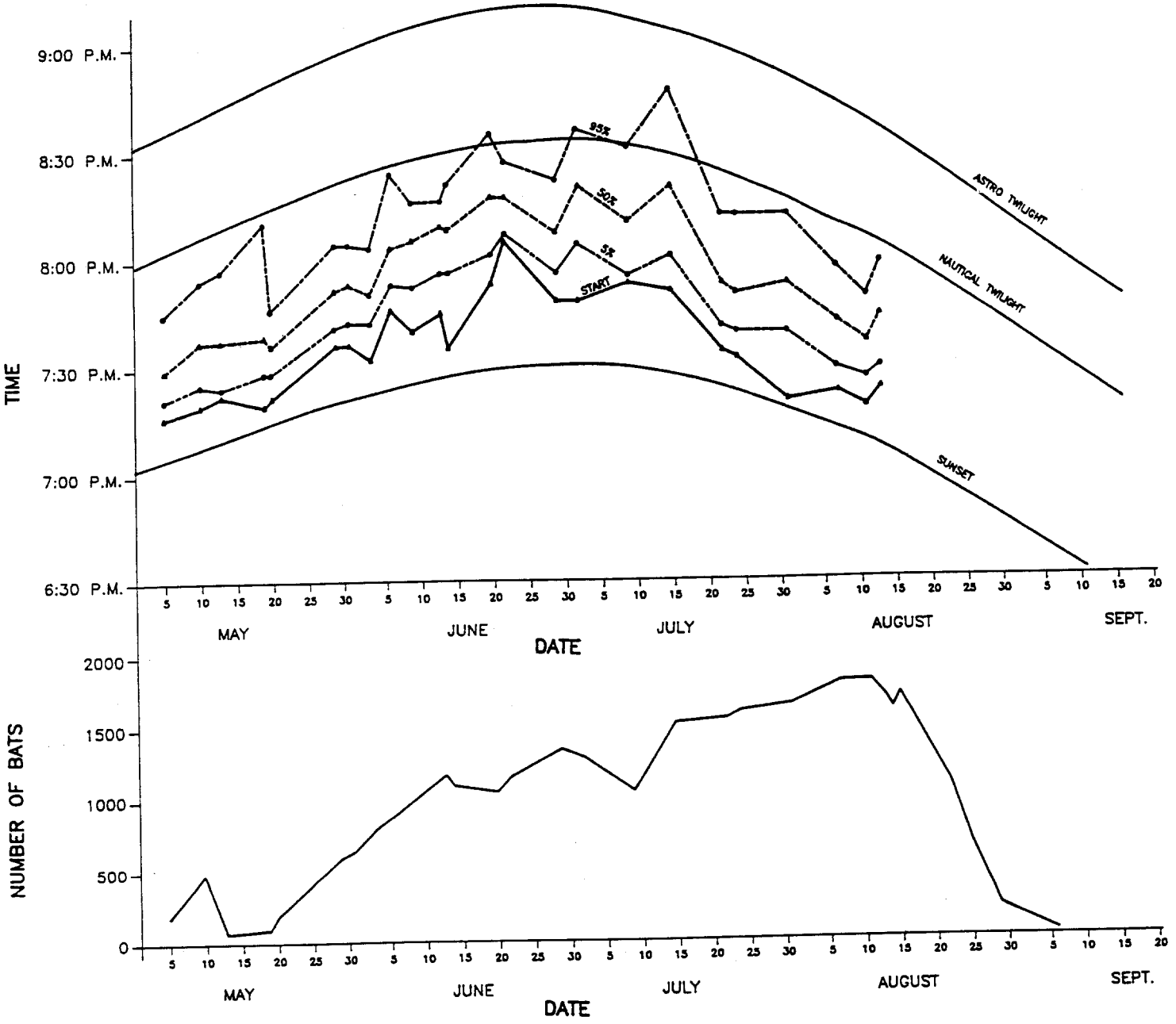
Additional evidence which further indicates that Myotis velifer bats are the primary species of bat using the cave was found in 1989. On 14 June 1989, two solitary female Myotis velifer were captured and identified on the wall of the Anticipation Room. A bat photographed while it exited through the "Blow Hole" on 10 May 1989 was a Myotis velifer.

During the summer of 1989 bats were netted at the southwest water tank on 6 separate nights. On March 24, no bats were captured. On April 9, two bats were captured, one of which was a Myotis velifer. On June 3, 18 bats were captured, 17 of these were Myotis velifer. Of these, 10 were pregnant (59%) - see Figure 81, 2 were non pregnant females and 5 were males. On June 23, 3 bats were captured: two were Myotis velifer (one of which was pregnant). On July 20, 27 bats were caught: of these, 23 were Myotis velifer. Fifteen of the bats were lactating females (65%), 4 were non-reproductive females, 3 were males and one was a juvenile male. On August 15, 11 bats were captured, all were Myotis velifer. Of these, 4 were juveniles, 6 were post-lactating females (55%) and one was a non-reproductive female. Nets were set for a total of 43 hours and 61 bats were captured (54 Myotis velifer) for a capture rate of 1.4 bats per hour. Six different species were captured. Fifty-three Myotis velifer were banded, 42 females and 11 males.

On July 9, a cluster of juvenile bats was photographed on the ceiling above Sharon's Saddle after the adults had left the cave to feed. Examination of the photograph shows that the cluster was comprised of 4 adults, 125 grey juveniles and 17 pink juveniles for a total of 142 immature bats.

A sequence of reproductive characteristics were documented among the Myotis velifer netted at the cattle tank from 3 June to 15 July 1989 which corresponded with maternity events occurring in the cave.

Choeronycteris mexicana (nectar feeding bat) were observed in the entrance passage above the Blockade Room in May and September and also in the Archeo Site Cave in September.



ASTRO TWILIGHT = 6.0×10^{-5} FOOT-CANDLES
NAUTICAL TWILIGHT = 7.7×10^{-4} FOOT-CANDLES
SUNSET = 42 FOOT-CANDLES

KARTCHNER CAVERNS BAT FLIGHTS
1989

FIGURE 78

1990 Fieldwork

Skeletal material was collected on January 31 from Main Corridor, Guano pile #20, Guano pile 9c and the floor beyond Kartchner Towers. All of the specimens were identified as Myotis velifer.

Plecotus townsendii was observed numerous times hanging in the Crinoid Room in March and April. One Choeronycteris mexicana was observed in the Archeo Site Cave on the north side of the hill on August, 29, 1990.

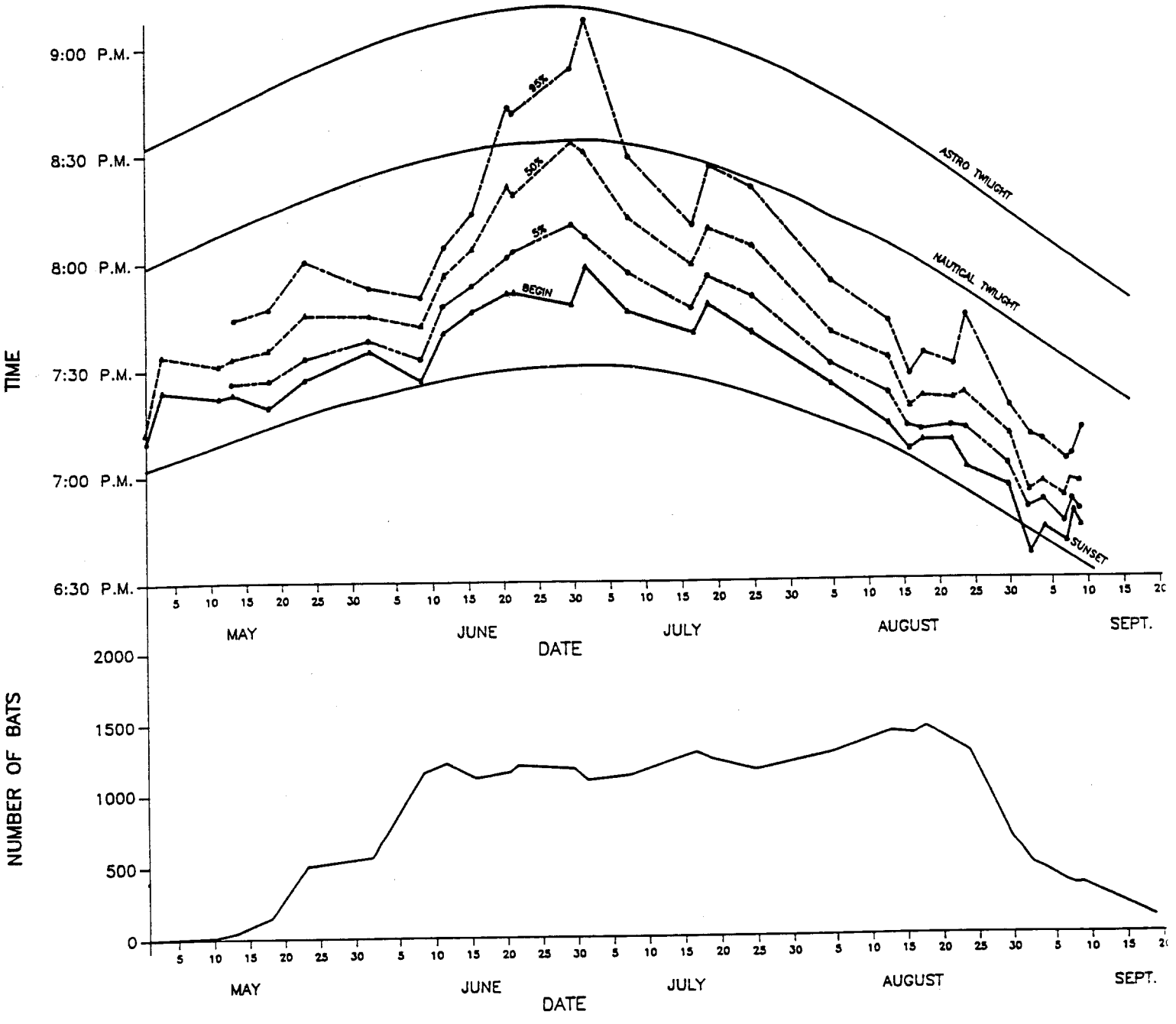
In early May a BCI Bat house was installed on a 10 foot pole near the main bat roost over Sharon's Saddle to see if it would be used if available. Installation of the bat house in proximity to a favored roosting site was an attempt to see if these bats could be coaxed into using an artificial structure under their preferred conditions, with the idea that it might be possible to relocate the bats at some point. While its presence did not appear to disturb the bats (i.e., they returned to this area), they apparently did not use the house with any regularity. It should be left in place for a longer period, however, before being considered ineffective. A temperature probe was also installed and hooked up to the data logger. This allowed us to determine if the bat house was being used from the temperature record. Apparently the bats never used the bat house. We felt that the reason bats did not use the house was that it was much lower than the ceiling and also was attached to a pole which might interfere with flying.

A total of 36 bat exit counts were made in the sinkhole. Bats were first counted on April 25, 1990 when four were seen. The number of bats increased at a steady rate through May and early June. By the middle of June the population had stabilized at approximately 1100 bats and remained at this level until early August. In early August the number of bats increased slightly. The peak number of bats counted was 1493 on August 17. After the peak, the number of bats steadily decreased. The last exit flight count was on September 19 when 121 bats were observed. Information on the numbers of bats observed and characteristics of the bats flights are presented in Figure 79.

Bats were netted at both the southwest cattle tank and outside of the Kartchner sinkhole on a total of four nights. A total of 21 bats were caught in the nets this year, which included 3 different species of bat.. A majority of the bats (19) were Myotis velifer. Bats were caught at a rate of 1.5 per hour. Nets set at the southwest cattle tank for two nights yielded only three different bat species, and the capture rate dropped to 0.25 bat/hour. On June 29th 2 bats were caught, one of which was a Myotis velifer. On July 24, three bats were netted at the cattle tank, two of these were Myotis velifer.

Netting outside the cavern sinkhole on 3 May and 6 September provided additional evidence that the exiting bats that are counted are most likely Myotis velifer, because that is the only species we caught there, one Myotis velifer in May and 15 in September.

The Myotis velifer which were caught this year were banded, and reflective tape was put on the bands. A system was initiated to make determination of males and females possible at a later date without handling the animals by observing the reflective tags. In previous years white reflective tape was put on the bands of 19 bats, and because 16 of these were females, it was decided that white would be used for females hereafter. Red tape was placed on the bands of males.



KARTCHNER CAVERNS BAT FLIGHT

1990

ASTRO TWILIGHT = 6.0×10^{-5} FOOT-CANDLES

NAUTICAL TWILIGHT = 7.7×10^{-4} FOOT-CANDLES

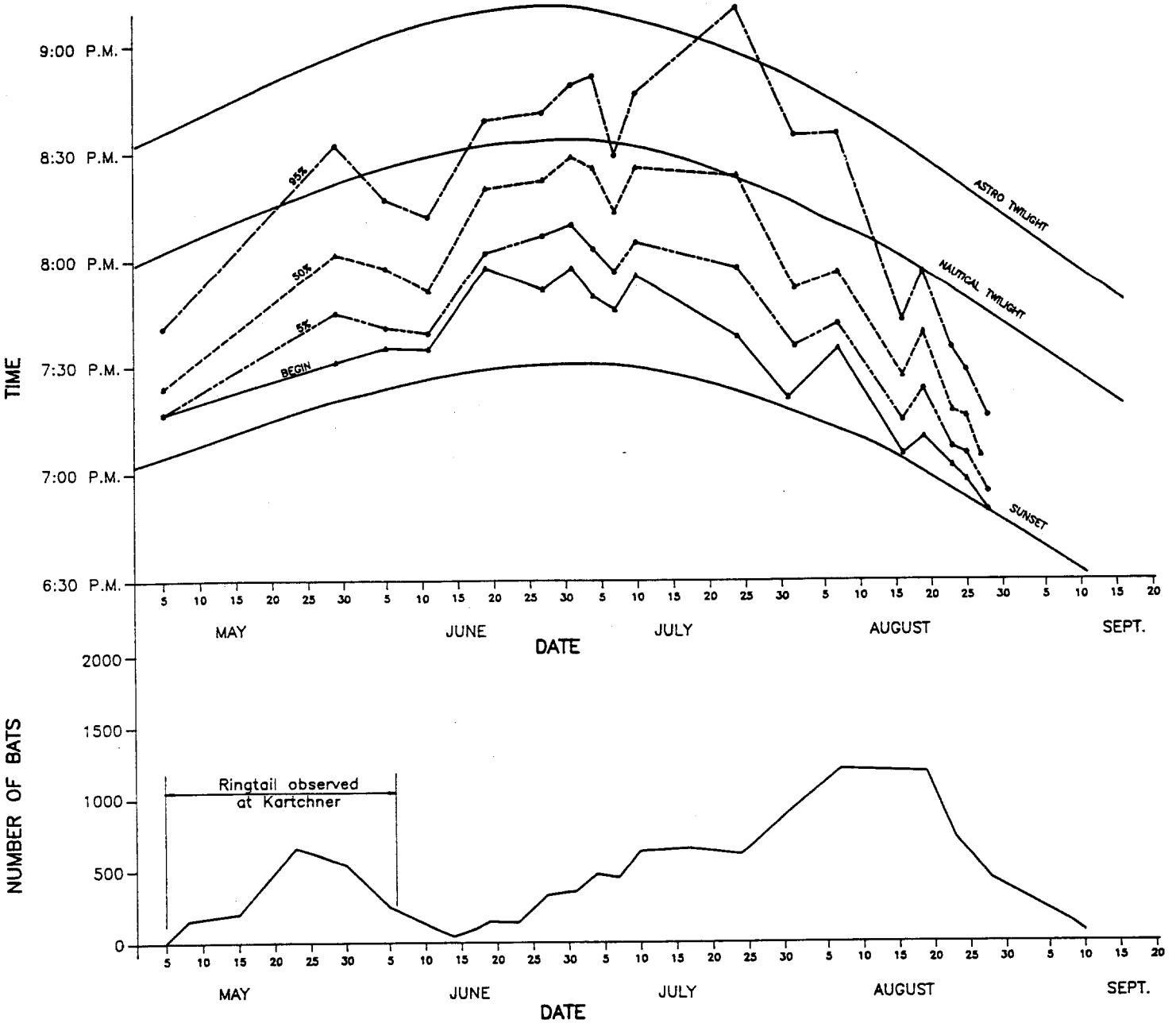
SUNSET = 42 FOOT-CANDLES

FIGURE 79

The first juveniles may have appeared as early as June 21, when three gray juveniles were observed on the ceiling above Guano pile #9C. This is quite early to observe juveniles that are this well developed. Juveniles were definitely present on July 1, when a cluster of juveniles was photographed on the ceiling. Later examination of the photograph shows approximately 43 juveniles ranging from small newborn pinkies to advanced grey juveniles. On 16 July, a juvenile cluster was observed on the ceiling above the undisturbed floor beyond Kartchner Towers and the Bishop. Because of the distance, it was difficult to see this cluster well; it was not possible to discern differences between pink (younger) and gray (older) juveniles, nor was it easy to count individuals. The cluster was estimated to contain perhaps 100 juveniles. Comparison of these maternity events in 1990 with those in 1989 shows roughly the same maternity period. But parturition (birth) may have been initiated earlier in 1990.

1991 Fieldwork

Bat counts in the Kartchner Caverns entrance sinkhole were continued this year and counts were made on 39 evenings. The first count was on April 25 when 4 bats were counted leaving the cave. The number of bats rose to a peak of 663 on May 23. At this time the exit flights became delayed, sporadic and total numbers of bats declined. On June 4, the carcasses of 45 dead bats were found in the "Bat window" above the steel gate in the Blockade Room. These were removed from the cave to determine the cause of death. Observers counting bats on the next couple of nights observed a ringtail cat (Bassariscas astutus) leaving the cave. Apparently this animal was responsible for killing the bats. In prior years, ringtail cats had been observed in the entrance sinkhole several times. They would apparently try to catch bats as they flew through the "Bat Window". No dead bats or other remains were found to indicate whether they had been successful in catching bats. The dead bats found in early June were unusual in that only one or two showed any indication that the ringtail had attempted to eat the bats. The ringtail cat was last seen in the cave on June 6. No additional dead bats were found in the cave but the numbers of bats continued to fall. The bat population reached a minimum on June 14 when 49 bats were counted leaving the cave. The rapid decline in the number of bats using the cave illustrates how quickly the bat population is impacted by external events. Similar declines could be cause by rockfall which could block the "Bat window" or the return of other predators. The number of bats slowly increased for the next six weeks as bats apparently returned to the cave. By the beginning of July the population had reached 400. This may indicate that Kartchner Caverns is superior to any other nearby roost. In late July the number of bats began to increase. The peak number of bats observed was 1210 on August 7 and remained high for about two weeks. The number of bats declined through the last part of August and the last count was made on September 10 when 81 bats were counted. Information on the numbers of bats observed and characteristics of the 1991 bats flights are presented in Figure 80, graphs of the individual counts are shown in Appendix O. The total usage of the cave by bats during 1991 was 61,700 bat-days, the lowest of the four years of record. The peak number of bats was also the lowest of the four years but roughly the same as in 1988 (only 12 counts were made in 1988 and the peak and overall usage may be underestimated).



ASTRO TWILIGHT = 6.0×10^{-5} FOOT-CANDLES

NAUTICAL TWILIGHT = 7.7×10^{-4} FOOT-CANDLES

SUNSET = 42 FOOT-CANDLES

KARTCHNER CAVERNS BAT FLIGHTS

1991

FIGURE 80

On July 4, a cluster of juveniles was photographed on the ceiling above Sharon's Saddle. Examination of the photograph shows that the cluster contains approximately 80 juveniles, including small pinkies, and medium-sized to advanced-looking gray juveniles on this date; see Figure 82. This photograph also shows one adult bat with a metal band visible. Also visible is an adult carrying her baby to a place of safety to avoid the disturbance caused by our presence.

In the spring of 1991 the original bat house was removed and two new ones were installed on the ceiling near the roost site. One of these was a new BCI wooden bat house similar to the one previously installed. The second bat house was constructed from two large plastic flower pots, nested together and hung upside down. A temperature probe was installed in the BCI bat house. Both bat houses were washed with a mixture of water and bat guano from the cave to provide a familiar "lived in odor". Preliminary results indicate that neither of these bat houses were occupied during the summer of 1991. A third bat house was placed on the ceiling of the Crinoid Room. This location is quite close to the entrance to the cave but is relatively cool. A piece of netting was placed on the floor below the bat house to catch bat guano and provide an indication if it had been used. There was no evidence that bats ever attempted to use this bat house during 1991. This indicates that it is unlikely that attempts to relocate the bats to other areas of the cave would be successful.

A total of 57 bats were netted at the entrance sinkhole on August, 16 and 17, 1991 were all of these were Myotis velifer.

Bats were also observed in several of the other small caves on the park. Species of bats, other than Myotis velifer, were usually seen near the cavern entrance. For example, Plecotus townsendii and "non-velifer" Myotis species (and Choeronycteris mexicana in previous years) were observed in the sinkhole or Crinoid Rooms only. Presumably a few Choeronycteris mexicana were seen in the small caves on the north side of the hill (the Archeo-site).

RESULTS

The differences and changes in population size (Figures 77 to 80) between 1989 and 1991 may represent a range of normal changes from year to year. On the other hand, large differences from year to year may signal a problem. If the population varies naturally in size as we have recorded it in just four years, then the years with low peak populations (1988 and 1991) may not be cause for alarm, because the peak in 1990 is higher than the peak observed in 1988. A continued downward trend that extends for two or more years would raise concerns about the stability of the bat population.

In interpreting the results of the bat counts, two aspects of each years' work must be considered. First, the peak numbers of bats observed is only approximate. Because the peak occurs over a relatively brief period of a few days, the actual peak may have been missed between counts. The accuracy of the counts also decreases at higher numbers when many bats may leave simultaneously. Also, the bats at Kartchner are not an isolated population, there appears to be some movement of bats to and from other unknown roosts. Observed increases may represent a growth in population or simply the movement of bats between roosts. A second, and perhaps better interpretation, can be based on the overall pattern of bat usage. This can be seen in the similar shape of the graph formed by the individual counts. Total usage of the cave

Figure 81. A pregnant Myotis velifer captured at the cattle tank.

Figure 82. A nursery cluster of immature Myotis velifer bats on the ceiling of the Big Room. Note that one adult (left side of photo) has an identification band and another is fleeing with its young.

can be measured as the area under the curve, this has the units of bat-days. Because the overall pattern is based on many counts, the chances for a few anomalous observations distorting the interpretation is much less.

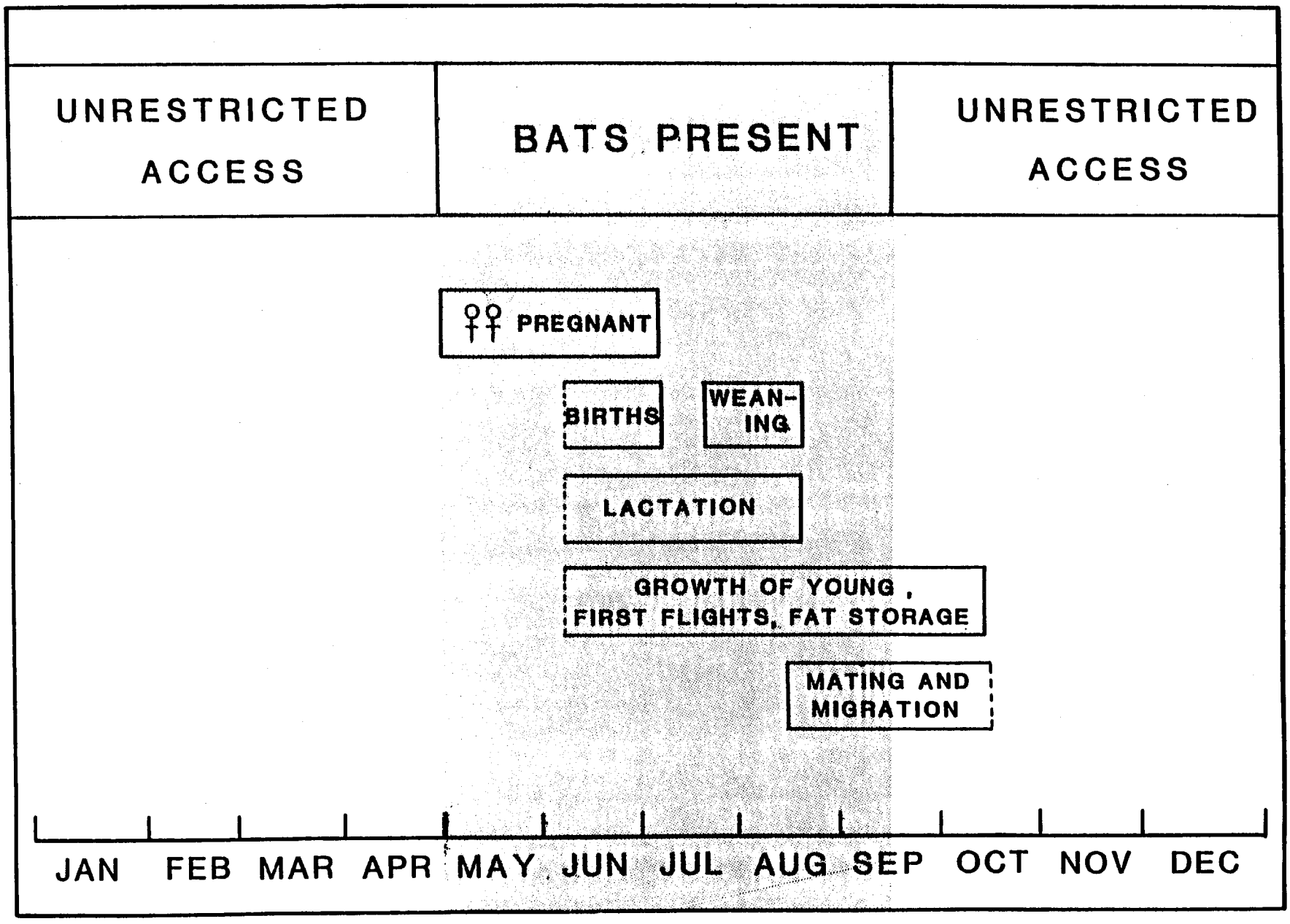
Information regarding the reproductive cycle of M. velifer was obtained during the netting effort at the cattle tank where pregnant , lactating and post lactating bats were caught at different times of the summer. By combining this information with observations of juvenile bats from inside the cavern, we are able to estimate the period of pregnancy, lactation, and juvenile growth of M. velifer at Kartchner Cavern; see Figure 83. This was all accomplished with minimal disturbance to the bat population.

The bat species netted or observed at Kartchner Caverns during the summers of 1988 through 1991 are summarized in Tables 27 and 28. Although the Myotis velifer is the only species that utilizes the cave in large numbers, the other bats use the park to forage or roost in other small caves on the park.

TABLE 27
Bat Species Netted or Observed on the Surface at Kartchner Caverns State Park

Bat Species	Primary Food
Myotis velifer (Cave Bat)	insects
Myotis thysanodes (Fringed Myotis)	insects
Eptesicus fuscus (Big Brown Bat)	insects
Myotis californicus (California Myotis)	insects
Myotis ciliolabrum (Western Small-footed Myotis)	insects
Antrozous pallidus (Pallid Bat)	insects
Plecotus townsendii (Townsend's Big-eared Bat)	insects
Leptonycteris sanbornii (Sanborn's Long-nosed Bat)	nectar/pollen
Choeronycteris mexicana (Mexican Long-tongued Bat)	nectar/pollen

The majority of bats using Kartchner Caverns during the summer months are Myotis velifer. During this study a total of 118 bats were either netted immediately outside of the sinkhole or carcasses were recovered from the cave. All of these bats were Myotis velifer, no other species has been caught. Myotis velifer represent the overwhelming majority of bats found at the cave but occasionally other species have been observed or skeletal material recovered, see Table 28. There have been several sightings of Plecotus townsendii and Choeronycteris mexicana in the sinkhole and entrance passages.



SUMMER BAT ROOST TIMETABLE

FIGURE 83

Arizona Conservation Projects, Inc. 1992

TABLE 28
Bat Species From the Interior of Kartchner Caverns

Bat species identified from the interior of Kartchner Caverns with locations indicated for each. These data are based upon observations of live bats and collection of preserved material. (Identifications by R. Sidner unless otherwise noted.)

Live bats observed.

Myotis spp.
- 23 Apr 1989, Bacon Rind
- 31 May 1989, Sharon's Saddle
- 14 June 1989, Anticipation Room
- 2 July 1989, (Juveniles), Sharon's Saddle
- 9 July 1989, Crinoid Room

Myotis velifer
- 7 July 1985, Big Room?: G.S. Mills
- 2 Aug 1988, Sinkhole
- 10 May 1989, LEM Room
- 10 May 1989, Blowhole, photo by B. Buecher
- 9 July 1989, Crinoid Room

Plecotus townsendii
- 11 Mar 1989, Anticipation Room
- 19 May 1989, Sinkhole

Choeronycteris mexicana
- ? 7 July 1985, near entrance?: G.S. Mills
- 7 Sep 1987, flying out of Sinkhole, photo by G. Kartchner
- 31 May 1989, Sinkhole

"small bat" species (small Myotis spp. or Pipistrellus)
- 19 May 1989, Sinkhole

From identified bone specimens. (Located by R. Sidner, D. Buecher, B. Buecher, T. Strong, C. Aley, C. Welbourn)

Myotis spp.
- Crinoid Room, Main Corridor, Echo Passage/Cul-de-Sac, Big Room floor

Myotis velifer
- Anticipation Room, Main Corridor, Bacon Rind, Big Room floor

Myotis occultus
- Echo Passage/Cul-de-Sac, Big Room floor, Sharon's Saddle

Leptonycteris sanborni
- Crinoid Room

vespertilionid bat bones
- Crinoid Room, Anticipation Room, Main Corridor

Poor netting results at the southwest water tank in 1990 most likely reflect the changes caused by its repair; it contained very little water and different odors during 1990. If the Myotis velifer and other species were using the tank for drinking water, it did not provide the same quality and quantity as before. If they were using it as a place over which to forage, the changed water level and substances used for repair may well have caused changes in insect abundance and composition. If the tank continues in this condition, other water tanks in the vicinity should be monitored.

It is possible that at any point in time, individuals of any of the species which were netted at the cattle tank could use Kartchner Caverns or any of the other small caves on the park for temporary roost use. In addition, these bats may be foraging over the Park property. This means that they would be consuming different kinds of insects or pollinating certain plants while obtaining nectar.

The only endangered species occurring in our state at this time is Sanborn's Long-nosed Bat, Leptonycteris sanborni. Only one bone has been located in the cavern (Crinoid Room) that is identifiable to Leptonycteris sanborni, a nectar-feeding bat with endangered (federal) species status. It is possible that Leptonycteris occasionally use the outer portions of the cavern like the other nectar feeder, Choeronycteris mexicana, but no live Leptonycteris have been observed in the cavern. We have netted a Leptonycteris at the cattle tank, suggesting that they forage on the Park property.

Based on the four years of data, a reasonably consistent pattern of use can be seen. Few bats use the cave during the winter months. One or two bats, usually Plecotus townsendii can be found in the entrance passages throughout the winter. Myotis velifer begin their return to the cave around April 20th. Early in the spring the bats first roost above the Bacon Rind Trail near the Lunch Spot. By the middle of May the roost usually shifts to an area above the trail between Sharon's Saddle and Kartchner Towers. The numbers steadily increase to at least 500 by the end of May but in some years twice as many may be present. By the middle of June the population has reached a stable size. At this time the bats have always roosted above the spur trail at Sharon's Saddle. During July the population shows a slight increase that may be due to either juveniles fledging early or recruitment from other roosts. However, other roosts are not known in the area. In the first two weeks of August there is usually a sharp increase in the numbers of bats as the young begin to fly. The peak lasts for only a week before the population begins to rapidly decline. Most of the initial decline is apparently due to adults leaving the cave as the remaining population is increasingly made up of juveniles. At this time the location of the roost within the cave begins to shift, typically locations near the start of the River Passage, above Kartchner Towers and above the Bishop are favored. By the middle of September the bats have usually all left the cave.

This pattern indicates that the number of adult bats increased over the period from April through July (they reached a peak adult population size by late July, before juveniles would become volant), and then abruptly increased in early August; the abrupt increase was interpreted as the addition of fledgling juveniles. Such an abrupt increase in early August is not seen in 1990. This may be due to the unusually severe weather which occurred during the first two weeks of August, 1990. During that time a total of nine rainstorms were recorded at the park with a total precipitation of 5.41 inches. A large, cold storm also struck from August 12 to 16. The unusually bad

weather may have caused a reduction in the peak number of bats leaving the cave. A comparison of the total usage of the cave by bats in 1990 shows that this year had the second highest number of bat-days. Figure 83 depicts the critical events of the bats' life cycle that occur during the few months that they use Kartchner Caverns. Care must be taken during these months to avoid disturbance of the bats.

A rough estimate of the number of young born each year can be made by comparing the "adult population size" with the "peak population size" (after juveniles fledge); see Table 29. The estimate of adult population size is the mean of the counts recorded for a seven-week period between 7 June and 24 July, which is the period ending just before juveniles would fledge. The peak population size is calculated as the mean of the two highest counts in August. This comparison shows that the largest percentage increase in juveniles occurred in 1988 but the largest numeric increase was in 1989 (Table 29).

Table 29
Characteristics of Kartchner Caverns Bat Population

Year	June/July Population	August Peak	% Increase (juveniles?)	# Increase (juveniles?)	Total Usage
1988	638	1245	+95%	607	74,800
1989	1023	1804	+76%	781	107,200
1990	1191	1469	+23%	278	117,500
1991	634	1198	+89%	564	61,700

An estimate of the expected number of young born each year can be made from the number of pregnant bats caught at the cattle tank in 1989. In mid-June, 17 Myotis velifer were captured, of these 10 were pregnant (59%). On July 23, 23 bats were caught, 15 of these were lactating females(65%). If the make-up of the bat population remains the same throughout this period we would expect the population to increase by about 60% when the juveniles fledge (fly). As can be seen in Table 29, in three years the percent increase was greater than 60%, only in 1990 was it less than 60%. The larger percentage of increase may be due to bats from other roosts moving into Kartchner or that more than 60% of the June/July population gives birth.

Many possibilities exist that could explain the decreased magnitude and different pattern of the size of population estimates (Figure 77 to 80). Four years of bat population data are insufficient to determine the cause. However, the possible causes should be considered in order to clarify the need for accumulating additional data in future years, and to identify areas of potential disturbance to the population. It is possible that: (1) fewer females bore offspring, (2) fewer juveniles survived, (3) more males made up the adult population, or that (4) fewer flying juveniles or adult males dispersed to the cavern in 1990. One of these possibilities warrants further speculation supported by published information concerning reproduction in Myotis velifer. It is possible that changes in population structure affected the peak population size. It has been reported that M. velifer females reproduce in their first year (T. Kunz; in Kansas), but it's possible that some females in our desert subspecies may delay reproduction until their second year. If this were the case, and non-pregnant yearling females returned to their natal roost, then an adult population that appeared to be

stable or increasing, would produce fewer juveniles. If the proposed estimates in Table 29 are reasonable, then the positive increase in population size, but at a decreasing rate from 1988 to 1990, would fit the pattern.

Bats appear to use the warmest parts of the cave to roost. A comparison of the locations of the bat guano piles (Figure 84) and the map of soil temperatures (Figure 25) shows that bats currently use areas with soil temperatures of 68°F or above. The air temperature at the elevation of the ceiling is expected to be several degrees higher. This is not surprising because a warmer roost is advantageous in raising young who must be constantly kept warm. This may also indicate that other, cooler, parts of the cave are not suitable for use as a maternity roost.

Some areas of the cave are warm enough but are still not used by bats. These areas, parts of the Cul de Sac and Red River Passage, appear to be unsuitable for bats because of the thin layer of mud on the walls. Examination of the walls in these areas shows that they are covered with tiny grooves scratched into the mud as bats attempted to find a toe hold.

The time at which bats begin to leave the cave usually occurs 15 to 20 minutes after sunset, see Figures 77 to 80. A positive correlation exists between time of sunset and initiation of bat flight, but these data have not yet been analyzed in detail. The exit flight typically takes about an hour, with the majority of the bats leaving within a 15 minute period. The shape of the time distribution varies depending on the time of year, see Figure 85. Early in the summer and late in the summer the distribution is narrow with a high peak. During July, when adult females are nursing, the exit flight exhibits a broader pattern with a smaller peak. This may be due in part to the multiple trips taken in and out of the cave to feed their young. Changes in patterns of exiting bats are intriguing because they invite speculation about cause. An analysis of the flight distribution of 31 bat counts from 1990 was performed. Given the small size of the "bat window", we should expect an increase in duration of exit period when the number of exiting bats increases. And this is what happens, to a certain extent. If we eliminate the wait time between stragglers at the beginning and end of the counts by using the "5% to 95% exit period", there is a small effect of the total bats on the duration (regression coefficient=0.25). However, what is affected to a much greater degree when the number of exiting bats increases, is the rate at which bats exit (regression coefficient=0.73). Perhaps this suggests that there is some value to exiting quickly as a group, presumably to avoid attracting predators to a site with an obvious accumulation of prey. Another possibility is the pairing of female and young during the exit flight. Little is known of the training period for recently volant young and if they forage with their mothers.

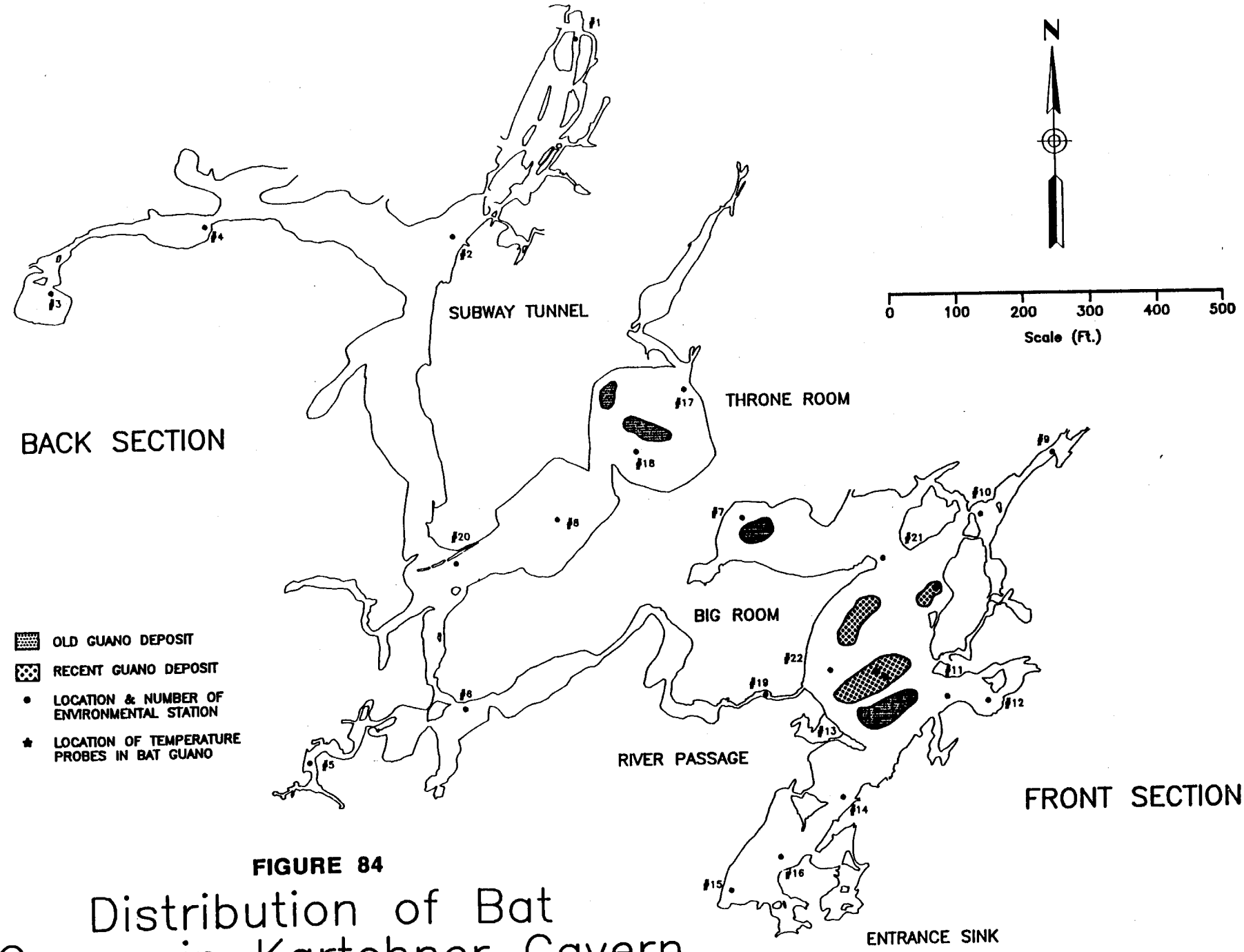
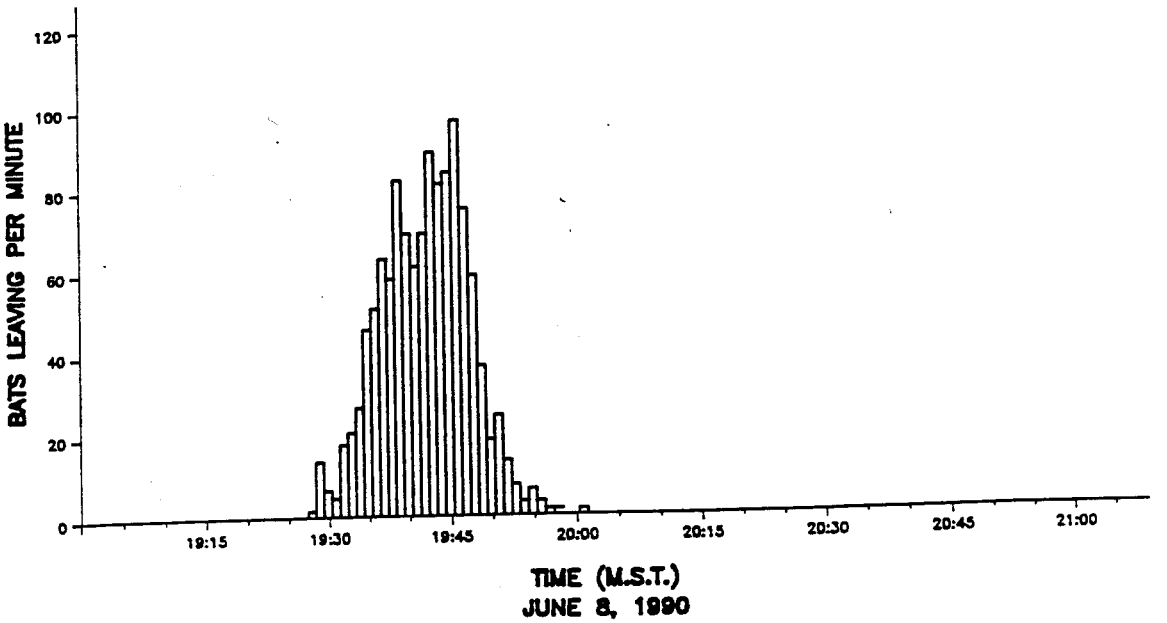
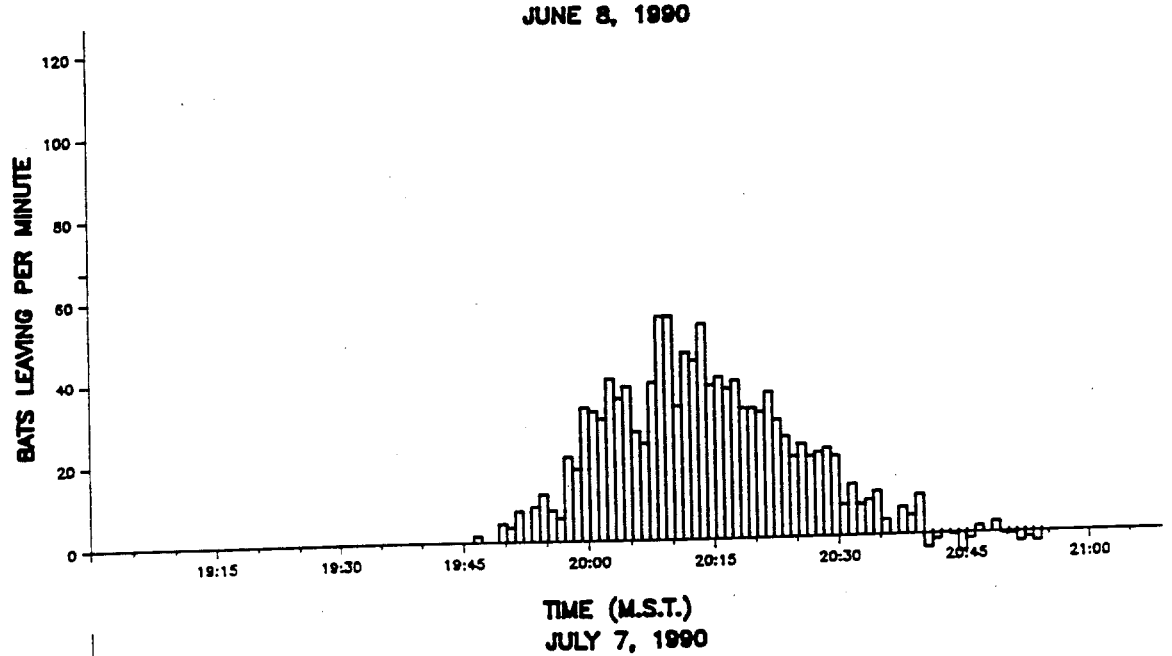


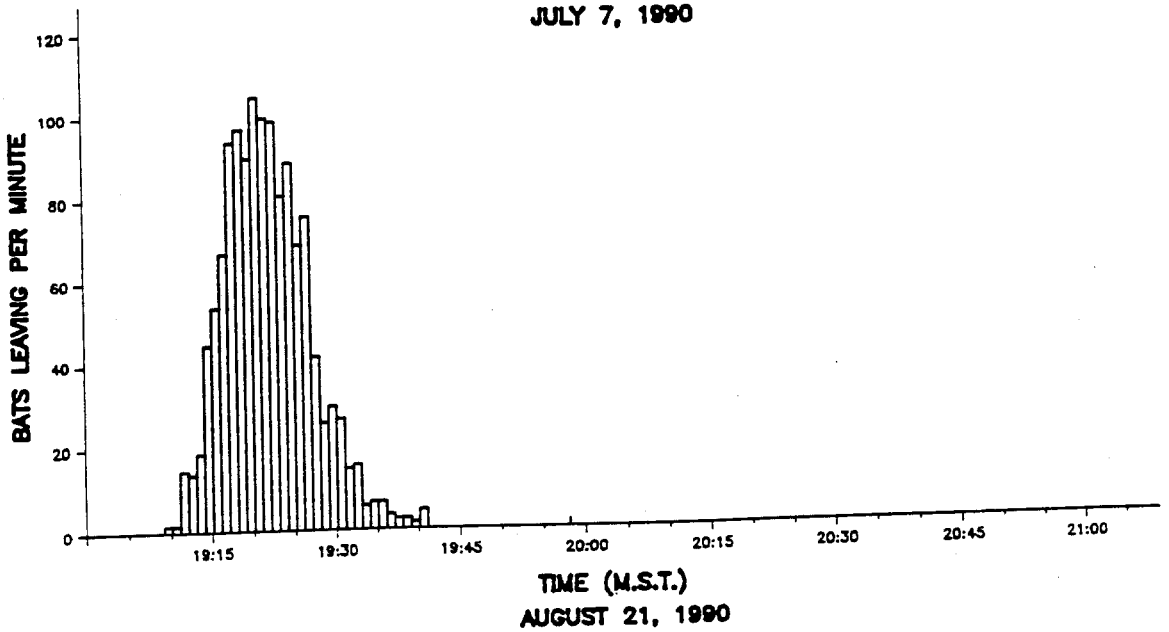
FIGURE 84

Distribution of Bat Guano in Kartchner Cavern

A.C.P.I. © 1991







REPRESENTATIVE PLOTS OF KARTCHNER BAT FLIGHTS

FIGURE 85

PREHISTORIC USE OF THE CAVE BY BATS

Several guano piles are located in the Throne and Rotunda Rooms. These piles appear to be very old as the guano has lost all visible texture and piles have been severely eroded by drip water. The two largest guano piles are located below the Overlook in the Throne Room, smaller piles are located along the western edge of the room and behind the Kubla Khan column. The Rotunda Room has one small guano pile located below Environmental Monitoring Station #8 at the edge of the breakdown slope. Numerous other small, cohesive clumps of guano are found on the breakdown, in the Rotunda Room, up to approximately the level of the monitoring station. The location of these clumps among the breakdown make it difficult to envision how they could have been naturally deposited below a bat roost. There is no evidence on the ceilings above these remnant pieces to indicate that these areas were used as roosting sites by bats. Dr. Welbourn has speculated that these pieces are the remains of a pile of guano that was floated up onto the breakdown during a large flood. Similar clumps of guano are also found in the Cul de Sac area of the cave.

Skeletal material from an undetermined species of bat has also been found in the Throne Room. The bones are located under a very large breakdown block on the left side of the trail just before the Bacon Rind near Photo point PP93. Several partial skulls and mandibles have been removed for identification. Because the bones are located so close to the trail, extreme care should be taken to preserve this site.

In 1991, Dr. Owen Davis from the University of Arizona Department of Geosciences collected samples of ancient bat guano from the Throne Room and Rotunda Room. These samples were examined for pollen which would provide clues to the past climate at the time bats were using this part of the cave. The age of the bat guano was also determined by Carbon 14 dating techniques at the University of Arizona Laboratory of Isotope Geochemistry. The results of dates on four samples are given in Table 30.

Table 30

Kartchner Caverns Bat Guano Age Dates

U of A A#	Sample Label	Location	Age (years)	$\delta^{13}C_{PDB}$(%)
6341	KC1	Throne Room behind Kubla Khan	45,790*	-21.0
6342	KC2	Throne Room near PP91	49,340*	-20.8
6343	KC3	Rotunda Room below EMS#8	45,540*	-18.1
6344	KC4	Rotunda Room floater below EMS#8	40,220	-17.3

* Ages for these samples are near the limits of the Carbon-14 dating technique used and may represent samples that are much older than 50,000 years but contain small amounts of younger contaminants.

PUBLIC HEALTH CONCERNS ASSOCIATED WITH BATS

While bats are a significant feature of the cave, there are also health concerns associated with having bats or any other wild animal in a location where they may come into contact with the public. For bats there are two areas of concern: bats, like other mammals can transmit rabies. The second concern is the fungal disease, histoplasmosis. Histoplasmosis infects the lungs and produces symptoms similar to those of tuberculosis. The spores are frequently found in the droppings of birds and bats. People visiting or working in bat or bird roosts, particularly under dry conditions, are frequently exposed to the disease. The disease is occasionally debilitating or fatal. As part of the Plant Growth study conducted by OUL several air and bat guano samples were tested for the presence on Histoplasma capsulatum. It was not found in any of the samples from Kartchner Caverns, (Aley, 1990).

Bats, like dogs and some other mammals, can be infected by rabies and can transmit the disease to humans. Rabies is a serious disease and is almost always fatal. There have been 14 recorded fatalities in the U.S. since 1953 when rabies transmission from bat bites was first recognized. An article in the "Annals of Internal Medicine" (May, 1984, Volume 100, Number 5) reviewed all known cases of human rabies from 1960 to 1979. There were 38 cases of human rabies in the United States and territories. In five of these cases the source was identified as a bite from a bat, in six of the cases the source of the rabies virus was unknown.

A large percentage of bats tested for rabies by health departments are identified as having rabies. These statistics are somewhat misleading because the animals tested are usually sick or acting in an abnormal fashion. It does point out that the risks are much greater with a sick animal. Rabies infections are much lower in natural populations. Surveys for rabies in asymptomatic bat populations in the U.S. usually reveal infection rates of 0.5% or less.

In spite of their reputation, bats are a relatively infrequent source of rabies virus considering their abundance and distribution throughout the United States. The following quotes are taken from "Just Bats" by Dr. M. Brock Fenton. "Rabies is separated into two clinical forms: 'furious' and 'dumb' rabies. An animal with the furious form usually goes berserk, attacking anything and everything in its path. Dumb rabies is characterized by increasing paralysis that progressively weakens and immobilizes the victim. Although it might seem that the animal with furious rabies would be the bigger threat, at least it is easily recognized as dangerous. Animals with dumb rabies, however are often in need of assistance and become objects of pity. But they still have the strength to bite. People should avoid any animal they observe behaving abnormally."

It would be unusual for visitors to come in contact with bats in the cave, bats are so easily disturbed that it is unlikely that they would remain in an area where they could come into contact with people. Visitors should be warned not to touch or pick up any bat that they may find inside the cave or on the surface. Any dead bats found in the cave should be sent to the University of Arizona Department of Veterinary Science for rabies testing. Do not freeze the carcass as this will make it impossible to test.

In June of 1991, as a result of predation, 45 dead bats were found in the Blockade Room of Kartchner Caverns. Five of the carcasses were fresh enough to be tested for rabies. The results were negative for all five bats.

CONCLUSIONS

- The predominant species of bat found within the cave is Myotis velifer, the Cave Bat. Virtually all bats netted near the sinkhole were Myotis velifer. A small number of other bat species have been observed but are apparently represented by only a few individuals.
- Myotis velifer bats are presently known to use only the Big Room area of the cave and entrance passages. The primary roosting sites are above Sharon's Saddle and near the Lunch Spot. Other locations are occasionally used and include; the area around Kartchner Towers, near the Big Room Overlook and near the Bishop formation. Accumulations of bat guano in numerous other locations around the Big Room indicate that the locations favored by the bats may change.
- Myotis velifer are present in the cave from late April to the middle of September each year. Myotis velifer begin to return to the cave around April 20th and generally leave by September 15. Small numbers of Plecotus townsendii, and perhaps other species, use the entrance passages year round.
- Myotis velifer use the cave as a maternity site during the summer. The time period from the middle of June to early August is a critical period. During this time the bats give birth and care for their young. If disturbed during this time they may be forced to abandon their young.
- The number of bats found in the cave varies from year to year but averages approximately 1000. The numbers increase in August when the young begin to fly and may peak at close to 2000 bats. Peak population estimates of the adult population and total bat usage show considerable year to year variation. No definite trend to larger or smaller bat populations is seen in the data.
- Conditions within the cave appear to be ideal for a Myotis velifer maternity roost. Kartchner is apparently superior to any other nearby roost because bats returned to the cave in 1991 a few weeks after many were killed by a ringtail cat. The limiting factor on the use of the cave may be predation which occurs in the small entrance passages.
- No endangered species of bat has been found inside the cave. The endangered species Leptonycteris sanborni has been observed on the surface near the cattle tank. Bones from a single Leptonycteris have also been found in the Crinoid Room.
- The Throne Room and Rotunda Room were inhabited by bats 40,000 to 50,000 years ago. There is no indication that these areas have been used by bats in modern times. The prehistoric use of these areas by bats is also an indication that the cave may have had another entrance into the Back Section at one time.
- Bat guano forms the basic food supply for the invertebrates found in the cave. These organisms are dependent on the continued presence of the bats.
- Other small caves on the park are also used by small numbers of bats during the summer and winter.
- Predation on the bats in the small passages near the entrance has been noted on several occasions. This indicates that in the future other predators may be attracted to the cave because of development. This could result in conflicting use of the "Bat Window"

RECOMMENDATIONS

From both public-interest and scientific viewpoints, Kartchner Caverns is even more exciting as a bat roost because it houses a maternity colony. This means also that continued responsible and knowledgeable management is necessary for the bats. From our observations in the cavern and at the cattle tank, we know the period from mid-June to early August is the time when females are in late stages of pregnancy, parturition, or lactation, and juveniles are developing and fledging. This is the critical period of time when the bats require non-disturbance to assure healthy behavior, and in turn, successful reproduction and a stable population.

For Kartchner Caverns, bats occupy a vital niche in the ecosystem below the surface. Not only do these flying mammals use the outside environment, but because of their capacity to echolocate with sonar, they can utilize areas of the cave inaccessible to other higher vertebrates. In so doing, bats provide organic materials from the exterior to organisms which are obligate and permanent cave residents. The bats then are an important and necessary aspect of the healthy cave environment. As such, they require special attention because of their specialized life history.

It should be clear, however, that the bats cannot be protected solely within the cavern. Their food requirements, which in southern Arizona are either insects or flower nectar, must be obtained on the surface. This means that vegetation which provides food directly (i.e., flower nectar of few plants) or in directly (i.e., food and shelter for insects) must be preserved as well.

DEVELOPMENT OPTIONS

The presence of a healthy bat population in Kartchner Caverns provides much potential for scientific interest. For a state park, however, what is perhaps more important is that the bat population provides the opportunity for public education about these increasingly popular animals and about the exciting and interesting ecology of a subterranean ecosystem. Our studies have shown that Myotis velifer are easily disturbed by lights and noise. The presence of tours and general lighting of the areas of the cave which they use will almost certainly make them abandon the cave. To maintain the bat population will require that development of the cave not disturb the bats or drive them from the cave. Options for maintaining the bat population after development are, in order of preference:

- Limit visitor use of the Big Room while bats are present .
- Attempt to entice the bats to use another portion of the cave.
- Mitigate the impacts of development on the bats by trail alignment, low level lights and providing a bat house on the ceiling.

The first option is clear but would limit visitation to the Big Room from May to the middle of September. This is the only option which appears to be likely to succeed. The second options has never been successfully implemented in any other cave. Suggestions were made regarding the use of bat houses, in order to provide alternate roost sites for the bats, so that the Big Room might be developed without detriment to the bats (i.e., the bats could be moved into houses and placed elsewhere). Unfortunately, bat houses have shown minimal success in the United States (and no success in desert scrub or desert grassland environments in Arizona). The two bat houses that were placed in the cave provided the best possible chance for occupation by bats; i.e., they were placed in an area where conditions were known to be

acceptable to the bats and yet these structures were never inhabited by the bats. The preliminary results from the bat houses placed in Kartchner indicate that there is little reason to expect that the bats could be successfully relocated.

The third option, of routing the trail away from the bat roost and utilizing low level lights, is also unlikely to succeed. Our experience in observing these bats is that they are easily disturbed by sound and light, even at low levels. There is a slight chance that the last two options could be combined. A bat house could be constructed which could be sound proofed and also provide shelter from light, but there is no evidence that it would be successful.

RECOMMENDATIONS CONCERNING ACTIVITIES WHEN BATS ARE PRESENT

The following guidelines for working inside the cave while bats are present have been developed as part of the study of the bats. These were developed to minimize the possibility of disturbing the bats and driving them from the cave. They are based on our experiences and observations of the behavior of the bats. Each and every cave visitor should receive instruction in these suggestions, at least on an annual basis. Noise and other effects of workers and casual visitors to the cavern are potential sources of disturbance to bats residing within the cave that could cause pregnant females to abort fetuses or abandon young. Whatever the causes, caution and the least amount of disturbance possible should continue to be the rule. Eight months (September through April) are available during which few bats are in residence and most disturbing cave work may be accomplished.

The management policy should include these mitigating measures to prevent high levels of disturbance to bats when they are in the cavern. When bats are in residence, each and every worker that must enter the Big Room should receive instruction in these recommendations.

A. When bats are detected, visitors/workers should immediately consider the least disturbing solution. This may mean retreating to use an alternate route; however, less disturbance may be caused by just moving on out of the area as quickly as possible. Visitors/workers should not shine lights directly on the bats, and should move along the trail without talking or creating more noise than absolutely necessary. Out of the area, the visitor should record the location of the bats and report these observations that day to park personnel so that others may avoid the area if possible.
B. When bats are known to be using a particular area, visitors/workers should attempt to use other trails. If bats continue to use the roost above Sharon's Saddle, the trail over the breakdown should not be used while bats are present. If it is absolutely necessary to move past a bat roost, visitors should be prepared before arriving at the known bat location, so that they do not stop there, do not shine lights on the bats, move quickly through that area, and keep noise to a minimum.
C. When possible, red lights should be used in the area where bats are known to roost. If the use of red lights cannot be accommodated without increasing the noise level due to the discomfort of not being able to see or move about, then such lights do not improve the situation, and moving quickly through the area with

dim white lights would result in less disturbance. (Red lights are not invisible to the bats. Bats are very susceptible to sounds such as voices, foot traffic, and movements of pack and clothing.)

D. Visits to and from the cavern should never occur during the bat flight exits. The times of bat exit flights are now well known from many bat counts performed as part of this study. The upper half of Figures 77 to 80 give a good indication of the time at which flights typically start and end. To make sure, someone should watch the flight to make certain most bats have exited before visitors/workers enter at night. Also care should be taken when visitors/workers leave the cave at night so as not to be enroute when large numbers of bats are returning.
E. At the time of parturition (birth) in late June and early July, no one should enter the cave without prior discussion with the bat workers.
F. No one should enter the maternity roost area for any reason when adults are present, and should not be there even when juveniles are alone.
G. When bat biologists contract (or volunteer) to work on bats in the cave, they should be required to submit proposals for review that detail their proposed methods for working with or near bats in the cave. These methods should utilize low disturbance techniques. The proposals should be reviewed by at least two other bat biologists.
H. When other biologists or other kinds of scientists request access to the Big Room during the period when bats are in residence, they should be required to submit proposals for review that detail their methodologies. Their studies should be done during the 8-month period when bats are not in residence. If this is not possible, then they should be subject to all the stipulations of the management policy.

HEALTH ISSUES

Bats, like many other mammals, can carry rabies. It is, however, unlikely that any visitor would come into contact with a bat. Plans for deposition of dead bats (if they are found) should be specified in the management policy. All materials should be saved for identification by qualified bat biologists. Fresh carcasses should be refrigerated (not frozen) for submission to a laboratory for rabies examination. (Five bats from the cavern were tested during 1991 for rabies and all were negative.) Delicate skeletal materials should be left in place and their location recorded and marked for protection until later identification can be completed by a qualified bat biologist.

Visitors should be warned and instructed about the hazards of handling bats or any other wild animal. Suitable warning signs should be placed in the visitor's center, campgrounds, nature trails and in the cave.

LONG TERM BAT MANAGEMENT PLAN

Arizona State Parks should write a "long-term Management Policy Regarding the Status of Bats at Kartchner Caverns." Four years of data collection have contributed much baseline information regarding the several species of bats that roost inside the cave. There is more baseline information for KCSP than has been available for most state and federal parks prior to the development of their properties. This information should be used to write a

long-term management policy of how these animals will fit into the proposed cave development. With a policy in hand, there would not be a crisis situation whenever something happens regarding the bats. A number of items are suggested for inclusion in the policy:

1. Arizona State Parks should consult with the Arizona Game and Fish Department regarding management policies that concern the bats in the cavern and on the entire park. All species of bats are protected as state property by A.R.S. Title 17, which is administered by the Arizona Game and Fish Department.

2. Arizona State Parks should request simple consultation with the USFWS regarding the endangered species Leptonycteris curasoae (the Lesser Long-nosed Bat=Leptonycteris sanbornii), because a bone belonging to this species was found in the Crinoid Room.

3. The policy should include a section of guidelines on how interior cavern construction and development will be performed during the period when bats are in residence in the cave. We recommend that the actual physical development of the cavern should be conducted during the season when bats are not present. A period of nearly 8 months, from early September through late April, is available when the necessary construction would not disturb the roosting colony.

4. The presence of bats does not preclude the roost area from being developed and shown to the public. Some concessions will be necessary during the period of time when the bats are present. The management policy should include a "closed trail" status in the Big Room from late April through early September when a maternity colony of Cave Myotis bats are in residence. Management would then be consistent with the ecology of its bat inhabitants (and other organisms dependent upon those bats). The dates of closure should be specified in the management policy. This would mean that tours would not be taken there beginning on the specified date, rather than waiting to see if bats return before initiating the trail closure. During April and May, the Cave Myotis are known to move around to different sites within the Big Room; this is probably a testing period, a time to locate the most suitable sites and to begin to form roosting associations with each other. Delaying the closure of the trail, or closing only portions of the trail, while waiting for the bats to "settle" into a roost would not be justified, because the bats might never "settle" (or even re-establish the maternity colony) due to the disturbance from tours.

Developing and utilizing two different "seasonal trails" in the cave (for example, making the Big Room a winter tour and closing it in summer) have benefits beyond protection of the bats.

5. A schedule should be included in the policy specifying the dates at which the bat flight route through the cave should be checked. The wood panel insert in the Babbitt Hole should be removed at the beginning of May to make a larger opening for the bats. It should be closed down to the smaller size at the end of September. The Blow Hole Crawlway and "Bat Window" should be checked for obstructions. Consideration should also be give to installing more permanent fixtures at the Babbitt Hole and Blow Hole.

6 A methodology to deal with the removal of predators of bats should be given in the management policy. Occasional predation is to be expected. But changes to the natural cavern have been made and will continue to be made as development and visitation increase. A more suitable exit opening for bats should be constructed between the Breakdown Room and Crinoid Room. The existing passage used by the bats has been modified a number of times. The initial opening was changed by Porter and Larson in 1972, at a later date it was concreted closed and then reopened. Presently the interior end of the "bat window" is very unstable. These changes (for example, structural changes in the original opening through which bats exited, or the presence of food particles left by human visitors) may have attracted additional predators, perhaps in response to increased rodent prey. In any case, the structural alterations that were made between the Breakdown Room and the Crinoid Room resulted in alterations in the opening through which the bats enter and exit. These alterations created a portal at which certain species of predators (such as the ringtail cat during 1991) can sit and easily trap large numbers of bats that have no choice but to use this opening.

7. The park should continue to track the size of the bat population both on a yearly basis and throughout the summer. Park managers should be on the lookout for trends which may indicate that the bat population is experiencing problems, such as a continued decline over two or more years. The number of bats should be monitored on a regular basis (at least once a week), this will increase the accuracy of the yearly estimate and also alert the park manager to unexpected threats to the bat population. If sudden or long term declines are found, then corrective measures should be instituted. The weekly counts should be conducted at the sinkhole. This low disturbance technique has yielded more information about the bats than any other method. Counts should begin the week of 21 April and be continued <u>at least</u> once a week until early September or the time that the bats have left.

A methodology for the weekly counts of exiting bats at the sinkhole should be explained in the management policy. This is a low-disturbance management tool (when the methodology is followed) that yields information about the seasonal and monthly (or weekly) presence, numbers and general health of the Cave Myotis population. While these counts may not be accurate, precision is what is important for the information obtained and precision can be increased by having the same observer using the same methodology after minimal practice. Additionally, the park should investigate the possibilities of obtaining equipment which would automatically count bats entering and leaving

the cave. ACPI has constructed an inexpensive prototype that has been successful in counting bats in some of the smaller passages.

8. If a cooperative agreement can be made with the land owner/lessee who manages the cattle tank (just off the southwest boundary of the park property), there should be a stipulation that no alterations be made to the tank. If this is not possible, a new water tank with similar dimensions of open surface water area should be established on park property to continue to accommodate the flight style of bats.

Activities such as mist-netting for bats, observing banded bats and light-tagging bats have shown that bats from the cavern frequently use the tank. While that water supply may not be necessary to the survival of these bats, it would provide for future biological studies and for educational opportunities at the park (see interpretive and educational opportunities section).

9. Native vegetation and other aspects of natural habitat on the park property should be protected from alteration in order to manage for wildlife that are resident or passing through the park.

INTERPRETIVE AND EDUCATIONAL OPPORTUNITIES

Interpretive and educational opportunities are possible at Kartchner Caverns that incorporate the natural history of the bats within the cavern and on the park property.

a. Interpretive stations should be planned along the tour route that include skeletal materials that have become part of the flowstone. Interpretation can include not only information about the bats but also the fact that this skeletal material has provided biologists with information about the species of bats that use the cavern without having to disturb living bats. These materials serve also as a means of showing bats to the public without disturbing live animals. (Bat skeletons located in the cave during the baseline studies have been flagged for possible interpretive use.)

b. Interpretation along the tour route should also include the guano. Not only is the guano useful as an ecological tool, for example, it is the very substance that shows the flow of energy in the natural cave system. But the "ancient guano" is especially interesting because it tells geological and paleontological stories.

c. Interpretation should include the bat exit flight against the sunset sky. And, while viewing conditions at the sinkhole are not suitable for the public (and would be disturbing to the bats), a video camera should be set up in the sinkhole to transmit the event to the visitor center. If the center is closed at that time of day, then it can be recorded for the next day.

d. Roosting bats inside the cave might also be accessible by video camera. It would be essential that silent cameras attached to night vision devices (image intensifiers) be used for this purpose and that they be set up while bats were not in the roost. The public would then be treated to the sight of the roosting bats and would be able to view how they hang up, how they groom and how they fly.
e. Interpretive programs that include scheduled walks to the water tank should be scheduled. There, bats could be seen and heard on ultrasonic detectors.

SURVEY OF THE INVERTEBRATE CAVE FAUNA IN KARTCHNER CAVERNS

INTRODUCTION

Invertebrates, especially arthropods, make up the majority of all known cave organisms. If the Arizona State Parks Department is to minimize disturbance to all cave organisms and their habitat, they must also know what invertebrate species are present. With this information the Arizona State Parks Department can prevent the extinction, and/or reduction of species during and after development of Kartchner Caverns. After development, the information gathered on the invertebrate fauna can be used as a baseline for monitoring cave species and for interpretive programs.

There has been very little biospeleological work in Arizona. Preliminary work indicates there are several new species of cave adapted invertebrates, including at least one new species of cave isopod and a new mite species. The study of Kartchner Caverns is a unique opportunity for an extensive baseline study of the invertebrate cave fauna before development that will allow future follow up studies to determine the effect of development on the cave fauna.

MATERIAL AND METHODS

The inventory of the invertebrate cave fauna involved a total of 36 trips into Kartchner Caverns with over 164 hours underground between May 1989 and May 1991. Work in the cave was scheduled to minimize disturbance of the bats.

Collection of specimens in the cave was limited to those necessary for identification and laboratory study. All field-collected invertebrate specimens were returned to Ohio State University (OSU) for sorting and preliminary identification. Specimens in some groups were sent to specialists for confirmation of identification and/or specific determination.

Due to the numerous small invertebrates in bat guano, samples were taken for microarthropod extraction. All guano samples were returned to the cave after extraction. Also several soil and litter samples were taken from the surface for microarthropod extraction and comparison of edaphic and cave species.

RESULTS AND DISCUSSION

Thirty three invertebrate species were found in Kartchner Caverns during this study. Table 31 summarizes the species found in the cave. Of the 33 species, 5 (15%) are considered to be obligate cave dwellers (troglobites) and 16 (48%) are facultative cave dwellers (troglophiles). The camel cricket, Ceuthophilus pima, is a trogloxene because they leave the cave to feed. The remaining 11 (33%) species are either accidentals (10) or obligate parasites (1). Systematic work is continuing with the isopods, spiders, mites, flies, and pseudoscorpions listed in Table 31. Additional names and descriptions of new species are expected later. The distribution of arthropod species in Kartchner Caverns is presented in Figure 86.

All of the troglobites and troglophiles in Kartchner Caverns are dependent on organic material from the surface. Most of this organic material is deposited as Myotis velifer bat guano every summer. Small amounts of organic matter carried into the cave by periodic flooding of the Back Section provide a limited food supply in that area. The camel crickets are the only cave arthropod that is not dependent on organic material carried into the cave.

TABLE 31
SUMMARY OF INVERTEBRATE FAUNA FROM KARTCHNER CAVERNS*

	Ecological Group[1]	Guild[2]	Status[3]
NEMATODA			
undetermined material	troglophile	F	C
ARTHROPODA			
Class Arachnida			
Order Palpigrada			
Undetermined material	troglophile?	P	R
Order Scorpionida			
Undetermined material	accidental	P	R
Order Araneae			
Nesticidae			
Eidmanella pallida (Emerton)	troglobite?	P	C
Theraphosidae			
Undetermined genus	accidental	P	R
Order Acari			
Acaridae			
Sancassania sp.**	troglophile	F	C
Argasidae			
Argas sp.	parasite	PA	R
Histiostomatidae			
Undetermined genus	troglophile	F	R
Laelapidae			
Geolaelaps sp.**	troglophile	P	C
Neothrombiidae			
Ceuthothrombium sp.**	troglobite	PA/P	C
Rhagidiidae			
Poecilophysis sp.**	troglobite?	P	R
Stigmaeidae			
Eustigmaeus sp.**	troglophile	P	R
Undetermined Oribatida			
undetermined material (4 species)**	troglophile?	F	R
Order Pseudoscorpiones			
Undetermined genus	accidental	P	R
Class Chilopoda			
Undetermined scolopendromorph	accidental	P	R
Class Malacostraca			
Order Isopoda			
Trichoniscidae			
Brackenridgia sp.**	troglobite	F	C
Oniscidae			
Porcellio sp.	accidental	F	C

	Ecological Group[1]	Guild[2]	Status[3]
Class Insecta			
Order Thysanura			
Nicoletiidae			
Nicoletia sp.**	troglobite	F	R
Order Collembola			
Sminthuridae			
Undetermined genus	troglophile	F	R
Entomobryidae			
Undetermined genus	troglophile	F	R
Order Orthoptera			
Rhaphidophoridae			
Ceuthophilus pima Hubbell ***	trogloxene	S	C
Order Psocoptera			
Psyllipsocidae			
Psyllipsocus ramburii Selys-Longchamps	troglophile	F	C
Order Hemiptera			
Reduviidae			
Undetermined genus	accidental	P	R
Order Coleoptera			
Staphylinidae			
Undetermined material	accidental	F	R
Tenebrionidae			
Eleodes sp.	accidental	S	R
Undetermined fragments	accidental	U	R
Order Lepidoptera			
Undetermined material	accidental	U	R
Order Diptera			
Muscidae			
Undetermined genus	accidental	S	C
Sciaridae			
Undetermined genus (2 species)	troglophile	S	C
Order Hymenoptera			
Formicidae			
Undetermined genus	accidental?	U	R

1. Ecological group: Accidental = an animal that wanders or falls into the cave, but cannot survive in the cave; Trogloxene = an animal that lives part of its life cycle in the cave, but must leave the cave to feed; Troglophile = cave lover, an animal that can live its entire life in the cave, but is not restricted to the cave; Troglobite = an obligate cave animal
2. Guild: What the animal does in the cave community. P = predator; F = fungivore; S = scavenger; PA = parasite; U = unknown
3. Status: How frequently a group of animals was found in the cave. C = common; R = rare

* Based on currently available identifications
** possible new species
*** possible new subspecies

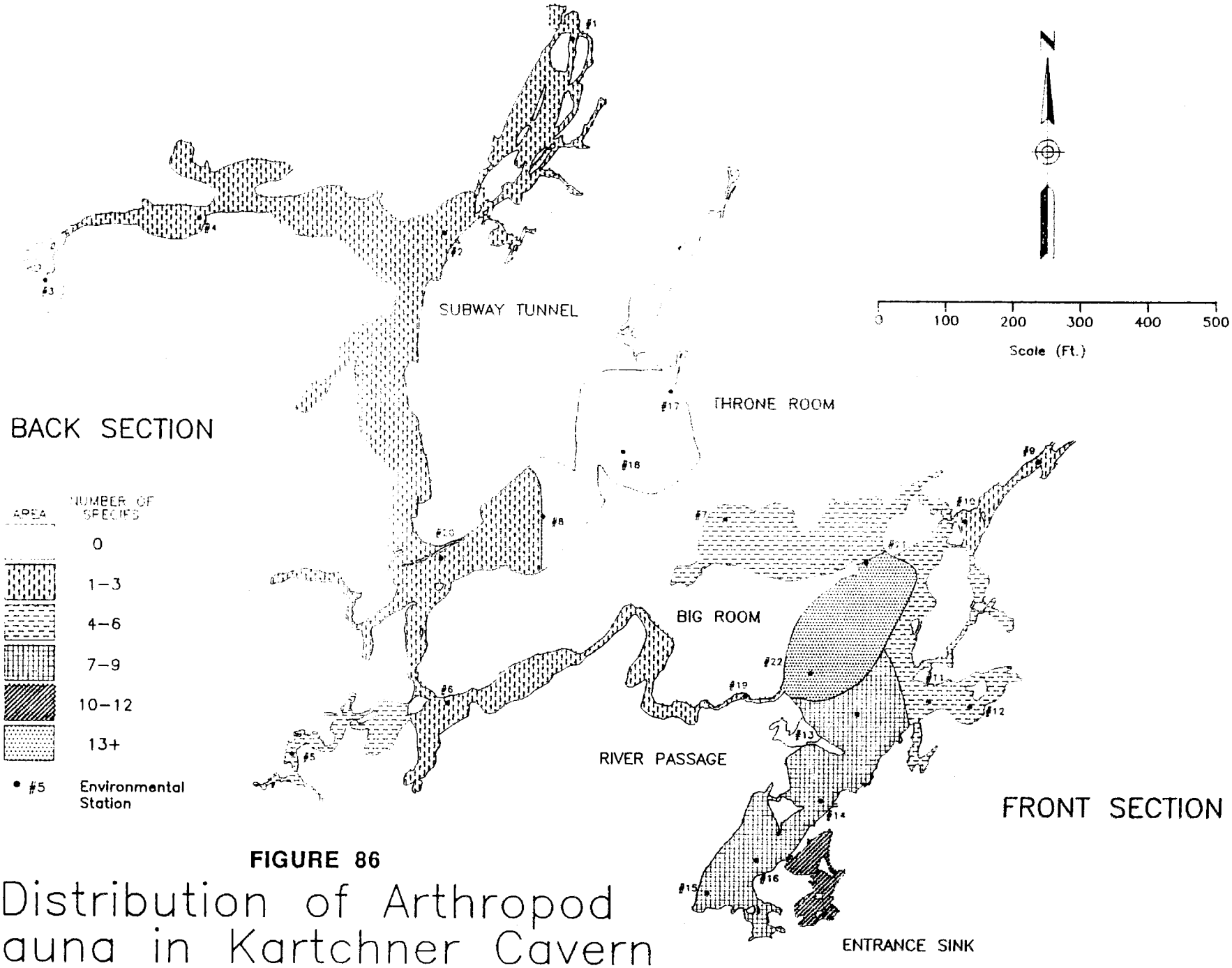


FIGURE 86

Distribution of Arthropod Fauna in Kartchner Cavern

The Back Section

Few invertebrates were found in the Back Section (Pyramid Room, Rotunda Room, Mushroom Passage, Throne Room, Subway Tunnel, Pirate's Den, and Sue's Room) of Kartchner Caverns. Granite Dells was the exception with several invertebrate species present (see below).

The only troglobitic invertebrate found beyond the Triangle Passage was the isopod, Brackenridgia. Brackenridgia lives in the mud areas and feeds primarily on organic material washed into the cave during periodic flooding. Evidence of these tiny terrestrial isopods can be found along the trails where many of the wooden trail markers have been eaten, leaving only reflective tape and frass. The periodic flooding of the Back Section especially (lower Rotunda Room, Mushroom Passage, Subway Tunnel and Pirate's Den) may locally eliminate or displace some isopods. The flooding also brings in organic material that provides food when the isopods are able to recolonize the flooded areas.

The only other arthropods observed in this part of the cave were occasional camel crickets (C. pima), a fly (Diptera) and a hemipteran (Reduviidae) that wandered from the Granite Dells area. The occurrence of insects beyond the Pyramid Room is accidental and they eventually become food for the isopods.

The Throne Room, Sue's Room and the upper portion of the Rotunda Room are without invertebrates. Even the wooden trail markers in these areas have not been disturbed by the invertebrates. Although there are several guano deposits in the Throne and Rotunda Rooms, they are very old and no invertebrates were found.

The Granite Dells area is biologically interesting. The presence of C. pima, a surface spider, and a lepidopteran indicates a direct connection to the surface. Even with a connection to the surface there were few individuals and species in this area due to lack of available organic material at the Granite Dells level. An attempt to locate C. pima marked on the surface was unsuccessful, suggesting other voids between the surface and Granite Dells that can support invertebrates. All the invertebrates found in this area, except C. pima and Brackenridgia, were accidentals.

The River Passage

The area between the Pyramid Room and Big Room (River Passage, Bathtub Room, Grand Canyon, Thunder Room) is a transition zone between the two parts of the cave. No invertebrates were regularly found in this area. Only C. pima, Brackenridgia and flies were occasionally observed in this section. Organic material is very limited, except for occasional bat guano pellets.

The Front Section

The Front Section (Big Room, Cul-de-Sac Passage, Echo Passage, Red River Passage, Grand Central Station, Main Corridor, Tarantula Room, Scorpion Room, LEM Room and entrance area) of Kartchner Caverns is the biological center of the cave with more than 13 invertebrate species in some areas (Figure 86).

In the Big Room and Cul-de-Sac there are a number of Myotis velifer guano piles of different sizes and ages that serve as the primary food source for most of the invertebrate cave fauna. The bats currently roost in two main areas, near the Lunch Spot (guano pile #20) and on the west side of Sharon's Saddle (guano pile #9c). Current roosting patterns indicate the bats roost over #20 in the early part of the summer and then move to Sharon's Saddle about mid-summer. In the late summer the bats are more likely to move around the Big Room, distributing guano over a wide

area. This movement of the bats significantly affects the number and species of invertebrates living in the guano. A proposed food chain for the guano is presented in Figure 87.

The first fresh guano stimulates growth of mold, bacteria and nematodes. This stimulates the primary guano arthropod, Sancassania (Acaridae) (Figure 90) to develop rapidly from non-feeding deutonymphs into adults. In 10-15 days the mite population can reach several hundred individuals per cubic inch of fresh guano. The seasonal response of Sancassania to the presence of fresh guano differs between the two major roost areas (Figure 88). At guano pile #20 the peak period for Sancassania was May through July (bottom graph) while the peak period for the same mite at guano pile #9c was July and August (top graph). Other fungivorous mites were also found feeding on fresh guano (Table 31), but never in large numbers. Flies also deposited their eggs in the fresh guano.

The dominant predator in the guano is a laelapid mite, Geolaelaps sp. (Laelapidae). Like many predators, this mite responds to the increase in prey with an increase in numbers of individuals. While population numbers were never close to the Sancassania, Geolaelaps is the second most common arthropod in the fresh guano, with 1-20 individuals per cubic inch. The peak number of Geolaelaps usually occurred just after the peak in the Sancassania population (Figure 88). The Sancassania and Geolaelaps are dominant invertebrates on the guano when the bats are present, from about May to September.

After the bats move to another roost or leave the cave, the invertebrate fauna changes rapidly. As the food resource is depleted the Sancassania stops development at the deutonymphal stage. The deutonymph is a non-feeding stage that can survive long periods without food. Within a month after the last fresh guano is deposited almost the entire population of Sancassania are deutonymphs (Figure 88). The deutonymphs usually bury themselves in the guano, sometimes in clumps of several hundred individuals and wait for the next fresh guano. It is not known how long the deutonymphs can survive in the guano without food, but a few individuals were found in many of the inactive guano piles. Other mite fauna in the guano included oribatids and a stigmaeid. As the guano ages, other arthropods move onto the guano, including crickets, spiders, psocopterans and an occasional isopod. Guano more than a year old supports very few invertebrates.

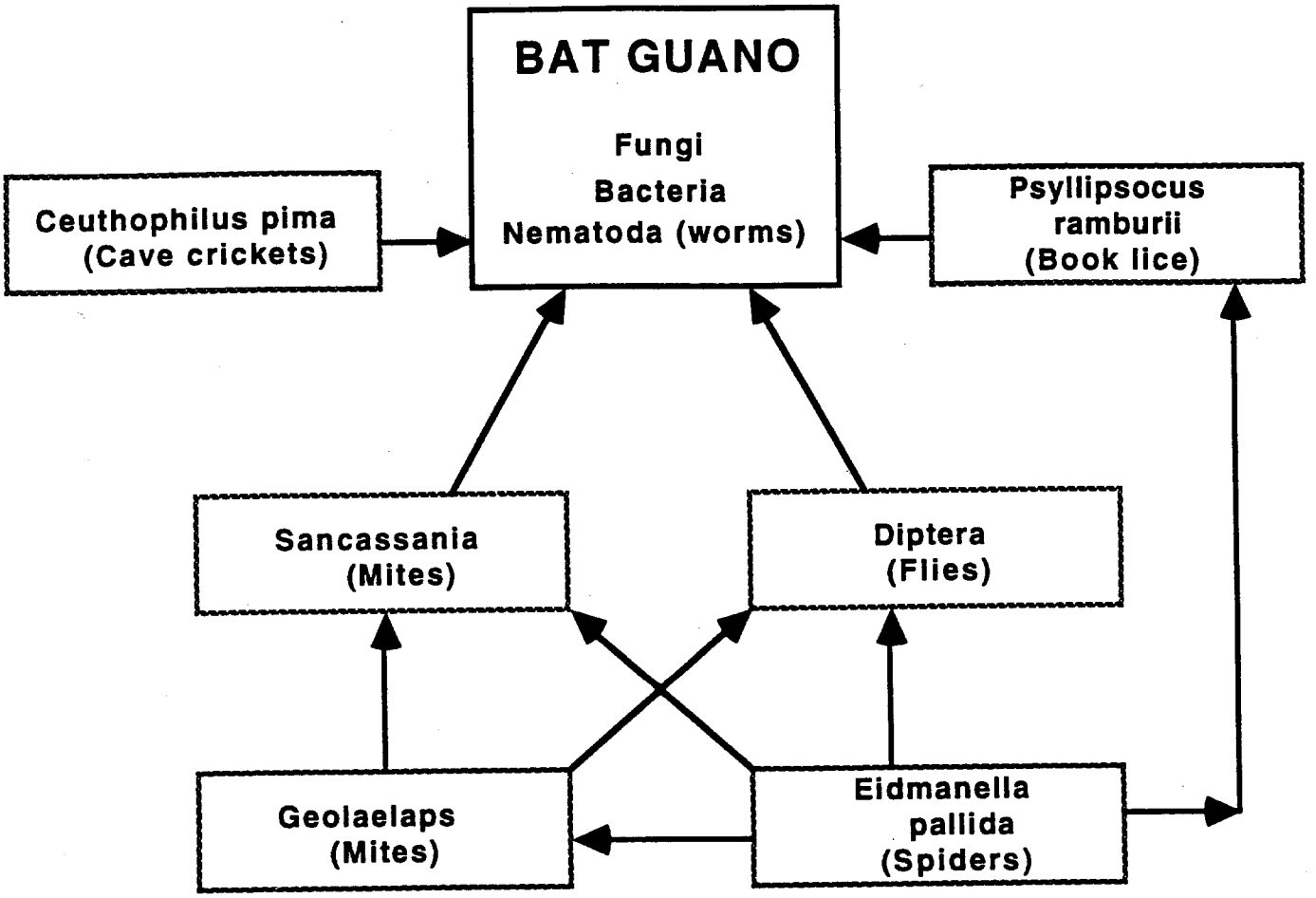
The area from the Pop-up Junction to the entrance is very different from the rest of the cave. There is a significant seasonal fluctuation in temperature and humidity and organic input is primarily limited to scattered guano pellets and occasional surface material carried in by rodents. The dominant cave arthropod is the camel cricket, C. pima. The other fauna in this area varies seasonally with moisture, but includes many of the accidental species found in the cave.

COMPARISON OF CAVE FAUNA OF KARTCHNER CAVERNS WITH OTHER CAVES

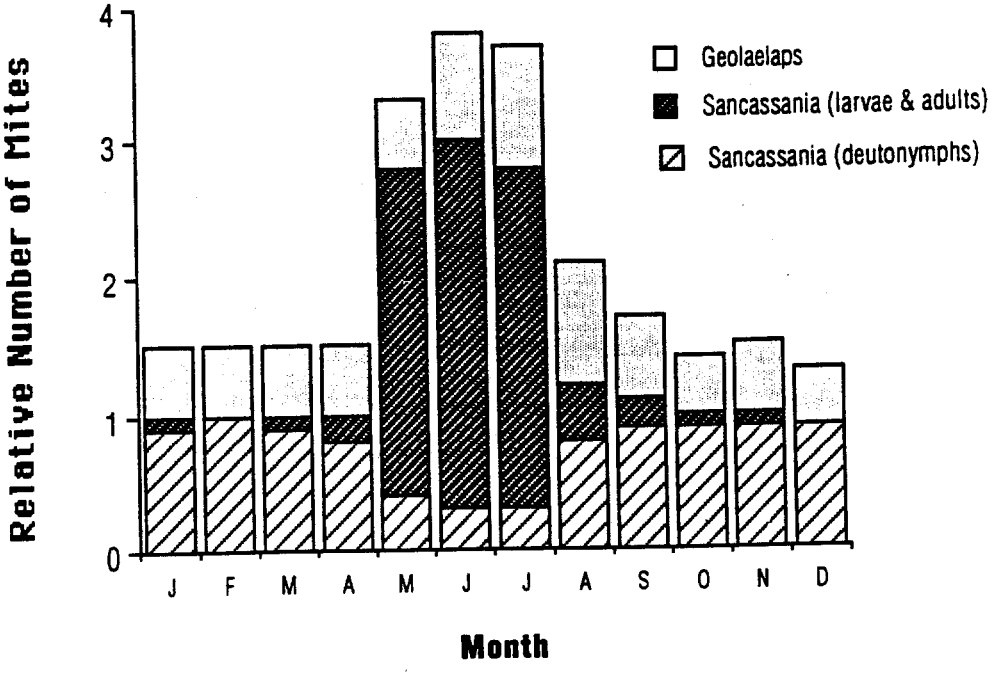
The invertebrate cave fauna and cave community of Kartchner Caverns is unique. Although the cave fauna of Arizona is not well known, some comparisons can be made (Table 32). There are significant differences in the cave fauna of Kartchner Caverns and other caves in the Huachuca, Santa Rita, Catalina and Whetstone Mountains . Most notable is the absence in Kartchner Caverns of several relatively

FIGURE 87

Kartchner Caverns Bat Guano Food Chain



Relative Population of Mites at Guano Pile 20



Relative Population of Mites at Guano Pile 9c

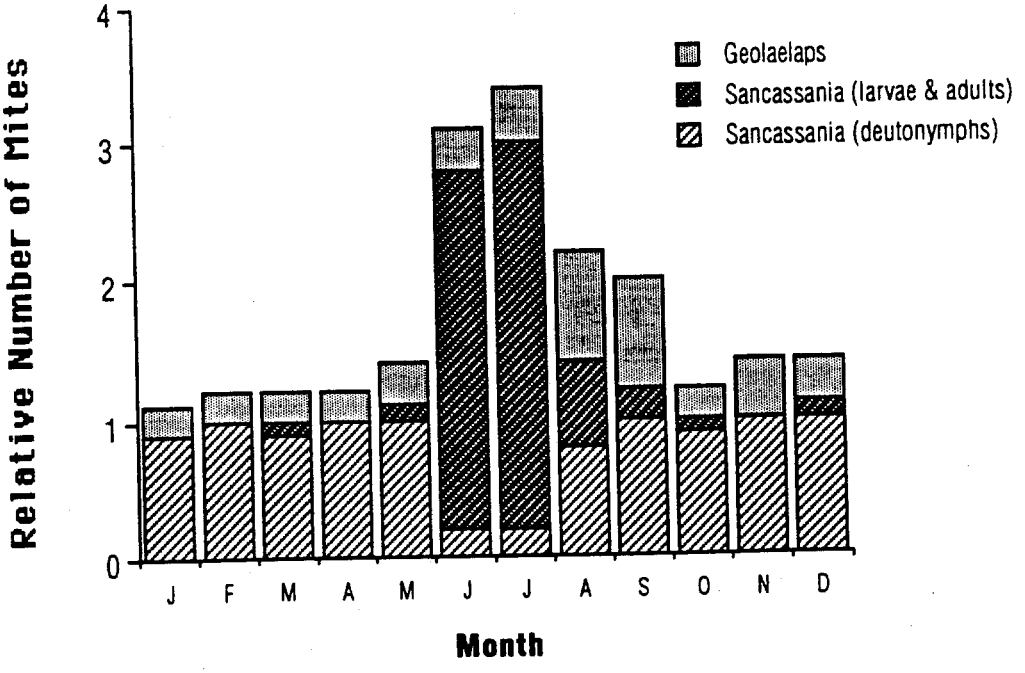


FIGURE 88

TABLE 32
COMPARISON OF THE CAVE FAUNA IN KARTCHNER CAVERNS WITH OTHER SOUTHERN ARIZONA CAVE FAUNA

		Kartchner Caverns	Whetstone Mountains	Huachuca Mountains	Santa Rita Mountains	Catalina Mountains
Number of Caves Examined			1	3	2	2
Elevation (feet, approximate)		4700	6100	5400-6300	5200-5500	4700-5000
Class Arachnida						
Order Opiliones						
harvestman spider	troglophile?	-*	+	+	+	+
Class Malacostraca						
Trichoniscidae (isopods)						
Brackenridgia sp.	troglobite	+	+	+	?	-
Class Insecta						
Campodeidae						
Plusiocampa sp.	troglobite	-	+	+	+	+
Rhaphidophoridae (cave cricket)						
Ceuthophilus pima	troglophile	+	+	-[1]	+	-[2]
Carabidae (ground beetle)						
Rhadine sp. (beetle)	troglophile	-	+	+	+	+

*A + indicates that the species has been sighted. A - indicates that it has not. A ? means that the presence of the species is suspected but not found.

1. Ceuthophilus allpaucispinosus present
2. Ceuthophilus papago present

common arthropods (a troglophilic opilionid, a carabid beetle, and a dipluran) found in other southern Arizona caves (Table 32).

There are two possible explanations for the absence of these cave forms. One is that they were present at one time, but for an unknown reason they became extinct in Kartchner. Another possibility is that Kartchner Caverns was only available for colonization when the climatic conditions were such that these cave forms were not able to colonize the cave. Additional information on the climatic history of the area and more detailed study of fauna in other caves may help to understand the differences in the cave fauna.

A comparison of Ceuthophilus in southern Arizona found C. pima in another cave in the Whetstone Mountains and in caves in the Santa Rita Mountains.

Ceuthophilus pima usually occurs above 5000 feet elevation with denser vegetation than now occurs around Kartchner suggesting the Kartchner population is a relict from when the climate was wetter and more vegetation occurred in the area. Caves in the Huachuca Mountains and Catalina Mountains have different species of Ceuthophilus, C. allpaucispinosus and papago respectively. This suggests the Whetstone and Santa Rita Mountains may share other cave fauna.

Although there has been little work with the guano mites, my work in Kartchner Caverns and Carlsbad Cavern (New Mexico) indicates the bat guano community is unique. Only the genus Geolaelaps is shared between Carlsbad Cavern and Kartchner Caverns.

CAVE FAUNA AND RELATIONS TO THE SURFACE AND POSSIBLE OTHER ENTRANCES

Based on my work with the cave fauna, there are currently only two openings from Kartchner Caverns to the surface. One is the current entrance used by the bats, humans and arthropods, while the other is in Granite Dells. The Granite Dells entrance is too small for anything other than arthropods and small rodents. Historically there have been other openings to the surface. The large collapses at Sue's Room and in the Throne Room and the very old guano suggest there were other entrances in the past that may have provided access and/or closed off that part of the cave. In the Front Section the collapse in the Tarantula Room was apparently very recent. Fragments of surface arthropods were found in that area, but the absence of cave crickets in the upper areas indicates no connection to the surface at the present time. The presence of more than an occasional camel cricket is a good indicator of an opening to the surface.

MANAGEMENT RECOMMENDATIONS

The invertebrate fauna of Kartchner Caverns is unique with several new species that may be endemic to Kartchner Caverns. Every effort should be made to keep disturbance of the cave soil to a minimum.

Development of Kartchner Caverns must be scheduled in a way to preserve the bat population in the Big Room. The loss of the bats from the Big Room in Kartchner Caverns would result in the extinction of most of the arthropod fauna in the cave. Development in the Back Section, especially the Throne and Rotunda Rooms would have the least impact on the cave fauna.

Care must be taken during construction and subsequent tours to insure the cave environment remains unchanged and exotic species are not introduced into the cave. A change in the environment and/or the introduction of surface species could

result in the disruption of the cave community and eventually the loss of one or more cave species.

Recommendations

1. Development must be planned and scheduled to minimize disturbance to the bat colony.
2. The current invertebrate cave fauna should be monitored at least twice a year to establish long term data on cave fauna populations and to note any changes that may occur during and after the cave is developed.
3. Care must be taken to prevent the introduction of exotic fauna into the cave during construction and subsequent public tours.
4. The area around the artificial entrance should be monitored to note any changes in the fauna and the introduction of any exotic species.
5. The surface area around the two known entrances (Entrance Sink and Granite Dells) should be maintained in a natural state.

SPECIES ACCOUNTS

CLASS NEMATODA

Bacterial-feeding nematodes were found in the fresh bat guano in the Big Room. These invertebrates are common inhabitants of bat guano and serve as prey for some of the arthropod predators.

CLASS ARACHNIDA

Order Palpigrada - Cave Spider (Figure 89)

A single specimen of palpigrade was found in the Big Room. This tiny arachnid is not common in caves and a single specimen is not sufficient to determine status or relationship to the cave.

Order Scorpionida - Scorpion

Scorpions have been in the entrance area of Kartchner Caverns on several occasions. In May, 1991 a single specimen was found on a guano pile (9C) at Sharon's Saddle in the Big Room. Prior to this observation the deepest penetration into the cave was a specimen found in what is now called the Scorpion Passages near Grand Central Station. These arachnids represent only accidental occurrence in the cave and are not cave adapted.

Order Araneae - Spider

Only one species of spider was regularly found in Kartchner Caverns. This species has been tentatively identified as Eidmanella pallida (Emerton), a pale colored spider that makes irregular webs in cracks and under rocks in caves throughout the southwest. Most individuals have reduced eyes and are considered troglophiles. In Kartchner Caverns, some individuals appear to be eyeless and may be troglobitic. E. pallida makes webs in cracks, under rocks, and on the trail flagging mostly in the Big Room and are common near the guano piles. E.pallida was rarely observed on fresh guano, but was frequently found on older guano. On one occasion 15 spiders were found on guano pile 9C six months after the bats had migrated. Breeding probably occurs year round, as females with egg cases were observed in May and October. E. pallida is a predator of small arthropods, with Diptera and mites as the primary prey.

The population size for E.pallida was difficult to estimate because observations were restricted to sites along the trails and the population size varied from year to year. Population estimates were made by counting the number of spiders along the Big Room loop trail. The maximum Big Room population occurred in May,1990 with an average of one spider every 25 feet. Most individuals were concentrated between Sharon's Saddle and Kartchner Towers and in the Lunch Spot area. The population was usually much lower with only one spider per 50-60 feet of trail. Critical habitat for this spider is the breakdown and formations in the vicinity of the Big Room guano deposits.

Order Acari - Mite (Figure 90)

Mites are the most numerous invertebrates in Kartchner Caverns, with at least 10 species. Nearly all of the mites are dependent on the annual renewal of the bat guano deposits in the Big Room for survival. Sancassania, a fungivore, is the most common mite in fresh guano with 50 to 500 individuals per cubic inch of fresh guano. Sancassania survive the periods without food by halting development at the non-feeding deutonymphal stage that can survive for long periods without food.

The primary predator in the bat guano is Geolaelaps (Laelapidae). This mite is usually common in fresh bat guano where they prey upon the Sancassania and other small arthropods. Unlike Sancassania, Geolaelaps does not have a non-feeding stage, but regulates its population in response to the available prey. Population estimates range from 1 to 20 per cubic inch of fresh guano. A related species of this mite also occurs in the bat guano at Carlsbad Cavern, New Mexico.

Most of the remaining bat guano mites, oribatids and Eustigmaeus (Stigmaeidae), are usually found in guano piles that receive only small amounts of fresh guano each year. The number of individuals ranged from 1 to 5 individuals per cubic inch of guano. Very little is known about the biology of these mites. The oribatid mites are still being studied and preliminary indication is there are at least an additional two or three species including possibly a new genus.

Only one species of parasitic mite was found on the guano. Two engorged larvae and two deutonymphs of a soft tick (Argasidae) were found on guano piles 9 and 10. The presence of only engorged larvae and deutonymphs suggests these parasites were carried into the cave by the bats from other roosts and do not reproduce in Kartchner Caverns. This tick is a specialized bat parasite and does not attack humans.

There were two mites not associated with bat guano in Kartchner Caverns. One, Poecilophysis sp. (Rhagidiidae), is known from only two specimens, one found in the Main Corridor and the other in the Anticipation Room. Rhagidiids are found in many caves and feed on other mites and small arthropods. The other mite, Ceuthothrombium (Neothrombiidae), is unique in that it spends its larval stage as a parasite of camel crickets (Ceuthophilus) and the rest of its life as a free-living predator of other mites and small arthropods. The larvae of Ceuthothrombium are common around the base of the legs of C. pima year round, with 1 to 8 mites per cricket. The parasitic larvae do not appear to have any effect on the cricket host as nearly all adult Ceuthophilus in Kartchner Caverns were parasitized. The white and eyeless active post-larval stage was discovered only by laboratory rearing, but probably occur in the cave soil. The critical habitat for these mites is the same as the host.

Order Pseudoscorpiones - Pseudoscorpion (Figure 91)

Two species of pseudoscorpions (as yet undescribed) were found in Kartchner Caverns. Both were found near the entrance with the deepest penetration just past the Babbitt Gate. A gravid female was observed in October, 1989. These arachnids are usually found under rocks and are predators of other arthropods. Only three individuals were observed, thus making a population estimate impossible.

CLASS CHILOPODA

Order Scolopendromorpha - Centipede

A single undetermined scolopendromorph centipede was observed in Grand Central Station and probably represents an accidental occurrence for Kartchner.

CLASS MALACOSTRACA

Order Isopoda - Isopod (Figure 92)

The most widespread invertebrate in Kartchner Caverns is the troglobitic isopod, Brackenridgia sp. (Trichoniscidae). This isopod was observed in nearly every part of the cave. Although individuals were not always present, their frass and evidence of feeding was observed on old wooden survey markers throughout Kartchner, except the Throne Room and upper portion of the Rotunda Room. These isopods prefer damp to wet soil and mud substrate, but were occasionally found on old bat guano. They rarely occurred on breakdown or formations. Little is known of their biology. Their population is patchy throughout the cave, with fewer than 5 individuals at a single food source. Critical habitat for Brackenridgia is the mud floored areas of the cave.

A surface isopod, Porcellio sp. (Oniscidae) was frequently observed in the entrance area as far as the Main Corridor. Occasionally individuals were observed on fresh bat guano in the Big Room. These surface isopods may be able to survive in the entrance area with frequent recolonization from the surface. Only adults were observed in the Big Room guano piles suggesting they are accidentals and can not survive in the deep cave.

CLASS INSECTA

Order Collembola

Collembola were not common in Kartchner Caverns. Only a few individuals of Sminthuridae and Entomobryidae were observed. Most collembolans were observed in the area between the Babbitt Gate and Main Corridor. The smithurids were usually found on the surface of small pools from the Main Corridor to the Strawberry Room. It is likely that collembolans are more widespread, but their small size, usually less than 5 mm, and low population make them difficult to find. Critical habitat would include small pools, mud floors and guano areas.

Order Psocoptera - Book Louse

The psocids or book louse, Psyllipsocus ramburii Selys-Longchamps (Psyllipsocidae), is widely distributed in many caves in the southwestern United States. In Kartchner Caverns psocids are distributed from the entrance through the Big Room. They were found on guano piles and other organic material in the Big Room. As with most of the other invertebrates the population level is very low with only one or two individuals observed at any one site. Critical habitat for this insect is the entrance area and the area around the guano piles.

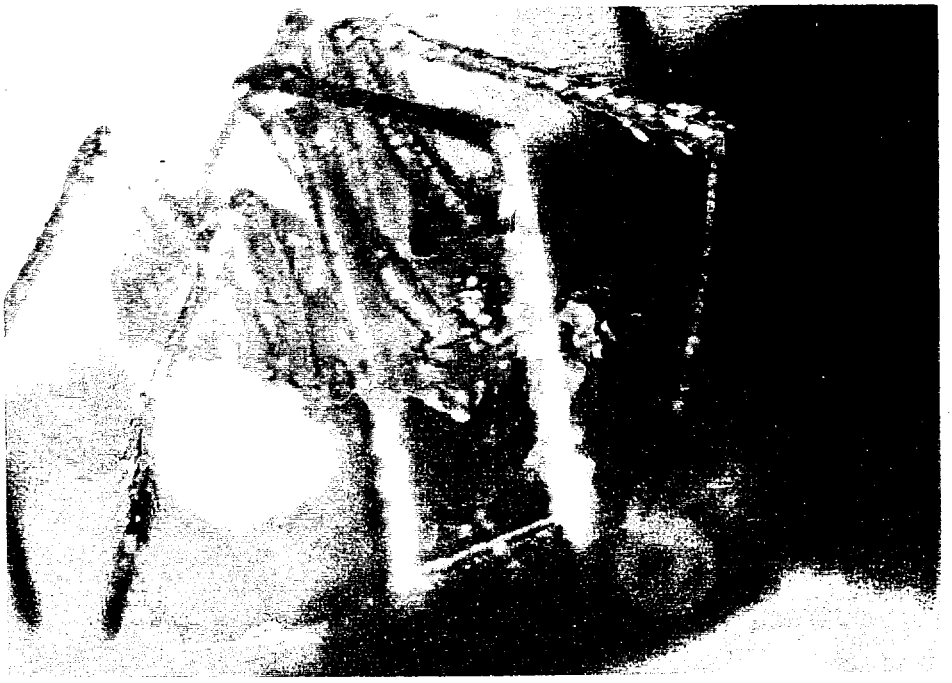


Figure 89. Microphotograph of a Cave-Adapted Spider (Eidmanella sp.). Size is approximately 1/4". Photo by Dr. Welbourn.

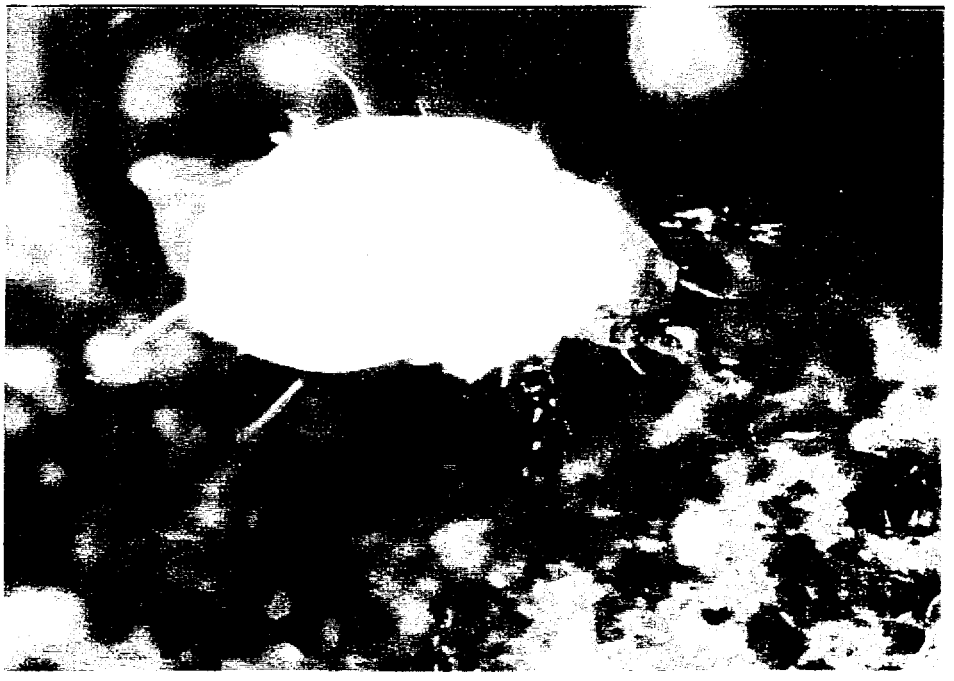


Figure 90. Microphotograph of a Mite, Acaridae (Sancassania sp.). Size is approximately 1/64". Photo by Dr. Welbourn.

Figure 91. Microphotograph of a Pseudoscorpion (undetermined genus). Size is approximately 1/8". Photo by Dr. Welbourn.

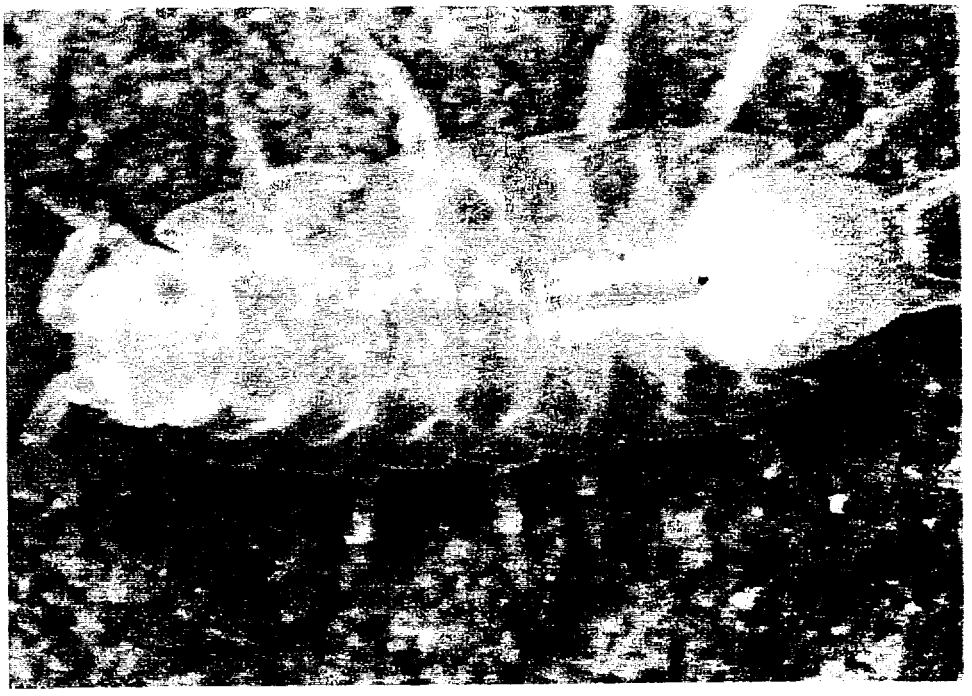


Figure 92. Microphotograph of an Isopod (Brackenridgia sp.). Photo by Dr. Welbourn.

Order Thysanura - Bristletail

Only three individuals of this rare bristletail, Nicoletia sp. (Nicoletiidae) were observed near the entrance to the Red River Passage in Kartchner Caverns. The genus is known from caves in Texas and this is the second record of the genus from an Arizona cave. Nothing is known of the biology and population size of Nicoletia in Kartchner. Critical habitat for this species appears to be the mud floor around the entrance to the Red River Passage.

Order Orthoptera

Next to the troglobitic isopod, Brackenridgia, the most common invertebrate observed in Kartchner Caverns was the camel cricket, Ceuthophilus pima Hubbell (Rhaphidophoridae). These crickets are common from the entrance area to the Main Corridor. While most are concentrated near the entrance, crickets were frequently found in the Big Room, usually on or near the fresh guano deposits. Like other species in the genus these crickets usually leave the cave to feed, but will feed on carrion or bat guano in the cave. Individuals from Kartchner have been found in the wash 200-300 feet from the entrance. The Kartchner Caverns population of C. pima is unique for the species in that reproductive adults can be found at any time of the year. It has been suggested that the Kartchner population my represent a distinct subspecies, but additional comparative study is needed to determine the status of the Kartchner population. Population estimates range from 300 to 800 individuals, with the peak population occurring in the mid to late summer.

A second small population of C. pima was found in the Granite Dells area of the cave, suggesting a direct opening to the surface in that area. Examination of the surface revealed several cracks, including one that was blowing moist air. Baiting in the vicinity of the crack resulted in 58 crickets in one night. All but a few specimens were marked with fluorescent powder and released. Crickets in the Granite Dells area were examined for fluorescence, but none were marked crickets. The large number of crickets from the surface cracks and low numbers (3-12) in the Granite Dells area suggests there are additional voids between Granite Dells and the surface that can support a large cricket population. C. pima was also found in the other small caves on the north side of the hill from the Kartchner Caverns entrance.

Occasional lost individuals (usually dead) were found in various parts of the cave suggesting the crickets have been in most parts of the cave, but only those areas with direct connection to the surface support a cricket population. There is probably not much interaction between the Granite Dells population and the Entrance Sink population.

Ceuthophilus pima is also found in another cave in the Whetstone Mountains and in caves in the Santa Rita Mountains usually above 5000 feet elevation. Caves in the Huachuca Mountains and Catalina Mountains have different species of Ceuthophilus, C. allpaucispinosus and papago respectively. The Kartchner Caverns population is different from other populations of C. pima in that it breeds year round, has pale coloration, and occurs in a more open habitat than the other populations. While additional study is needed, it appears that the Kartchner caverns population of C. pima has been isolated from other populations and may be a separate subspecies.

The critical habitat for C. pima in Kartchner is the main entrance area and the area between the surface cracks and Granite Dells. Egg deposition occurs in soft soil in the entrance area as far in as the LEM Room and into the sides of the abandoned stream passage in Grand Central Station. In the Granite Dells area there is also a

small area of soft soil that may be an egg deposition site. It is likely there are other inaccessible areas between Granite Dells and the surface that serve as cricket breeding areas.

Order Hemiptera

This hemipteran (Reduviidae) was found in several widely separated areas in 1990. Although this insect has been found in other western caves it is considered an accidental and not part of the regular cave fauna.

Order Coleoptera - Beetle

Only one undetermined beetle in the family Staphylinidae was observed in the Big Room near guano pile 9. Other beetles included undetermined fragments from the Tarantula Room and Eleodes sp. from the entrance area.

Order Lepidoptera

Three undetermined moths were observed in Kartchner Caverns. Two were near the entrance and the third was found in the Granite Dells area. The moth in Granite Dells adds additional support to the possibility of a direct connection to the surface in that area.

Order Diptera

Flies are relatively common in the Big Room and are frequently attracted to cavers lights. Two species have been observed with the common species belonging to the family Sciaridae. The flies appear to breed in the fresh guano because maggots were found between May and August. Adult flies are most common in the Big Room between Sharon's Saddle and Kartchner Towers. Undetermined fly larvae were also found in a dead cave cricket in Grand Central Station. The critical habitat for the fly appears to be the guano piles where breeding occurs.

Order Hymenoptera - Ant

While ants (Formicidae) were not observed in the cave during this study, extensive "trails" were observed in Mud Flats,at the entrance to Red River Passage, and along the first part of the Red River Passage. It is not possible to determine how long it had been since the ants were active in the cave, but the position of one trail, which had been routed around the edge of a footprint, suggests ants have been active since the discovery of the Big Room.

PLANT GROWTH POTENTIAL

A study of the potential for plant growth potential in Kartchner Caverns was conducted by the Ozark Underground Laboratory (OUL) (Aley and Aley, 1990a). A draft version of the report was submitted in July 1989. To date, revisions to the report requested as part of ACPI's Quality Assurance review have not been addressed. The report also appears to be deficient in that no growth testing of samples fertilized by materials such as lint, cave sediment and hair has been performed. The draft report confirms the presence of viable algae and fungal spores in the cave, but it has not shown that the materials in the cave are capable of supporting growth with the addition of light and suitable nutrients.

For the purposes of this report, "plants" include fungus, cyanobacteria, algae, moss and moss protonema, and ferns. "Exotic" plant growth includes any unnatural or enhanced growth of any of these plants.

The growth of fungus, cyanobacteria (formerly called blue-green algae) algae, moss, and ferns on speleothems and other cave surfaces is a common situation in electrically-lighted show caves. Such growth is generally considered to be a problem for four reasons:

1. The growth detracts from the natural appearance of the cave.
2. The growth can significantly damage speleothems.
3. The growth provides unnatural food for cave animals and may thus alter the composition and distribution of the cave fauna.
4. Fungal hyphae may be implicated in orienting the growth of soda straws; the absence of fungal hyphae may be implicated in the growth of helictites. The existence of fungal effects on speleothem deposition is the subject of scientific debate.

Exotic plant growth in electrically-lighted caves requires, or is enhanced by, the following five important factors:

1. Light intensities as low as 0.8 foot candles, or even less, have caused plant growth in some American show caves.
2. Moist surfaces.
3. Soft substrates (such as sediment on speleothems or moonmilk deposits).
4. Nutrients; these include lint, hair, and bat guano.
5. Time; this may be related to the development of adequate nutrient enrichment of substrates to facilitate plant growth.

A number of plant control strategies are reviewed. These have included the use of various herbicides and algacides, hot water steam, germicidal lamps, green lights, and oxidizing agents. The most effective and least damaging plant control strategy involves minimizing light intensities on sensitive substrates and frequent inspection and control with a 5.25% sodium hypochlorite solution. Light intensity guidelines for Oregon Caves and Carlsbad Caverns are summarized.

Three taxa of green algae were isolated from substrate samples collected in Kartchner Caverns. These were Chlorella, Chlorococcum, and Spongiococcum. None of the algae were found growing in any of the numerous samples collected; instead, the algae were present only in a dormant stage.

An extensive literature review was made of algal taxa reported growing in total darkness in caves or found in exotic plant growth in caves around electric lights. Chlorella and Chlorococcum have both been found growing in both dark and lighted conditions in caves; readily visible growth of Chlorococcum has been found in Oregon

Caves at light intensities as low as 0.79 foot candles. Chlorella was used in growth plot studies in Oregon Caves, and was found to thrive on substrates which included sediment and lint coatings. Based upon our literature review, Spongiococcum has not been reported from any cave other than Kartchner Caverns. However, it grew more rapidly than any of the other taxa found in Kartchner after receiving light and nutrients.

Attempts were made to isolate algae spores in cave air by drawing samples through glass filters at a number of sites in Kartchner Caverns. No algae were found in any of the sample filters.

Fungal studies were also made in Kartchner Caverns. One or more species of fungus were found in 68% of the substrate samples studied and in 73% of the air filter samples. The four most common fungi were Scopulariopsis asperula, Aspergillus nidulans, Alternaia alternata, and Penicillium glabrum; all of these were found in both substrate and air filter samples. The fungal studies in Kartchner Caverns involved plating out samples on various mediums. The plates showed little or no growth for a period of some weeks, but eventually growth did appear on most plates. This slow growth is attributed to the absence of actively growing fungi in the samples. The samples appear to have contained only spores.

Neither substrate nor air samples recovered any systemic fungal pathogens. Histoplasma capsulatum is an example of a systemic fungal pathogen which is sometimes found in caves; it was not found in any of the samples from Kartchner Caverns.

The cave management implications of the plant growth studies are discussed in detail. While there was no detected growths of algae, cyanobacteria, and fungi in Kartchner Caverns, dormant stages of algae and fungal spores are present within the cave. There are at least three taxa of green algae isolated in a dormant stage from the cave that, with the addition of light and nutrients, will grow reasonably rapidly. Similarly, many of the fungi will also grow when provided with proper substrates.

The presence of a thin film of sediment on many speleothems in Kartchner Caverns is of concern. The sediment consists of charged clay particles which will adsorb lint and tend to create a favorable substrate for plant growth in the cave. The common plant control approach in electrically-lighted caves is to kill plant growth with a mist of a 5.25% sodium hypochlorite solution followed by a water rinse. This approach would remove the natural sediment from the speleothems, thus altering the natural integrity of Kartchner Caverns. Various strategies which could be used to deal with this situation include major efforts to reduce the input of nutrients to the cave, coupled with the use of non-fixed lights (except for dim trail lights).

The recovery of two genera of algae (Chlorella and Chlorococcum) from the whitish crust on cracked floor sediments is of significant concern. The sediments at the sampling site are undoubtedly within an area which is periodically inundated by storm waters. We see no reason for these sediments to be appreciably different from the sediments which lightly coat many speleothems in Kartchner Caverns. We must anticipate that dormant stages of algae exist on some (and perhaps many) of the sediment-coated speleothems in the Caverns. If light and additional nutrients are added to the cave, algal growth on speleothems must be anticipated.

Mud-coated speleothems (and other mud-coated cave surfaces) will be particularly prone to algal growth when light is added to the Caverns. There are two reasons for this. First, the mud-coated speleothems provide a better substrate for algal growth than is provided by clean speleothems; this has been clearly shown by work in Carlsbad Caverns and Oregon Caves (Aley and Aley; 1984 and 1985), and is

supported by observations of other workers (Aley, 1990). Both Chlorella and Chlorococcum were associated with muddy bedrock and speleothem surfaces in Oregon Caves and Carlsbad Caverns (Aley and Aley; 1985 and 1984).

The second reason why mud-coated speleothems and other mud-coated cave surfaces will be particularly prone to algal growth is that the cave mud consists predominantly of clay-sized particles. Clay particles are charged, and for this reason adsorb lint particles and other charged particles. A common result in show-caves are "clay-worms" (vermiculations) composed of clay particles, lint, and other detritus. Since most lint particles have been through a laundry with detergents that contain phosphates, the lint particles in turn contain appreciable concentrations of phosphates. Studies in Oregon Caves and Carlsbad Caverns (Aley and Aley, 1985 and 1984) have clearly demonstrated that lint deposits are strongly correlated with accelerated plant growth in electrically-lighted caves.

The absence of algae in filters through which air was passed suggests that, under present conditions, algae are rare and perhaps absent in cave air. This finding would have been more encouraging for cave management had we not found that dormant stages of algae already exist within the Caverns. While airborne transport of viable algal materials may be minimal within the Caverns, waterborne transport and transport by bats undoubtedly occurs. Similarly, some viable algal materials are undoubtedly transported by people visiting the Caverns. While minimal airborne transport of viable algal material may retard the establishment of algal growths within the Caverns after show-cave development, we see no reason to expect the Caverns to be protected from algal growth because of minimal airborne transport.

As noted earlier, the algologist was impressed by the paucity of algae existing within Kartchner Caverns. A somewhat similar suite of samples collected in unlighted portions of Tumbling Creek Cave, Missouri, contained a much more extensive algal and cyanobacterial flora than that recovered in Kartchner Caverns. Part of the difference may lie in the fact that Kartchner Caverns is located in an arid region where algae are less abundant than they are in the humid lands of Missouri. However, we must not presume that, because the present algal and cyanobacterial materials in Kartchner Caverns are limited, plant growth will be minimal if artificial lighting is added to theCaverns. That is, unfortunately, not likely to be the case.

Management of exotic plant growth in electrically-lighted caves typically involves both growth preventing and growth control efforts. Prevention of exotic plant growth relies heavily on careful control of light intensity reaching sensitive growth substrates. Control of exotic plant growth relies on frequent inspection and treatment of plant growth as it first becomes established. The treatment which is the most effective and has the least harmful impacts upon cave resources is the application of a light mist of 5.25% sodium hypochlorite (bleach). This treatment is usually followed by washing with a spray of water to remove dead plant material and sodium chloride resulting from the sodium hypochlorite solution.

It has already been noted that many of the speleothems and bedrock surfaces in Kartchner Caverns are lightly coated with sediment from flooding. Standard treatment of such surfaces to control plant growth would remove some, or perhaps most, of this sediment from treated areas. This would change the natural appearance of the cave features. Treatment of the cave surfaces without a water rinse would, in the long run, also change the natural appearance of cave features. The no-treatment option would result in the greatest change to the natural appearance of cave features and would be an unacceptable strategy if exotic plant growth became established on the cave

features. The no-treatment option would also permanently damage speleothems upon which exotic plant growth occurred.

An alternate management strategy would be to prevent exotic plant growth in Kartchner Caverns. This would require that no fixed lights be used to illuminate speleothems or other cave features which were coated with sediment. Fixed trail lights could be used if the areas they illuminated could be periodically treated with a 5.25% sodium hypochlorite solution (this would generally create no significant problems). Illumination of speleothems or other cave features which were coated with sediment would rely entirely on non-fixed lights. To avoid any confusion, non-fixed lights could be hand-held or, perhaps, anchored along the trail in such a way that the guides and/or visitors could use them to point out various features in the Caverns. Such a light in Oregon Caves is the only light in that cave which has no plant growth associated with it.

Aley and Aley (1984) recommended the following light intensity guidelines for fixed lights in Carlsbad Caverns:

> Maximum light intensities reaching moist alcove surfaces should be less than 0.9 foot candles if plant growth is to be largely prevented in such sites. Maximum light intensities reaching moist non-alcove surfaces should be less than 2.8 foot candles if plant growth is to be largely prevented. Where this value is undesirable for interpretive or other reasons, plant growth can be minimized and often prevented by keeping light intensities reaching moist surfaces at less than 3.6 foot candles.

Aley and Aley (1985) recommended the following light intensity guidelines for fixed lights in Oregon Caves:

> Light intensities reaching moist surfaces should not exceed 4.2 foot candles. For ideal plant growth prevention, sensitive cave features should receive light intensities of not more than 2.5 foot candles.

If the prevention of exotic plant growth strategy were to be implemented in Kartchner Caverns, it should be accompanied by efforts to minimize the introduction and accumulation of lint, hair, and similar visitor-derived materials. Visitors could be encouraged not to bring sweaters and similar "linty" garments into the cave, yet this would probably not be very effective in minimizing lint additions to the Caverns. Steve Fairchild (personal communication, 1989) examined lint accumulations in California Caverns and concluded that the majority of it is derived from jeans and slacks, and that the lint is a product of normal walking. An alternate approach would be to require cave visitors to wear something such as a disposable "clean room" suit; this approach could be very effective in minimizing lint additions to the Caverns.

Exotic fungal and bacterial growths in show caves are less common problems than the exotic growths of algae, cyanobacteria, and mosses. This is due in part to the fact that fungus and bacterial growths are seldom as visible as are growths of the algae, cyanobacteria, and mosses. However, fungal and/or bacterial growth may be an important precursor to algal and cyanobacterial growth in caves (Cubbon, 1976) by

enriching the substrate and thus permitting extensive and rapid growth of algae and cyanobacteria.

Fungal and bacterial growth is dependent upon moisture and nutrients. Kartchner Caverns certainly has adequate moisture; as is the case in most caves, it is the nutrients which are missing. The extensive growth of a black fungal coating on the ceiling of the Snowball Dining Room in Mammoth Cave (Aley and Aley, 1986 and 1990b) was correlated with increased moisture and major increases in nutrients in this portion of the cave. Fungal and bacterial growths of sufficient magnitude to produce readily visible impacts in caves are likely to be uncommon and restricted only to caves which receive major nutrient additions.

The fungal studies of substrate and air filter samples in Kartchner Caverns involved plating out samples on various mediums. The plates showed little or no growth for a period of some weeks, but eventually growth did appear on most plates. This slow growth is attributed to the absence of actively growing fungi in the samples. The samples appear to have contained only spores. These findings have important cave management significance since they suggest that Kartchner Caverns has little or no fungal growth at present. However, the studies clearly demonstrate that fungal spores are present and fungal growth could become established if changes in cave conditions provide suitable conditions for such growth. It is likely that nutrients are the limiting factor which presently minimizes or prevents appreciable fungal growth in the Caverns.

Another finding of cave management significance is that neither substrate nor air samples recovered any systemic fungal pathogens. Systemic fungal pathogens include Histoplasma capsulatum. This is the causative agent for the disease histoplasmosis. Histoplasmosis has resulted from visits to some caves, and in particular to caves in moist, tropical environments.

SMALL MAMMALS
AT KARTCHNER CAVERNS STATE PARK

INTRODUCTION

In this final report, I summarize the data collected on the small mammals found around cave entrances at Kartchner Caverns State Park during four censuses in 1989. The following five cave entrances were checked: 1) Main entrance, 2) West cave, 3,4,5) North #1, #2, #3 caves. The Main entrance is a large sinkhole that leads into the cavern. The West cave is a large opening approximately 50m southwest of the Main entrance. The other three caves are on the north side of the hill that contains the Main entrance. These three small caves are within 50m of each other and are greater than 0.5 km from the Main entrance.

The four censuses corresponded to the four seasons of the year. The censuses were conducted during the following days: Winter, Feb 26-March 10; Spring, April 29-May 1; Summer, August 15-18; Autumn, October 13-15. Each census period lasted at least three days.

Small mammals were counted using Sherman live traps. Each day, several traps were placed at each site at dusk and then checked the following morning. Usually, six traps were placed at each entrance with the exception of North #2, a small cavelet, where I placed two traps. Each individual was identified, sexed, weighed, marked and then released.

MAMMAL CENSUS RESULTS

Total census effort consisted of 302 trap-nights. Over the course of the year, I captured 92 individuals. A total of five species was recorded. The white-throated woodrat (Neotoma albigula), cactus mouse (Peromyscus eremicus), and brush mouse (Peromyscus boylei) were captured repeatedly. In addition, I captured one Merriam's kangaroo rat (Dipodomys merriami) during the summer census and one Bailey's pocket mouse (Chaetodipus baileyi) during the autumn.

Figure 93 summarizes the capture results for the three most common species. The numbers for N. albigula peaked in the winter and then declined throughout the year. P. boylei was common in the winter and spring but was not captured in the last two census periods. P. eremicus numbers steadily increased during the year.

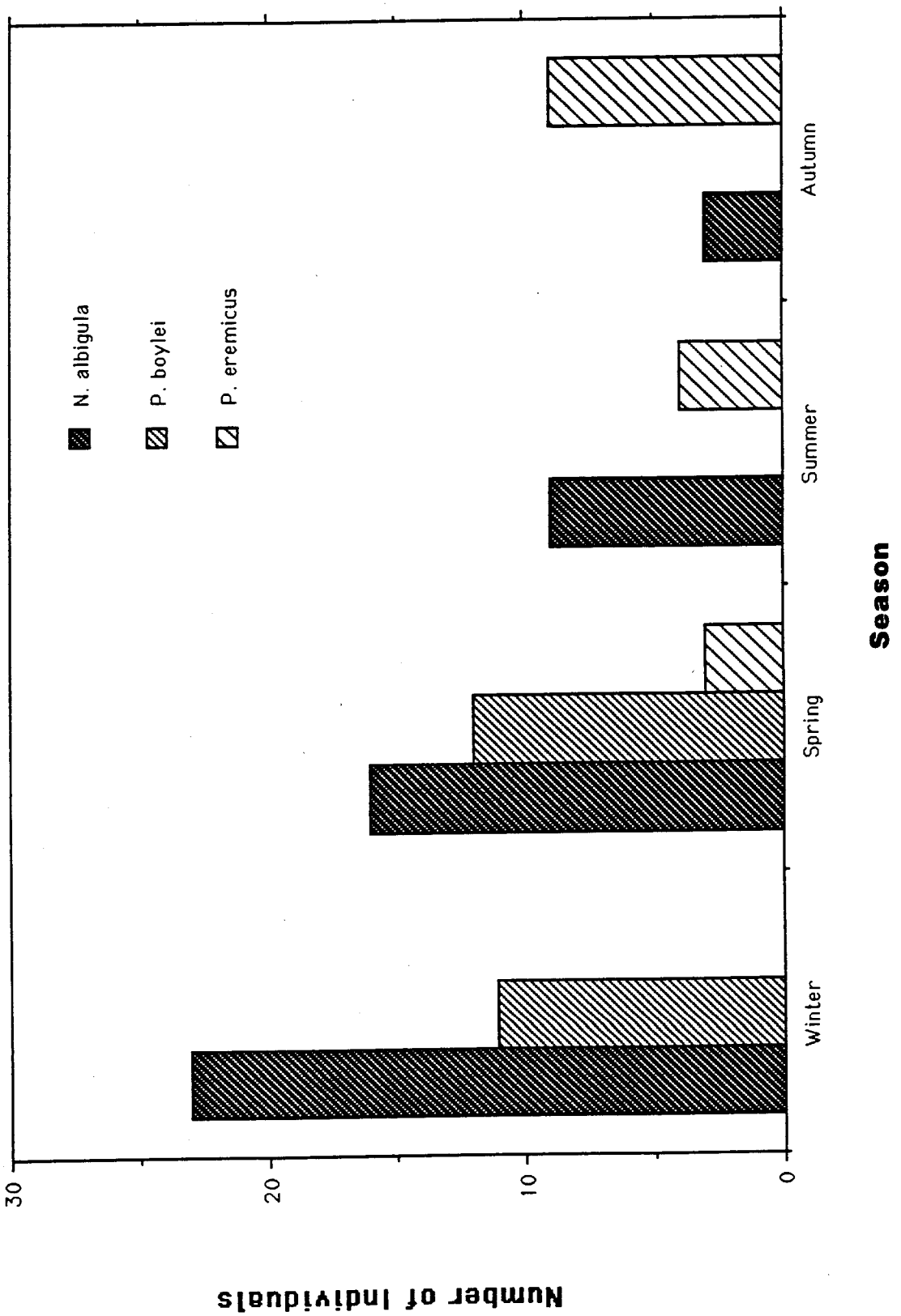
While performing these censuses, I also observed two spotted skunks (Spilogale gracilis); one was in the West cave (autumn), the other was seen in the North #1 cave (winter). I also observed a small herd (5 individuals) of mule deer (Odocoileus hemionus) just west of the Main entrance and heard coyotes (Canis latrans) on several occasions.

RECOMMENDATIONS

None of the mammals recorded in the cave entrances is on the endangered species list. All are common throughout the southwestern United States. Development of the Main entrance for public use should have minimal impact on the small mammals at the site. The larger mammals recorded (deer and coyote), however, may be affected by extensive development of the site. One way to potentially minimize the impact on large mammals is to leave large tracts of adjacent land undeveloped. This will allow these mammals to use the park freely and at the same time also allow them a refuge from any development.

FIGURE 93

KARTCHNER CAVERNS STATE PARK
RESULTS OF SMALL MAMMALS TRAPPING
(all sites combined)



AMPHIBIANS AND REPTILES

A field study of the amphibians and reptiles was conducted at Kartchner Caverns State Park (KCSP) from March to December 1989 and reported on in detail in ACPI's Interim Report (Buecher, 1991). Twenty-two species were observed during eighteen field-person days (twenty-two calendar days) at the site. No amphibians were observed during June, or in September-November, and none of the herpetofauna were seen in December. About half of the time was spent intensively searching the vicinities of five cave entrances. The remainder of the time was spent searching throughout the park. When possible, individual animals were marked for future identification.

The primary objective was to determine which species frequent the cave entrances. This study did not attempt to survey the entire herpetofauna of the park. Several field guides adequately account for the reptiles and amphibians of the geographical region. The species listed here represent a significant part of the diversity present.

Six species of reptiles were observed utilizing cave entrances during this study. These are the Western Diamondback Rattlesnake, Crotalus atrox; Black-tailed Rattlesnake, Crotalus molossus; Gila Monster, Heloderma suspectum; Tree Lizard, Urosauraus ornatus; Clark Spiny Lizard, Sceloporus clarki; and the Desert Grassland Whiptail Lizard, Cnemidophorus uniparens. The Gila Monster is an Endangered Species and should be protected as such.

Because of concerns for visitor safety, we emphasize that the first three species are dangerously venomous. Aside from being part of the limited assemblage of species that utilized the cave entrance, they also were the only three dangerously venomous species found elsewhere in KCSP.

The two rattlesnake species were commonly found by us and other persons working on the grounds. They were the most commonly encountered of all snakes found here, and were most frequently located in the immediate vicinity of the cave entrances. The poisonous Gila Monster is less of a risk and hazard to humans. Rattlesnakes are also both large-bodied and abundant on the site. They are cryptically-colored, may not rattle and they certainly utilize cave entrances. They are also beautiful and ecologically important and should be protected. It is important for staff and visitors to look carefully before placing hands and feet at all times. One or more posted signs should clearly alert visitors.

Large numbers of diamondbacks may aggregate at the cave entrances and use the caverns for hibernacula. The species disperses from these areas in March and April and returns in September through November. It preys on cottontail rabbits, squirrels, other rodents, birds and lizards, often waiting in a tight coil beside a trail, day or night.

In contrast to most rattlesnakes, the Gila Monster is a widely foraging carnivore. It will utilize cave entrances for refuge occasionally to regularly and may hibernate inside. The Gila Monster is mainly diurnal and searches for nests, preying on young cottontail rabbits, rodents and ground-nesting birds. An adult typically consumes a meal (e.g., a nest of small squirrels) three to four times a year.

At KCSP, and elsewhere in Arizona, the Western Diamondback and Black-tailed Rattlesnake are sympatic species. The former is ecologically distributed upwards into the Park from the bajada east, the latter ranging downwards from the high rocky slopes of the Whetstone Mountains west of the Park. KCSP not only contains a unique geological wonder, but also a unique natural environment for these two rattlesnakes. Many individuals of both species include the cave entrances within their seasonal

home ranges (C. atrox), if not during the entire course of the year (C. molossus). Due to the clustering of these microhabitats and at least one other denning site at KCSP, the two rattlesnake species may be more commonly seen within KCSP than in adjacent areas beyond its boundaries. They were the largest, most conspicuous and distinctive vertebrate denizens of the cave entrances.

C. atrox was observed most frequently in the early-spring and late-fall months, in fact being the only reptile or amphibian found in late October and November. C. molossus was most evident during the mid-summer to early-fall months. Thus a species of rattlesnake may be seen on the surface at KCSP from at least March to November.

Communal winter denning of C. atrox is well documented in literature. C. atrox basks frequently and is thus conspicuous in fall when they gradually gather at the cave entrances and elsewhere to hibernate, and even more so in spring when they explosively emerge. They then leave their winter dens for the summer months. During hibernation, these snakes remain concealed in narrow crevices near the outer parts of the cave entrances. The snakes probably seldom, if ever, penetrate the deeper recesses of the cave.

Unlike C. atrox, there are no references in literature to winter assemblages of C. molossus. Communal denning in this species may not have evolved because of its southerly distribution, despite the high montane limits it attains within its geographical range. It may be possible that the species is present at the cave sites in spring and fall in numbers but remain inconspicuous. Although in Arizona C. molossus has been found on the surface from February to December, numerous authors have emphasized summer observations of this species. Most of our observations of this species corresponded to this time of the year. Future investigations may show the co-habitation of both species hibernating at the cave entrances.

So may future investigations reveal more information on the Gila Monster. Although only two individuals were seen during this study, one was found at the main entrance. (Editor's note: three Gila Monsters were also sighted independently by ACPI employees, leading us to believe there may be a reasonably-sized population on the park. More study may be needed on this endangered species.)

The cave entrances do not appear to be of significant importance to the local populations of the three remaining lizard species noted. They were otherwise abundant throughout the Park in a variety of microhabitats. The cave entrances were included in the home ranges of just a small number of the respective species. Two of them, the Tree Lizard and Clark Spiny Lizard, may utilize these sites frequently, the cave entrances functioning as a favored locality within the home ranges of several individuals.

CONSERVATION AND FUTURE STUDY

Rattlesnakes present a disturbing paradox for park managers. On the one hand, they are dangerously venomous and visitor safety is of utmost importance. On the other hand, most parks mandate that all wild things be protected from collection and hunting.

Few long-term natural history studies have been undertaken with rattlesnakes, and C. molossus remains especially neglected. A main reason for the lack of our knowledge is tahat rattlesnakes and their denning sites have been historically abused by man either by collecting or destruction. As a result, undisturbed rattlesnake dens are uncommon, and persons with such knowledge of them are understandably reluctant to reveal such localities to others. At KCSP, future investigators now have the opportunity to study further two sympatic rattlesnakes in a protected natural environment, where they appear to be common and occurring in a unique geological habitat.

It will, unfortunately, certainly be necessary to remove or kill rattlesnakes from time to time where visitor use is concentrated. This will be especially certain if the main, or other lesser entrance, is to be designated as public access to the caverns below. Otherwise, rattlesnake-visitor encounters may be no more frequent on the Park grounds than in other natural areas in southern Arizona. If necessary, the remaining caves utilized by the rattlesnakes could simply remain segregated and off-limits to the visiting public. This would not only leave the snakes in peace, but also prevent the public from other injuries that could be expected from "poking around" such sites.

More imaginative interpretive programs at KCSP could even capitalize on the Park's unique rattlesnake assemblages. Park-Service-guided nature walks could be conducted seasonally, where visitors could view the snakes from a safe, predetermined vantage point.

Because of the unique geology of KCSP, two little-studied sympatic rattlesnakes are exploiting a novel environment. Because the snakes and their den sites will be protected, and so much undeveloped natural public and private land surround the Park, the possibilities for long-term study and appreciation of these marvelous reptiles are enormous.

BIRDS AT KARTCHNER CAVERNS STATE PARK

INTRODUCTION

In this final report, I summarize the data collected on the birds found around cave entrances at Kartchner Caverns State Park during four censuses in 1989. The following five cave entrances were checked: 1) Main entrance; 2) West cave; 3,4,5) North #1, #2, #3 caves. The Main entrance is a large sinkhole that leads into the cavern. The West cave is a large opening approximately 50m southwest of the Main entrance. The other three caves are on the north side of the hill that contains the Main entrance. These three small caves are within 50m of each other and are greater than 0.5 km from the Main entrance.

The four censuses corresponded to the four seasons of the year and were conducted during the following days: Winter, Feb 26-March 10; Spring, April 29-May 1; Summer, August 15-18; Autumn, October 13-15. Each census period lasted at least three days. All censuses were conducted during the first two hours of light. During a census, I recorded the number of birds seen or heard within 40m of an entrance. This circular plot method gives an indication of those individuals utilizing the areas near the entrances.

BIRD CENSUS RESULTS

Very few birds were observed in the cave entrances. A pair of Canyon wrens (Catherpes mexicanus) nested on a ledge in the Main entrance during the spring. In addition, I observed a Northern Cardinal (Cardinalis cardinalis) and a Northern Flicker (Colaptes auratus) fly out of the North #1 entrance in the winter and summer, respectively. However, no nests were observed in this entrance. Table 33 lists all birds recorded during the year and indicates the census period(s) during which they were observed.

RECOMMENDATIONS

None of the birds recorded in the cave entrances is on the endangered species list. All are common throughout the southwestern United States. Development of the park for public use should have minimal impact on the birds at the site.

TABLE 33
Birds Recorded at Kartchner Caverns State Park*

Species - Common Name (Scientific name)	W	Sp	Su	A
1. Cooper's Hawk (Accipter cooperii)				X
2. Mourning Dove (Zendaida macroura)		X		
3. White-winged Dove (Zendaida asiatica)		X		
4. Black-chinned Hummingbird (Archilochus alexandri)		X	X	X
5. Costa's Hummingbird (Calypte costae)		X		
6. Gila Woodpecker (Melanerpes uropygialis)			X	X
7. Northern Flicker (Colaptes auratus)				X
8. Ladder-backed Woodpecker (Picoides scalaris)	X		X	
9. Cassin's Kingbird (Tyrannus vociferans)		X		X
10. Ash-throated Flycatcher (Myiarchus cinerascens)		X		
11. Say's Phoebe (Sayornis saya)	X			
12. Vermillion Flycatcher (Pyrocephalus rubinus)	X			
13. Gray-breasted Jay (Aphelocoma ultramarina)				X
14. Bridled Titmouse (Parus wollweberi)			X	
15. Verdin (Auriparus flaviceps)	X	X	X	X
16. White-breasted Nuthatch (Sitta carolinensis)				X
17. Bewick's Wren (Thryomanes bewickii)	X	X		X
18. Canyon Wren (Catherpes mexicanus)	X	X		
19. Cactus Wren (Campylorhynchus brunneicapillus)	X	X	X	X
20. Ruby-crowned Kinglet (Regulus calendula)	X	X	X	
21. Black-tailed Gnatcatcher (Popioptila melanura)	X	X		X
22. Northern Mockingbird (Mimus polyglottos)		X	X	X
23. Curve-billed Thrasher (Toxostoma curvirostre)	X			
24. Phainopepla (Phainopepla nitens)	X	X	X	X
25. Bell's Vireo (Vireo bellii)		X	X	X
26. Solitary Vireo (Vireo solitarius)		X		
27. Yellow-rumped Warbler (Dendroica coronata)				X
28. Northern Cardinal (Cardinalis cardinalis)		X	X	
29. Brown Towhee (Pipilo fuscus)	X	X	X	X
30. Vesper Sparrow (Pooecetes gramineus)				X
31. Lark Sparrow (Chondestes grammacus)		X		
32. Black-throated Sparrow (Amphispiza bilineata)	X	X	X	X
33. Cassin's Sparrow (Aimophila cassinii)		X		
34. Rufous-crowned Sparrow (Aimophila ruficeps)		X		
35. Chipping Sparrow (Spizella passerina)	X			
36. White-crowned Sparrow (Zonotrichia leucophrys)	X			
37. Western Meadowlark (Sturnella neglecta)				X
38. Brown-headed Cowbird (Molothrus ater)		X		
39. Scott's Oriole (Icterus parisorum)		X		
40. House Finch (Carpodacus mexicanus)	X	X	X	X

*Based on four seasonal censuses taken in 1989.

SURVEY AND MAPPING OF KARTCHNER CAVERNS

ACPI has completed a map of the cave based on several surveys of the cave. A more complete description of the methods and results may be found in the survey report (Buecher, 1990). The goal of the survey of Kartchner Caverns was to provide a complete and accurate understanding of the basic relationship of the various parts of the cave.

The goals of the Survey task were to:

- Depict the cave passages and features in an accurate manner.
- Accurately locate the cave in relation to the surface features and topography.
- Provide a base map for use in other studies.
- Establish vertical and horizontal control throughout the cave.
- Provide dimensions of the rooms and passages of the cave.

To accomplish these goals, three separate surveys have been performed.

- The initial compass survey of the cave was performed by the discoverers of the cave and the Kartchner family to determine the extent of the cave and relationship of the passages.
- The trail survey was performed by ACPI to locate the existing trails in the cave, tie into the original survey stations, identify and correct errors in the original compass survey, and provide uniform sketch detail for the entire cave.
- The theodolite survey by ACPI provides a precise and accurate framework for future construction in the cave. It also provides highly accurate elevations and permanent stations.

The original and trail surveys provide the basic information for the overall map of the cave showing walls, ceiling heights and floor features. The theodolite survey provides additional information that allows for the accurate positioning of the original survey and trail surveys.

INITIAL SURVEY

The original survey of Kartchner Caverns and trail survey were done with a handheld compass. While of limited accuracy, the use of these simple survey instruments allows the cave to be mapped with sufficient accuracy for most non-construction purposes.

The original survey of Kartchner Caverns was started in 1977 by Orion Knox, Gary Tenen and Randy Tufts. The work continued with the aid of the Kartchner family and by 1983 all of the major passages had been mapped. The number of survey trips is unknown but the data is contained in 11 survey notebooks. Many of the notebooks contain data from several trips but frequently no date is given for the trips. It is estimated that approximately 30 trips were taken to complete the survey. The original survey covered all of the known passage in the cave. The "official" length of Kartchner Caverns, (2.385 miles) is based on this original survey.

A map at a scale of 1"=30' was drawn up by Orion Knox of the front portions of the cave. Additional detail of the back section of cave was later added by Gary Tenen and Randy Tufts.

TRAIL SURVEY

As part of its contract , ACPI is required to inventory and locate the existing trails in Kartchner Caverns. The existing trails have been surveyed in by compass. During the trail survey, any of the original survey stations found were tied into the trail survey. This has allowed us to identify and correct errors in the original survey. A majority of the floor detail and walls of the cave were re-sketched to provide a more consistent look to the map. Cross-sections and profiles were made of the major rooms and passages. For the larger rooms of the cave cross sections were made using a laser spot as a target and measuring distances with an optical rangefinder. This system allows highly accurate cross sections to be created in a minimum of time. For smaller passages cross sections were sketched to approximate dimensions.

THEODOLITE SURVEY

The goal of the theodolite survey was to provide accurate survey control for Kartchner Caverns. This does not mean that a high accuracy survey of all passages of Kartchner Caverns was done but rather an accurate survey framework was constructed of the main passages. This survey framework will have two uses. First, the theodolite survey was carried to the ends of the major passages of the cave. This will provide precise locations for those passages. Secondly, the theodolite survey will be used to control the less precise compass survey of secondary passages, trails and floor detail.

Because of the difficult nature of surveying in the cave with a theodolite, the traverse is open ended and there is no internal check on the accuracy of the survey. The accuracy of the survey is dependent on the methods used and the care in which the measurements were taken. The close agreement between the theodolite and compass surveys indicates that there are no major errors in either survey.

The theodolite survey was accomplished in 14 trips from November 1989 to April 1990. A total of 215 points were set or tied into. The length of the theodolite survey is 7858.99 feet (1.488 miles) which represents 62% of the known passages in the cave. Smaller side passages were not surveyed because of the difficulty in surveying with the theodolite without causing additional damage in these little traveled passages.

The original and trail surveys were combined and adjusted by least squares to fit the theodolite survey after obvious survey blunders had been removed from the data. Preliminary maps were drawn on individual sheets at a scale of 1"=20' and later reduced and combined into a final 1"=50' map. This map has been separately submitted to Arizona State Parks. Figure 94 (in a back pocket) is a copy of the final map of Kartchner Caverns at a reduced scale of 1" = 100'.

Information from the survey and mapping of the cave is vital for other studies of the cave. Good maps allow other features to be precisely located. A variety of other information can also be derived from the maps and cross sections. The volume and surface area of the cave can be calculated based on passage dimensions and measured cross sections (see Appendix K). Additional information can be found by examining the aggregate of the survey data. Figure 95 shows the distribution of the elevations of the survey stations. This shows that the majority of the cave lies within a narrow range of elevations. It also shows that the natural entrance is one of the highest points in the cave, this type of information is essential in understanding how the microclimate of the cave operates.

RECOMMENDATIONS

The compass survey has an accuracy of approximately ± 8 feet at the extreme ends of the cave. The theodolite survey has an assumed accuracy of ±1 foot at the extreme ends of the survey based on the methods used and on a simulation of the cumulative effect of small random errors.

This level of accuracy is sufficient for the predevelopment planning and also for internal construction in the cave. However, for the construction of tunnels into the cave or between distant portions of the cave, the survey results should be confirmed. A suggested independent means of verifying the locations within the cave is the use of cave radio location equipment. This method uses specialized radios which can accurately home in on a transmitter located in the cave. Such equipment is capable of locating a point to within 2-3 feet from the surface. The chief advantage of radio locations is that it is an entirely independent method which does not rely on the existing surveys. This would provide a low cost way of confirming the locations prior to the construction of a tunnel.

Second, a set of surface monuments should be established over known portions of the cave. This would provide a physical reference point for locating the cave from the surface. Surface monuments will make it easier to understand the relationship of the cave to the overlying topography.

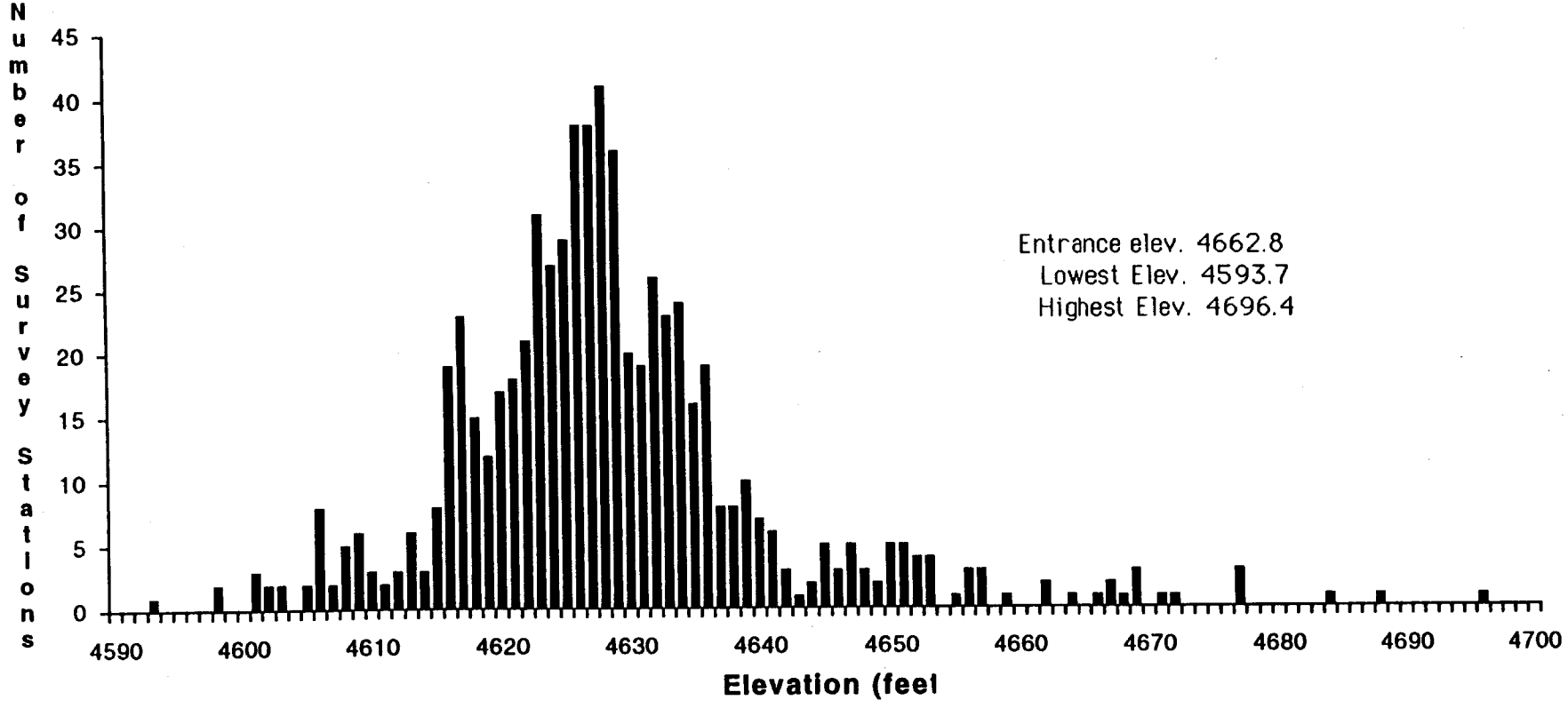
ARCHAEO-SITE CAVE

On the north side of the hill from Kartchner Caverns lies the second largest cave on the property. It has tentatively been identifed as an archaeological site and bats have been encountered there, notably Choeronycteris and Plecotus. A map of the cave is shown in Figure 96. Since it is an archaeological site and is being used by bats, it should be protected from disturbance.

FIGURE 95

Distribution of Survey Station Elevations

(678 Survey Stations)

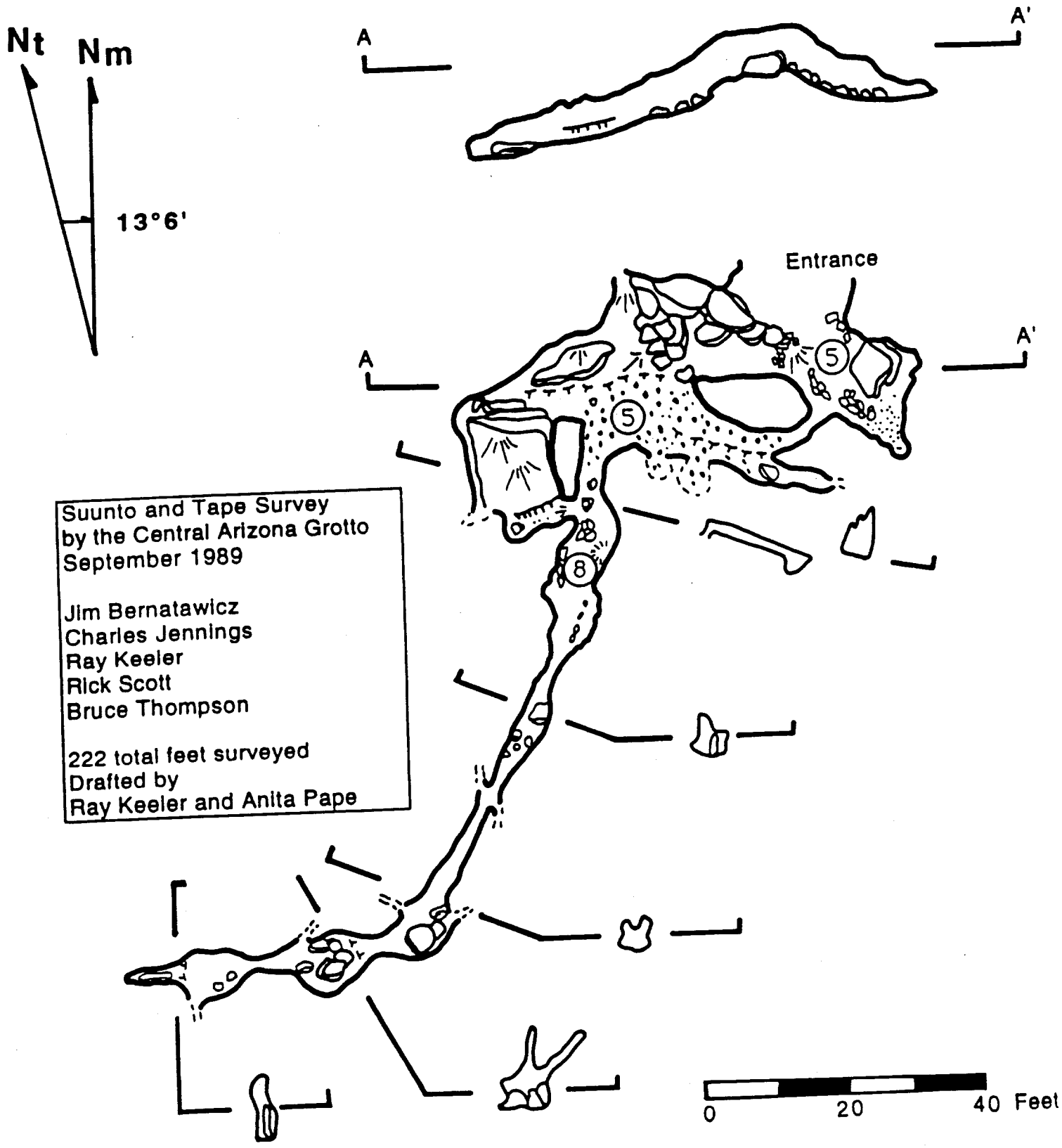


Arizona Conservation Projects, Inc. 1992

FIGURE 96

Archaeo-Site Cave

Kartchner Caverns State Park



ASSESSMENT OF EXISTING IMPACTS

ACPI has assessed the existing human-caused impacts to the cavern from the time of discovery to present. A unique feature of Kartchner Caverns is the large areas that have remained untouched by man. The untrampled and pristine nature of much of the cave is a significant feature of the cave and should be preserved to the greatest extent possible. See Figure 97 for a picture of untouched mud floor. Proper development of Kartchner Caverns can give members of the public the opportunity to see areas that are totally untouched by man.

To manage the cave properly during these studies has meant balancing the need for studies off the established trails with the need to preserve pristine cave features. Unwarranted departure from the established trail system will slowly degrade this pristine resource unless cave managers instigate an aggressive policy of resource preservation. Such a management policy must be based on a clear understanding of what the nature and distribution of existing impacts from the prior visitation has been.

In order to understand the impact prior visitation has had, each portion of the cave has been assessed and coded onto a map. Impact mapping allows cave managers to document the present condition of the resource and establishes the susceptilibity of various areas to additional damage. Human impacts to the cave have occurred in two phases. First, there was the exploration and mapping of the known cave by the original discoverers and associates. Their goal was to discover the extent of the cave and note significant features. They generally inspected the main features in the cave and walked the periphery of each room, taking pains to minimize their impact on cave features. At the end of the exploration phase, the majority of cave features were still largely untouched and in pristine condition. In the second phase, people visited the cave to view the features and to enjoy the unusual environment. These trips included a number of tours for Kartchner family members and individuals connected with the State Parks' acquisition of the cave. These trips have usually involved only the Big Room vicinity with a smaller number of trips to the "back" section. All these tour trips have followed definite routes laid out by the discoverers specifically to confine impact to small areas.

Human-caused impacts can be divided into four categories based on the severity of the damage and fragility of the original features.

- Pristine - these areas have either never been touched by man or show no evidence of human-caused changes.
- Lightly Impacted - these areas show only minor evidence of human traffic. Usually these are areas where the surfaces are more resistant to damage such as bedrock or breakdown. Generally these are areas for which impacts are not immediately obvious.
- Heavily Impacted - these are areas of high use by humans and show large amounts of disturbance to the original features. Trails across even the most resistant surfaces soon have obvious damage.
- Severely Impacted - these are surfaces which have had a high volume of traffic and which are also usually across delicate surfaces. Examples of these areas are the trails across the mud floors in the back of the cave and trails over breakdown that has a thin crust of lighter materials.

A total of 78.6% of the cave was assessed. The remaining 21.4% of the cave was not assessed and is comprised of seldom-visited side passages. It was felt that the

assessment of these passages, many of which have been only entered once or twice, would inflict greater damage than is worthwhile. In 67% of the assessed area, no human-caused impacts are visible. By adding the percent of "pristine" areas to the percent of flagged trails and subtracting from 100%, a figure for off-trail impacts can be derived. For Kartchner Caverns this is about 30%. In theory, these impacts could have been avoided but would have required a foreknowledge of where the major features of the cave were.. If "off-trail" impacts had not occurred, the most floor area which could have been kept pristine would have been about 85% [100% minus (% of flagged trails)]. A summary of the various classes of impacts for each section of the cave is in Table 34.

Cave surfaces were also classified by the fragility of the surface and the difficulty of restoring features. Four categories were used:

- Extremely Fragile - these are surfaces which can be extensively damaged by minimal traffic. Examples of these areas are the mud-floored room in the back of the cave, rimstone pools in the Strawberry Room and areas covered by a thin crust. Other unique cave resources also fall into this category, such as bone deposits, unusual mineral occurrences and stratified sediments. Restoration of these areas is extremely difficult. Impacts are caused not only by physical damage to the features but also by mixing of materials. For instance, movement through flooded areas of the cave stirs up fine silts which settle in a wide swath of light-colored material on either side of the trail. Additionally, it is difficult to access damaged areas without creating more impacts. Impacts to extremely fragile areas are essentially semi-permanent changes to the cave.
- Very Fragile - These areas contain delicate cave formations such as helictites, soda straws, rimstone dams and light-colored flowstone. Major difficulties in restoring these areas are the small delicate nature of the features and additional damage caused by restoration attempts. Restoration is usually a painstakingly slow process.
- Moderately Fragile - These areas include travertine-covered floors, breakdown and generally massive flowstone formations. Damage to these areas can usually be restored by scrubbing with water , gluing together broken formations, etc.
- Non-Fragile - These are areas which are very resistant to traffic such as bedrock, some types of breakdown and compacted sediments. Damage to these areas can usually be repaired by washing and restoring the original contours.

Observations and Comments on Impact Assessment

1) Most severe floor impacts are confined to areas within flagged trails. This can be seen in the calculations since the percent of flagged trails is nearly equal to the percent of severely impacted areas. Degradation of cave resources along trails will continue as long as the unimproved trails continue to be used. Future use of unimproved trails should be balanced against the damage to the resource.

2) Occasional flooding of the back sections of the cave has not restored the mud surfaces to their original condition. Many of the features preserved in the mud were formed long ago during periods of extreme dryness and these conditions cannot be duplicated today. Use of the trails when they are under water results in further widespread damage to the area. Sediments which are stirred up are lighter in color

and settle out as wide light-colored bands along either side of the trail. No trips should be allowed to use flooded or partially flooded trails.

3) Lightly impacted floor areas only account for about 6% of all mapped areas. Light impacts are mostly one-time-use trails which were probably established during initial exploration and immediately abandoned.

4) Ceiling impact maps do not reflect the degree of severity of formation breakage. This information is included in notes on the impact maps which estimate size and number of broken formations in each area. The most severely impacted ceiling areas, in terms of formation breakage, are the Pool Room, River Passage and the Entrance Rooms.

5) Probably only half of the broken formation pieces are available for repair. (This is a rough estimate.)

6) Mud floors and crust-covered breakdown areas were mapped as extremely fragile. It is doubtful these areas could be repaired. A temporary flooding of the Subway Passage has obliterated some footprints. However, impacts are still obvious here since the floor contour is disrupted. Impacts to crust-covered breakdown areas are perhaps not as visually obtrusive as impacts to mud floors.

7) Most "off-trail" impacts seem to be associated with initial exploration and pre-trail flagging activities. However there are a few areas where the floor was "unjustifiably" trampled. These include the Mushroom Passage, portions of the Big Room, portions of the Throne Room, and the central portion of the Subway Passage.

8) Perhaps the best preserved extremely fragile floor is in the Water Room. Also, most of the mud floor in the Rotunda Room is in pristine condition.

Figure 97. Untrodden, mud-cracked floor in the Rotunda Room.

Table 34
Floor Impact Assessment Summary

Section of Cave	Section Areas In Square Feet						
	Not Assessed	Flagged Trails	None Observed	Light Impacts	Heavy Impacts	Severe Impacts	Total Area S.F.
Entrance Sink	0.0	0.0	0.0	26.4	249.0	120.9	396.3
Blockade Room	0.0	0.0	0.0	30.0	0.0	57.1	87.1
Crinoid Room	193.4	349.5	968.0	80.0	72.5	349.5	1663.4
LEM Room	0.0	391.5	450.6	122.6	32.5	391.5	997.2
Blowhole Crawl	0.0	0.0	107.7	0.0	30.0	175.8	313.5
Anticipation Room	0.0	395.6	1582.4	0.0	169.2	580.4	2332.0
Grand Central Station	100.5	1400.0	8744.8	636.6	2419.1	496.6	12397.6
Scorpion Passages	2582.4	0.0	0.0	0.0	0.0	0.0	2582.4
Australia	1311.9	0.0	2000.6	275.0	336.2	0.0	3923.7
Main Corridor (SW half)	0.0	639.3	2729.2	42.6	242.1	639.3	3653.2
Main Corridor (NE half)	0.0	650.6	3659.3	108.5	109.1	650.6	4527.5
Arch Room	0.0	0.0	3026.8	795.2	366.3	353.8	4542.1
Big Room Sharon's Saddle	0.0	829.9	7587.3	79.1	502.3	829.9	8998.6
Big Room Kartchner Towers	1327.5	900.0	5381.5	363.3	610.3	1327.5	9010.1
Big Room NE Portion	539.6	1600.0	4652.8	446.7	488.0	1612.2	7739.3
Big Room SE portion	0.0	1200.0	4872.9	544.0	887.2	1292.7	7596.8
Big Room East Central	86.6	650.0	3894.6	649.2	330.6	807.8	5768.8
Big Room West Central	0.0	600.0	5776.6	181.6	710.6	1034.8	7703.6
Mud Flats	0.0	1110.0	3585.9	79.3	780.7	1281.3	5727.2
Tarantula Room	3052.7	216.0	1085.7	164.9	0.0	343.9	4647.2
Jackrabbitt Room	1230.8	0.0	0.0	0.0	0.0	0.0	1230.8
Red River	846.2	0.0	637.6	115.6	134.8	446.2	2180.4
Echo Passage	857.2	1100.0	2743.9	390.8	70.0	1336.8	5398.7
Bison Burial Ground	1532.4	0.0	0.0	0.0	0.0	0.0	1532.4
Cul-de-sac	6868.5	930.0	7874.4	312.0	489.6	1125.9	16670.4
Pool Room	0.0	880.0	1375.4	40.0	140.0	957.9	2513.3
Strawberry Rm. & Overlook	2893.5	1600.0	5002.4	1371.8	472.5	1814.3	11554.5
Big Room to Lovers Leap	0.0	413.2	109.4	15.0	0.0	413.2	537.6
Lovers Leap To Bathtub Roor	0.0	450.5	182.4	0.0	0.0	450.5	632.9
Bathtub Room	237.4	575.0	830.9	75.0	294.5	689.0	2126.8
Triangle Passage	899.4	700.0	1106.5	40.0	294.3	788.3	3128.5
Thunder Room	0.0	1277.1	2008.3	388.3	998.9	1279.1	4674.6
Shelf Passage	0.0	552.9	780.0	0.0	0.0	552.9	1332.9
Grand Canyon	2089.6	870.0	2496.0	271.0	297.6	972.6	6126.8
Pyramid Room (North half)	0.0	1150.0	1640.8	175.0	1026.6	1321.3	4163.7
Water Room	3405.0	275.5	1242.8	125.0	90.0	275.4	5138.2
Pyramid Room (south half)	646.2	0.0	1567.6	145.0	248.7	0.0	2607.5
Granite Dells	1645.6	650.0	1359.4	60.0	80.0	623.1	3768.1
Mud Trench	0.0	1925.0	5332.8	276.1	70.0	2162.9	7841.8
Onyx & Marble Passages	5402.5	0.0	0.0	0.0	0.0	0.0	5402.5
Rotunda Room (North part)	0.0	1710.0	1623.0	792.8	782.9	1710.0	4908.7
Rotunda Room (south part)	0.0	1310.2	5313.9	464.4	784.0	1310.2	7872.5
Throne Room	4534.6	2130.8	11795.2	1443.5	1653.2	1627.4	21053.9
North Passage	6500.0	0.0	0.0	0.0	0.0	0.0	6500.0
Subway (south central)	481.9	560.0	2289.5	96.6	193.9	604.0	3665.9
Subway (central)	0.0	1383.5	4211.5	1955.4	1288.2	1383.5	8838.6
Subway (Angel Wing)	0.0	620.0	1929.8	20.0	35.0	721.7	2706.5
Subway (north)	0.0	1856.5	11201.9	106.5	452.7	2289.6	14050.7
Pirate's Den (Southwest)	0.0	785.0	2644.8	100.0	246.5	899.4	3890.7
Pirate's Den (Main Side Pas)	0.0	453.0	1625.6	40.0	87.7	453.0	2206.3
Pirate's Den (Box Work)	1301.3	0.0	0.0	0.0	0.0	0.0	1301.3
Pirate's Den (Central)	0.0	939.3	6737.7	250.0	399.7	939.3	8326.7
Pirate's Den (Misc. Side Pas	3180.0	0.0	0.0	0.0	0.0	0.0	3180.0
Pirate's Den (Crow's Nest)	3391.0	400.0	643.5	0.0	80.0	441.9	4556.4
Hill Room (east)	1061.5	1456.8	7757.8	355.7	634.0	1456.8	11265.8
Hill Room (west)	932.7	902.7	5466.9	950.7	692.3	902.7	8945.3
Hill to Mushroom Passage	0.0	500.0	1370.1	0.0	0.0	735.0	2105.1
Snail Trail	6810.8	0.0	0.0	0.0	0.0	0.0	6810.8
Mushroom Passage	393.1	601.8	2603.8	20.0	1019.3	601.8	4638.0
Mushroom to Sue's Room	246.6	1139.2	1530.9	182.7	296.5	1139.2	3395.9
Sue's Room	1272.4	80.0	1896.8	218.3	501.5	195.4	4084.4
TOTAL AREA	67854.8	41110.4	167040.0	15422.2	22190.6	44965.9	317473.5
% of Total Area	21.4	12.9	52.6	4.9	7.0	14.2	100.0
% of Observed Area		16.5	66.9	6.2	8.9	18.0	

Table 34
Floor Impact Assessment Summary

Section of Cave	% of Total Area					
	Not Assessed	Flagged Trail	None Observed	Light Impact	Heavy Impact	Severe Impact
Entrance Sink	0.0	0.0	0.0	6.7	62.8	30.5
Blockade Room	0.0	0.0	0.0	34.4	0.0	65.6
Crinoid Room	11.6	21.0	58.2	4.8	4.4	21.0
LEM Room	0.0	39.3	45.2	12.3	3.3	39.3
Blowhole Crawl	0.0	0.0	34.4	0.0	9.6	56.1
Anticipation Room	0.0	17.0	67.9	0.0	7.3	24.9
Grand Central Station	0.8	11.3	70.5	5.1	19.5	4.0
Scorpion Passages						
Australia	33.4	0.0	51.0	7.0	8.6	0.0
Main Corridor (SW half)	0.0	17.5	74.7	1.2	6.6	17.5
Main Corridor (NE half)	0.0	14.4	80.8	2.4	2.4	14.4
Arch Room	0.0	0.0	66.6	17.5	8.1	7.8
Big Room Sharon's Saddle	0.0	9.2	84.3	0.9	5.6	9.2
Big Room Kartchner Towers	14.7	10.0	59.7	4.0	6.8	14.7
Big Room NE Portion	7.0	20.7	60.1	5.8	6.3	20.8
Big Room SE portion	0.0	15.8	64.1	7.2	11.7	17.0
Big Room East Central	1.5	11.3	67.5	11.3	5.7	14.0
Big Room West Central	0.0	7.8	75.0	2.4	9.2	13.4
Mud Flats	0.0	19.4	62.6	1.4	13.6	22.4
Tarantula Room	65.7	4.6	23.4	3.5	0.0	7.4
Jackrabbitt Room	100.0	0.0	0.0	0.0	0.0	0.0
Red River	38.8	0.0	29.2	5.3	6.2	20.5
Echo Passage	15.9	20.4	50.8	7.2	1.3	24.8
Bison Burial Ground	100.0	0.0	0.0	0.0	0.0	0.0
Cul-de-sac	41.2	5.6	47.2	1.9	2.9	6.8
Pool Room	0.0	35.0	54.7	1.6	5.6	38.1
Strawberry Rm. & Overlook	25.0	13.8	43.3	11.9	4.1	15.7
Big Room to Lovers Leap	0.0	76.9	20.3	2.8	0.0	76.9
Lovers Leap To Bathtub Roor	0.0	71.2	28.8	0.0	0.0	71.2
Bathtub Room	11.2	27.0	39.1	3.5	13.8	32.4
Triangle Passage	28.7	22.4	35.4	1.3	9.4	25.2
Thunder Room	0.0	27.3	43.0	8.3	21.4	27.4
Shelf Passage	0.0	41.5	58.5	0.0	0.0	41.5
Grand Canyon	34.1	14.2	40.7	4.4	4.9	15.9
Pyramid Room (North half)	0.0	27.6	39.4	4.2	24.7	31.7
Water Room	66.3	5.4	24.2	2.4	1.8	5.4
Pyramid Room (south half)	24.8	0.0	60.1	5.6	9.5	0.0
Granite Dells	43.7	17.3	36.1	1.6	2.1	16.5
Mud Trench	0.0	24.5	68.0	3.5	0.9	27.6
Onyx & Marble Passages	100.0	0.0	0.0	0.0	0.0	0.0
Rotunda Room (North part)	0.0	34.8	33.1	16.2	15.9	34.8
Rotunda Room (south part)	0.0	16.6	67.5	5.9	10.0	16.6
Throne Room	21.5	10.1	56.0	6.9	7.9	7.7
North Passage	100.0	0.0	0.0	0.0	0.0	0.0
Subway (south central)	13.1	15.3	62.5	2.6	5.3	16.5
Subway (central)	0.0	15.7	47.6	22.1	14.6	15.7
Subway (Angel Wing)	0.0	22.9	71.3	0.7	1.3	26.7
Subway (north)	0.0	13.2	79.7	0.8	3.2	16.3
Pirate's Den (Southwest)	0.0	20.2	68.0	2.6	6.3	23.1
Pirate's Den (Main Side Pas)	0.0	20.5	73.7	1.8	4.0	20.5
Pirate's Den (Box Work)	100.0	0.0	0.0	0.0	0.0	0.0
Pirate's Den (Central)	0.0	11.3	80.9	3.0	4.8	11.3
Pirate's Den (Misc. Side Pas	100.0	0.0	0.0	0.0	0.0	0.0
Pirate's Den (Crow's Nest)	74.4	8.8	14.1	0.0	1.8	9.7
Hill Room (east)	9.4	12.9	68.9	3.2	5.6	12.9
Hill Room (west)	10.4	10.1	61.1	10.6	7.7	10.1
Hill to Mushroom Passage	0.0	23.8	65.1	0.0	0.0	34.9
Snail Trail	100.0	0.0	0.0	0.0	0.0	0.0
Mushroom Passage	8.5	13.0	56.1	0.4	22.0	13.0
Mushroom to Sue's Room	7.3	33.5	45.1	5.4	8.7	33.5
Sue's Room	31.2	2.0	46.4	5.3	12.3	4.8

PHOTOMONITORING

Photomonitoring allows effectiveness and impact of cave management decisions to be evaluated and provides a procedure for documenting gradual changes in cave features. Its applicability is based on the fragile nature of cave features, especially in pristine caves like Kartchner Caverns. Because the cave environment is so delicate, changes are visible and can be easily identified on a series of photos taken over a period of time. For photomonitoring to be useful, photos must be repeated at intervals varying with the expected impacts on the area, the results analyzed and management action taken. **Photomonitoring is useful only when the cycle of taking and comparing two or more sets of pictures for changes is completed.** Photos must be taken in a way that is reproducible and which includes features that can be identified in successive photos and which are susceptible to damage. Each picture should contain a standard color reference. This will help to compensate for variations in color perception, cave lighting, film characteristics and developing. In a nearly pristine cave such as Kartchner Caverns, a balance must be struck in conducting photomonitoring so that photomonitoring does not become a major impact itself. For this reason, no photomonitoring was conducted in little-used side passages that may have been visited only once or twice.

ACPI has established 101 permanent photo points and selected a number of scenes to specifically measure certain formations for changes in color, monitor breakage, and to document foot travel impacts visible from the monitoring station. Photo stations were selected which represent as much of the cave as possible and to maximize the level of documentation in high traffic or sensitive areas where change is likely to occur first. The number of stations in a given area roughly correlates to the fragility of the area and expected volume of visitors. Of the 101 stations placed, 82 stations have been photographed once, leaving 19 stations to photograph. From four to seven photographs were taken at each station. Due to the flooding which occurred in August 1990 and during the winter of 1991, it has not been possible to reach many of the remaining photomonitoring stations in the back section of the cave.

Each selected photomonitoring station is identified with a permanent, brass marker stamped with the photomonitoring station number. Each location was numbered and described. Each photomonitoring station or shot was selected to minimize the need for any travel off of trails for purposes of illumination, scale, or other photographic need. A permanent logbook was prepared which describes the photographic work performed at each photo point.

The description includes the film type and speed, camera type, camera lens and focal length, F-stop, lighting including flash type and location, caver light source, and horizontal and vertical camera angles. A standard form was filled out for all pictures taken at each photomonitoring station.

A separate report which includes copies of all photographs, locations and camera settings will be submitted to Arizona State Parks. To continue the program of photomonitoring, staff at the cave need to become familiar with the photography techniques and the frequency of the monitoring should be written into the management plan. Facilities should be established to preserve the monitoring photos as the value of these pictures increases with time.

UNIMPROVED TRAIL SYSTEM

TRAIL SYSTEM

The original explorers of Kartchner Caverns stayed on the narrow pathways which they had established. They realized that, as the first to explore the cave, any tracks they left would be visible forever. Most of the initial traffic was kept to a few main trails, resulting in a minimum of off-trail disturbance. A few unobtrusive trail markers were installed to make following the trail easier. More markers were not needed as the original explorers knew the trail system well. ACPI has refined the original trail system to allow more efficient movement through the cave. Delineation of trails is a management tool to control the impact of foot traffic during the pre-development phase of the project by confining access to existing designated routes. Existing trail routes have limited impact on the cave while affording access to its principal chambers. The present trail system consists of 6,300 feet of marked trails. No off-trail travel is permitted. Figure 98 shows a map of the trail system.

The goals of the unimproved trail system are to:

- Protect the pristine nature of the cave by channeling traffic onto designated, marked trails.
- Aid in route finding through the cave by color coding trail markers.
- Provide a visual signal as to the access zone in the cave.
- Provide increased efficiency in moving through the cave.

TRAIL MARKERS

Trails are delineated by a variety of markers which differ according to the nature of the cave features and volume of traffic. The ideal trail markers should be non-biodegradable, easily cleaned, highly visible, available in different colors and large enough so that they are not easily lost. The material which most closely fits these criteria is plastic.

Edge of trail markers. Reflective tape attached to markers allows direction of route to be seen at a greater distance. Markers are usually placed in pairs, one on each side of the trail. However, this can sometimes be confusing when many markers are visible at once in areas of winding trails. They can also be objectionable in photographs where the reflective tape becomes highly visible in the camera's flash.

Plastic plant stakes: These are small, approximately 5" long and 1" wide, PVC plastic. The color is white and the finish is smooth. A laundry marking pen can be used for writing on them.

PVC survey flags: These are highly visible, more so than plastic plant stakes. A ring of reflective tape aids in visibility. They are also useful in areas which may flood. Not only will they project above the surface of the water but also above obscuring mud which travel stirs up. They can be difficult to place where the floor is hard. They can also be confusing if too many are used. It is best to use them to accent a trail delineated by other markers. Survey flags on metal wire should not be used as these will rust in the cave.

Plastic survey flagging: This method is used to delineate the main trails through the cave. The plastic flagging provides the most unambiguous trail marking. The trail can be delineated on each side by two ribbons of flagging. This creates a clearly defined trail which is easily followed. Plastic flagging is readily available in a variety of colors and patterns. We have found that 1" wide striped flagging is more highly visible

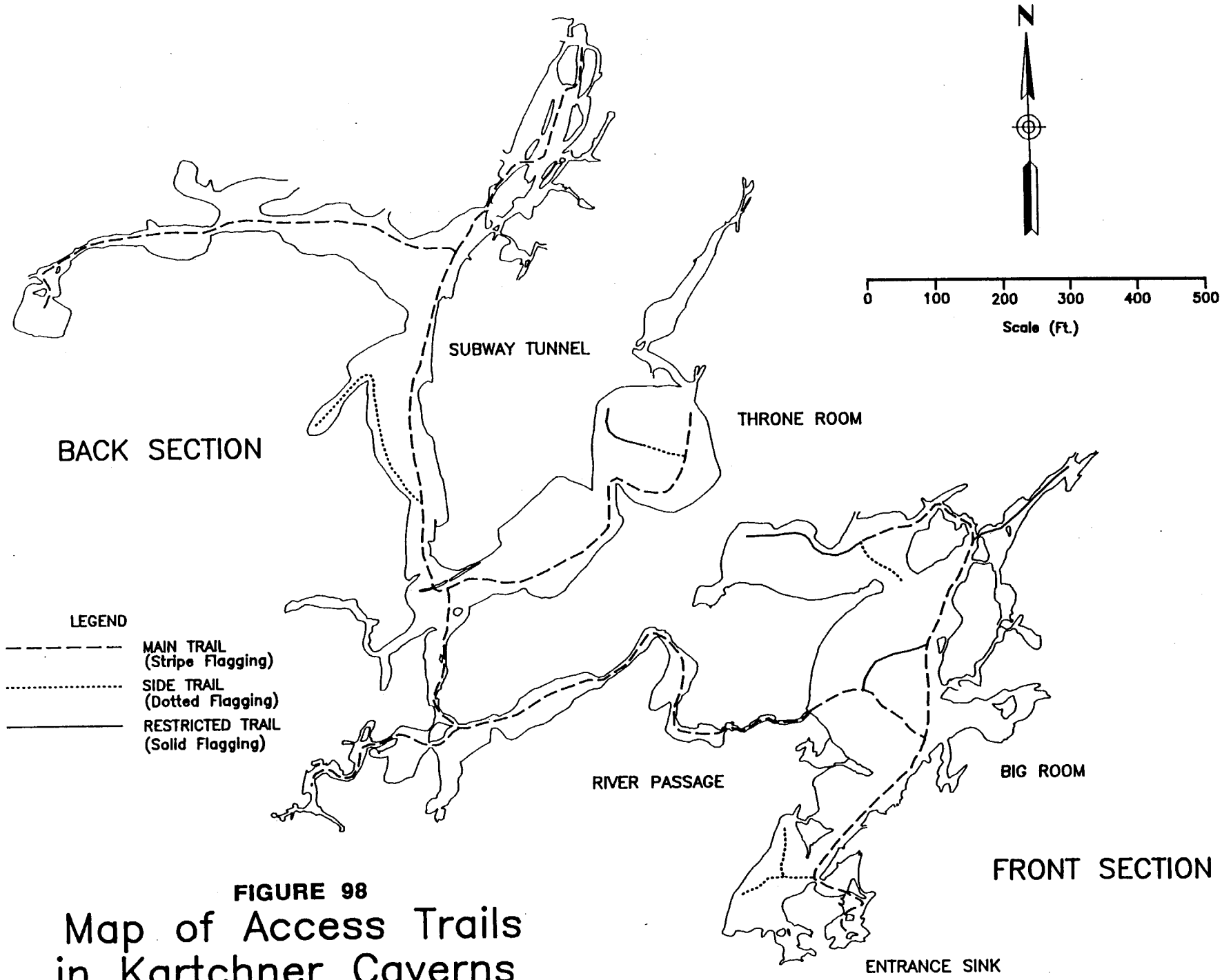


FIGURE 98

Map of Access Trails in Kartchner Caverns

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in the low light levels found in the cave. The alternating stripes give additional contrast which makes the flagging stand out. Only two colors are used throughout the cave, red stripes on white and blue stripes on white. These two patterns are used on alternating segments of the main trails. A total of 4140 feet of trail, 66% of the total trail footage, is marked with striped flagging.

Side trails are marked with polka-dot plastic flagging. These are trails that leave the main trail and go to a specific feature without branching. The color of the polka-dot trail flagging is the same as the main trail. A total of 1255 feet (20%) of trail is designated as side trail.

Solid-colored plastic flagging is used to mark restricted trails. These trails are infrequently used and usually go to a specific piece of monitoring equipment or mark a trail through a delicate area. A total of 905 feet of trail is designated as restricted (14% of the total).

Two-inch-wide, yellow plastic "CAUTION" flagging is used to indicate especially delicate areas. This type of flagging is used sparingly to insure that its message is respected.

While ideal for most trail delineation, plastic flagging has several drawbacks under certain conditions. In the muddy areas of the cave, the flagging can become too muddy to be seen. Plastic flagging can also become stuck to cavers' boots and dragged out of position. For these reasons, much of the muddy areas use PVC survey flags to delineate the trail. Maintaining the plastic flagging has also been a problem in areas near the natural entrance. Here, pack rats steal sections of flagging to use as nesting material. Sections of trail have been completely stripped of flagging within a few days. The loss can be reduced by stringing the flagging several inches above the floor and by frequently tying it off. No completely satisfactory way of protecting the flagging from the ravages of pack rats has been found.

OTHER MARKERS

Survey markers. In order for a survey to be truly useful, the location of the original survey stations must be identifiable and recoverable. Therefore, each survey performed in the cave has left some form of permanent marker. There are several categories of survey markers depending on the type of survey. The original surveyors of the cave marked stations with small pieces of plastic flagging. The color of the flagging corresponded to the survey letter designation. The "O" survey used orange flagging and the "C" survey used chartreuse flagging. The survey station name was marked on the flagging with an ink pen. The re-survey of the cave by ACPI utilized plastic plant stakes with green reflective tape and the station name. Both of these surveys were performed with compasses and the overall accuracy is on the order of a foot or two. For these types of surveys, a loose piece of flagging or plastic stake pushed into the ground next to the station was sufficient. The requirements of the theodolite survey were more stringent. These markers were more permanent and unambiguous and required a marker that could be firmly fixed. In order to reduce the number of various markers used in the cave, the photomonitoring points also serve as precision survey markers. Where necessary, additional theodolite survey markers were installed. The brass tags on these markers are stamped with a "T" designation and the survey station number.

Photomonitoring markers. Markers for the photomonitoring program are designed to be permanent. The photomonitoring program requires that the location of each photo must be recoverable so that future photos will portray the same area. Each is a

3/32" brass bolt, drilled into rock and cemented. A brass disc with the photomonitoring point number is attached to the bolt. In many cases, a white plastic marker with blue reflective tape is also attached. In areas where no solid rock outcrops could be found, the marker is attached to a 18" PVC pipe inserted into the mud.

SIGNS

Signs are used to aid in providing a standardized naming convention to points in the cave. They provide simple directions at trail junctions and aid in identifying the exact location in the cave. PVC plastic sheeting 30 mils thick is used to construct signs. The sheeting is thin and soft enough to be cut with paper scissors. Pieces up to about 12" square are rigid enough to stand without support. The sheeting is available in smooth white which is highly visible and easily cleaned. Waterproof felt tip marking pens such as laundry markers were used to letter the signs. Reflective tape was used to increase the visibility of the signs. Occasionally, plastic plant stakes without reflective tape are used as small signs or to identify a particular feature.

MUD BRIDGES

Portions of the back section of the cave are quite muddy (Figure 97). Through the first part of the mud, the original explorers established a trail along a stream channel. While this was clearly the least damaging route, it has become increasingly difficult to navigate. The original streambed was firm mud. However, footprints soon collected water in the depressions. This made the mud softer and soupier, which collected even more water in the depressions. Eventually, this section of trail became a mud bog one hundred feet long and at least three feet deep. It would take upwards of twenty minutes to travel through it.

After several people became so mired in the mud that they needed to be pulled out, it became obvious that this section needed to be improved. A system of bridges was devised to spread the weight over a larger area. Each bridge is approximately two feet wide and five feet long. They are constructed with a PVC frame with plastic mesh fencing wrapped around the frame and secured with nylon ties .

With an increased number of trips into the back sections of the cave, other sections of trail began to show signs of becoming another "Mud Trench". Additional mud bridges have been placed in these areas to prevent them from becoming worse.

TRAIL MAINTENANCE

The existing unimproved trail system should be more properly called a route system. The trails generally follow the easiest way through the cave. There have been only minor improvements in a few locations to make travel easier or to remove obstacles. Travel through the cave still has the attendant hazards of loose rocks, slippery slopes and low ceilings.

The present trail maintenance consists of replacing trail flagging and markers when necessary. For several portions of the Big Room trail, it has been necessary to remove accumulated layers of mud which made the area slippery.

Only two portions of the trail have improvements to aid in travel through the cave. A short 6-foot ladder has been installed at the climb-up on the trail to Sharon's Saddle. This has reduced the amount of mud accumulating on the flowstone and made the climb easier to negotiate. For safety purposes, a rope has been added to a steep slope in the Big Room. This slope can become quite slippery with mud and the rope is used as a handline.

MINERALOGY, SEDIMENTOLOGY AND SPELEOGENESIS OF KARTCHNER CAVERNS

MINERALOGY

The mineralogy of Kartchner Caverns is both diverse and significant. It is diverse in that six different chemical classes are represented by the cave mineralogy: the carbonates, nitrates, oxides, phosphates, silicates and sulfates. It is significant for a number of reasons:

1. World's longest soda straw (Figure 99).
2. Largest and most massive column in Arizona - Kubla Khan (Figure 100).
3. First reported occurrence of nontronite and rectorite as cave minerals.
4. First cave occurrence of "birdsnest" needle quartz. This type of quartz known only from Jeffrey Quarry, Arkansas.
5. Rare occurrence of nitrocalcite as a cave mineral. First modern description of this mineral.
6. One of the most extensive occurrences of brushite moonmilk in the world.
7. First reported occurrence of "turnip" shields."

The diverse and interesting mineralogy of Kartchner is due to an unusual set of circumstances. Unlike most limestone caves, Kartchner Caverns is located near igneous terrain. Alaskite granite borders the Escabrosa Limestone along fault zones to the west, and the Pinal Schist underlies the cave. The dry Arizona desert supplies another condition: the low relative humidity causes the efflorescence of nitrocalcite in the entrance zone of the cave. Bats add the third ingredient, phosphates and nitrates. In setting and mineralogy, Kartchner Caverns most nearly resembles the caves of the Transvaal, South Africa, where a hot and dry climate combined with an igneous rock-bat guano source of cations and anions has produced an unusual cave environment in which a number of minerals can form (Hill and Forti, 1986).

CAVE MINERALS AND SPELEOTHEMS

A "cave mineral" is defined as any secondary mineral in a cave (e.g., calcite). A "speleothem," on the other hand, is the <u>form</u> that the mineral takes (e.g., stalactites). While over 100 minerals have been found in caves, only about 30 speleothem types have been described (Hill and Forti, 1986). Figure 101 shows the locations of significant speleothems and minerals in Kartchner Caverns.

The general mechanism of speleothem deposition can be understood by carefully examining Figure 102. Rainwater picks up carbon dioxide from the air and soil zones above the cave to form a weak carbonic acid. This acidic water seeps underground, dissolving limestone bedrock as it vertically descends toward the water table. If these solutions reach an air-filled cave, they lose their excess carbon dioxide and precipitate calcium carbonate. While carbon dioxide is the primary factor causing the precipitation of carbonate minerals, evaporation is the primary factor causing the deposition of sulfate and nitrate minerals. Phosphate mineralization can be influenced by both factors, oxide mineralization by the oxidation (Eh) potential, and silicate deposition is dependent mostly on temperature.

Five basic hydrologic mechanisms control the shape of speleothems: dripping, flowing, seeping, pool, and condensation water (Figure 102). Dripping water

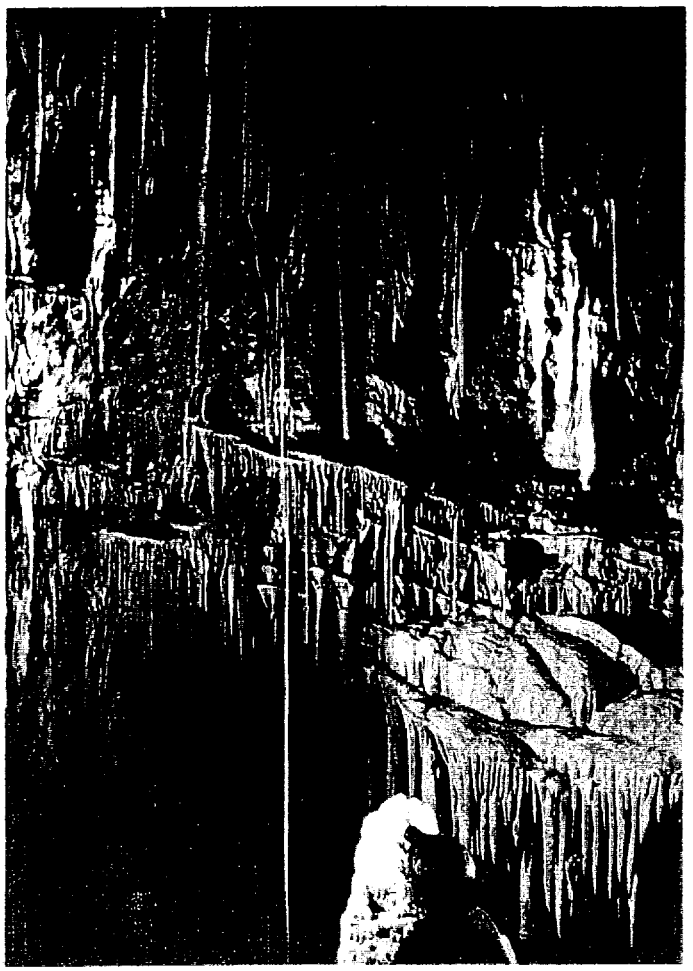


Figure 99. Longest Known Soda Straw in the World (21.16 feet). Randy Gruss is at lower right of picture.

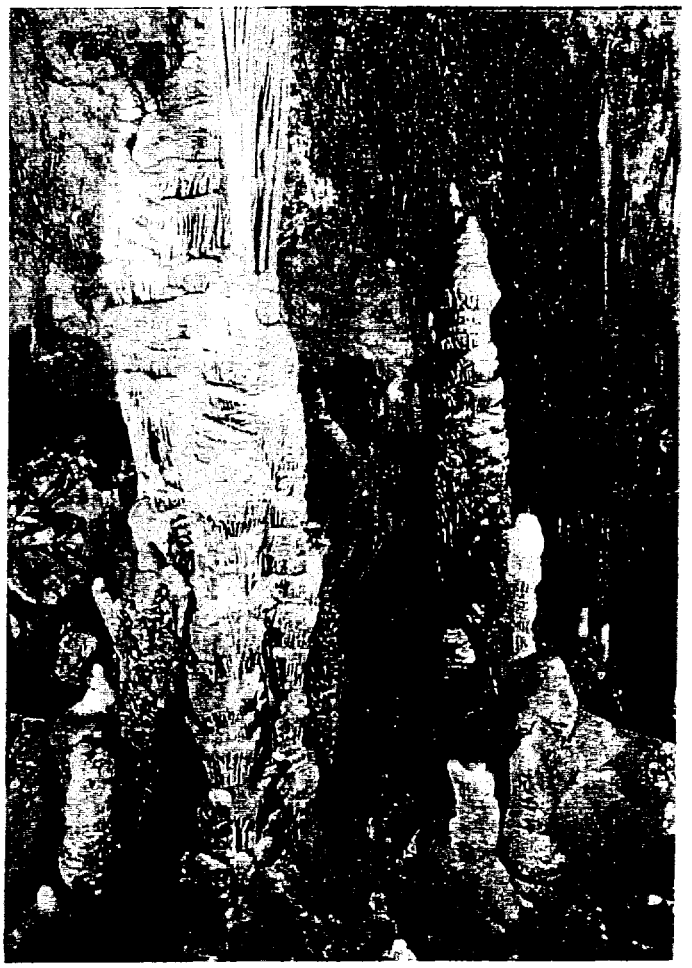


Figure 100. Kubla Khan Column in the Throne Room (58 feet tall). Anita Pape is standing at base of column.

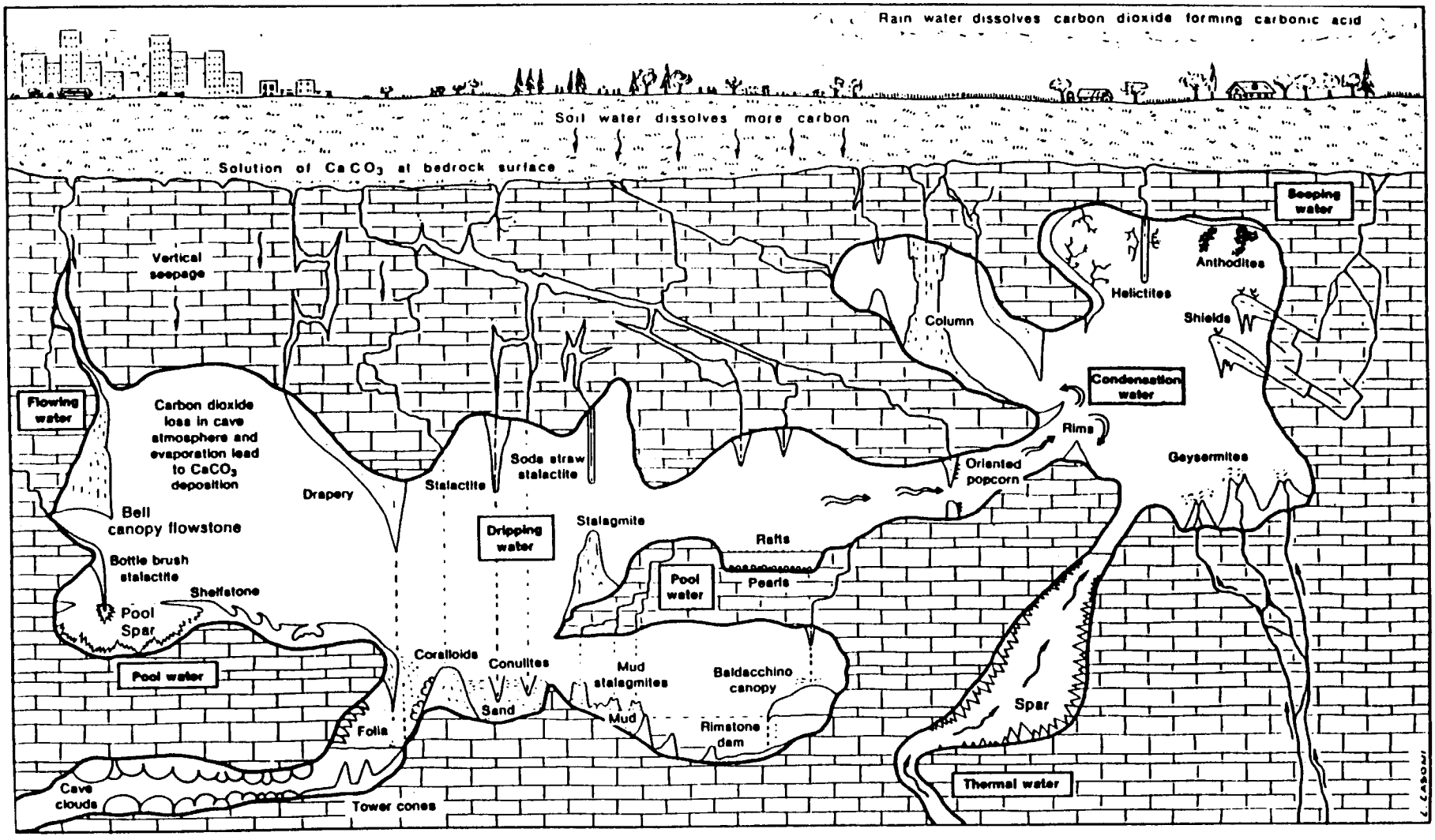


FIGURE 102

Diagram showing the influence of dripping, flowing, seeping, pool, condensation, and thermal water on speleothem development. After Hill and Forti (1986)

produces vertically-elongated speleothems like stalactites, stalagmites and columns because gravity forces water to drip in the vertical direction. Kubla Khan in the Throne Room is a prime example of a dripping water-controlled speleothem. Flowing water, where water flows over bedrock walls in thin sheets, causes flowstone speleothems to form. The massive waterfall-type of flowstone deposit called "The Wall" in the Big Room is an excellent example of a flowing water-controlled speleothem. Helictites are speleothems caused by seeping (capillary) water. Water seeps through bedrock and then slowly continues to seep through a tiny capillary tube within a growing helictite. Since capillary water can move against the force of gravity, helictites can twist in any direction, seemingly defying gravity. Cave cotton (a speleothem morphology exhibited by the sulfate and nitrate minerals) is another speleothem caused by seeping water - water seeps through porous cave sediment and "cotton" crystallizes by evaporation at the sediment surface. Cave rafts and shelfstone are examples of pool-water speleothems: they occur as flat, planar deposits because the form at or along the surface of a cave pool. And, where water condenses on bedrock or speleothem surfaces due to changes in temperature and/or relative humidity, rim speleothems can form. In Kartchner Caverns, rims can be seen lining the sides of stalagmites on the way from the Rotunda Room to the Throne Room.

Cave minerals and speleothem types and subtypes found in Kartchner Caverns are listed in Table 35 During the following discussion of speleothem types and subtypes, refer to Figure 102 for an illustration of how each speleothem occurs. For a more detailed discussion of the description and origin of cave minerals and speleothems, refer to Hill and Forti (1986).

Carbonates

The carbonate mineralogy of Kartchner Caverns is relatively simple, consisting almost entirely of calcite, $CaCO_3$. Aragonite ($CaCO_3$, the polymorph of calcite) also exists, but probably comprises less than one percent of the total carbonate mineralization in the cave. While mineralogy is simple, the number of carbonate speleothem types and subtypes is extensive (Table 35).

Calcite and Aragonite

Anthodites. Aragonite frostwork occurs at Crow's Nest Rock at the end of the Back Section, in Sue's Room, in the Entrance Passage, near the end of Echo Passage, in the Main Corridor between the Entrance Passage junction and the Y-Junction, just north of the Lunch Spot in the Big Room at the bottom of the Throne Room near "The Soda Straw," and elsewhere in the cave. In the first five occurrences, the aragonite is in a section where air flow is entering the cave: higher evaporation from dry incoming air preferentially causes aragonite to precipitate instead of calcite. In the Throne Room occurrence, the aragonite frostwork forms as spicules over botryoidal popcorn.

Boxwork. Calcite boxwork and quartz boxwork both occur in Kartchner Caverns. The calcite boxwork is composed of thin, friable fins protruding a centimeter or so out from the wall, while the quartz boxwork is thicker, more resistant and protruding, and is located along fault zones. Some of the best calcite boxwork can be seen in the Mushroom Passage associated with needle quartz. Calcite boxwork also occurs in the Main Corridor, Big Room, in the east wall and ceiling of the Thunder Room and elsewhere in the cave.

TABLE 35
CAVE MINERALS AND SPELEOTHEM TYPES AND SUBTYPES, KARTCHNER CAVERNS

TYPE	FOUND IN:
Carbonates	
Aragonite	Echo Passage, Sue's Room
Anthodites	Echo Passage
frostwork	Big Rm Overlook, Throne Rm., Triangle Psg, Rubble Rms,Crow's Nest Rock, Entrance Psg, Main Corridor
Coatings and crusts	
Helictites	Echo Passage, Throne Room
beaded	Echo Passage
Stalactites	
spathites	Echo Passage
Calcite	
Boxwork	Thunder Rm, Quartz Divide, Pirate's Den, Grand Central Station
Coatings and crusts	Throne Rm, Grand Central Station, Grand Canyon, Lunch Spot
Conulites	Big Room Lunch Spot
bird baths	Echo Passage
Coralloids	
popcorn	Main Corridor, Jared's End, Echo Passage, Kartchner Towers
grape	
subaqueous	
Coral pipes	Grand Canyon, Throne Room
Draperies	Everywhere
bacon	Big Room Lunch Spot, Throne Room
sawtooth	
Flowstone	
waterfall	Big Room
canopies	Grand Central Station, Shelf Passage
bell canopies	Big Room
stalactiflats	Entrance Passage
macrocystalline	Pirate's Den
Helictites	Everywhere
anemolites	Throne Room Overlook
Moonmilk	Throne Room
Pearls, Cave	Shelf Passage
Rafts, Cave	Thunder Room
Rims	Throne Room Overlook
vent rims	
Rimstone dams	
Chinese walls	Anticipation Room
Shelfstone	
crescent	Echo Passage, Anticipation Room
Shields	Echo Passage, Pool Room, Strawberry Room, Angel's Wing
welts	Shelf Passage, Lower Throne Room
beets	Big Room Rope Traverse

TABLE 35 (continued)
CAVE MINERALS AND SPELEOTHEM TYPES
AND SUBTYPES, KARTCHNER CAVERNS

Spar	
phreatic	Throne Room
pool	Shelf Passage
Stalactites	Common everywhere
soda straws	Throne Room
carrot	Throne Room Overlook
straw-mite	Shelf Passage, Big Room
Stalagmites	
columns	Throne Room
broomstick	Big Room, Throne Room
fried eggs	Big Room
Nitrates	
Nitrocalcite	
Cotton	Crinoid Room, LEM Room, Anticipation Room
Oxides	
Hematite	Everywhere
Phosphates	
Brushite	
Moonmilk	Big Room
Hydroxylapatite	
Crusts	Big Room
Silicates	
Clay minerals	Echo Passage
Illite	Red River Psg, Thunder Room, Main Corridor
Nontronite	Echo Passage
Rectorite	Main Corridor, Subway Tunnel
Quartz	
Boxwork	Quartz Divide, Crinoid Rm,Red River Psg, Subway, Jared's End, Sharon's Saddle
Needles	Sharon's Saddle, Red River Passage, Big Room Rope Traverse, River Passage, Quartz Divide,Mushroom Psg
Sulfates	
Gypsum	
Cotton	Big Room
Starburst	Big Room

Coatings and Crusts. Coatings and crusts exist in the cave, both on the walls and ceiling and also overlying sediment. In the Throne Room by the "Throne Room Bacon" is a pinkish calcite crust. The pink color is caused by a brownish mud residue inside of the crust. At the beginning of the Thunder Room, along the right wall, stark-white crusts of aragonite (small needles) cover fractures and small vugs in the wall. The crustal material is only about a centimeter or so wide and makes criss-cross markings on the bedrock wall.

"Clinker" crusts overlie sediment at Grand Central Station, Grand Canyon, Lunch Stop, Echo Passage and elsewhere in the cave. Such crusts form when calcite-rich solutions move through and to the surface of cave sediment.

Conulites. At the Lunch Spot in the Big Room, a 7 cm-tall, 6 cm-in-diameter, free-standing conulite exists in a soft "clinker" crust overlying bat guano. A less well-developed conulite (not free-standing) occurs to the left of the free-standing one.

A bird-bath conulite is a low-angle, bowl-shaped lining of calcite formed where depressions in mud are made by dripping water. In the Echo Passage, bird-bath conulites up to about 6 cm in diameter exist in soft mud; these conulites grade from unlined drip-drill pits to lined varieties with small stalagmites in their centers. In the Shelf Passage, a bird-bath conulite depression is filled with cave pearls.

Coralloids. Popcorn, grape, and subaqueous coralloids are all present in the cave. Popcorn coralloids exist on the lower tips of bedrock projections near the cave entrance or at passage terminations (e.g., Jared's End, Echo Passage). They are formed by an atmospheric phenomenon where cold dry air near the floor causes more evaporation and popcorn growth. In the Main Corridor, just before the Y-Junction, the popcorn forms a "line," which defines the contact between warmer, more humid, ceiling air and colder, drier floor air coming in from the nearby Entrance Passage. The popcorn line is approximately 0.75m above the floor and roughly parallel to the slope of the floor. Travertine and rock above the popcorn line are corroded.

It is possible to determine air-flow patterns in the cave by mapping the orientation of popcorn. At Kartchner Towers, popcorn points towards River Passage because dry air is flowing along the west wall of the Main Corridor and up into the Big Room near where River Passage joins with the Big Room. Directional popcorn can also be traced along the right wall of the Main Corridor and Big Room almost to the Lunch Spot.

Coral Pipes. Coral pipes exist in the Grand Canyon as linings in mud and in the Throne Room as drip linings in bat guano. Only a few of the drip pits in guano are travertine-lined and can be considered as true coral pipes. Some of the Throne Room coral-pipe linings are yellowish-orange in color; these are composed of calcite - possible manganese-rich or colored by included bat guano.

Draperies. Draperies occur everywhere in the cave, both in the Front and Back Sections. Some of these have sawtooth (serrated) edges where individual "teeth" are large scalenohedron crystals of calcite. A number of draperies are corroded or resolutioned. One particularly impressive drapery, the "Throne Room Bacon," is colored like a rind of bacon.

Flowstone. The most outstanding example of flowstone is "The Wall" in the Big Room, a massive waterfall-type of flowstone cascade about 15m high and 30m long. Why so much speleothemic water enters the cave at this location is not known: The Wall does not seem to correspond to a surface gully.

Canopy flowstone is well-developed in Grand Central Station and in the Shelf Passage. In both occurrences, travertine has formed over sediment, then the cave sediment has been removed, leaving the canopies in relief. In the Shelf Passage, one

crawls under the canopy and can view the cross-sectional bases of stalagmites on the bottomside of the canopy.

Bell canopy flowstone occurs as bell-like projections along the sides of stalagmites: a prime example of bell canopy growth are the horizontal protuberances on The Vulture stalagmite in the Big Room.

In the Entrance Passage and elsewhere, travertine has separated from the ceiling due to the subsidence of sediment. This set of events creates a flowstone variety called a "stalactiflat."

Helictites. Helictites exist in both the Back and Front Sections, sometimes in profusion. Filamental (thin, filament-like) and vermiform (worm-like) calcite varieties can both be found in the cave. Filamental helictites occur in Red River Passage and vermiform helictites occur in many passages, the best displays probably being in Echo Passage where numerous helictites are growing along a shield-lined bedding plane.

On the Balcony of the Throne Room, "anemolite" helictites all point in the same updip direction, parallel to the ceiling slope. The word "anemolite" is from the Greek meaning "stone from wind," and denotes any speleothem whose growth has been affected by air currents. The helictites on the Balcony are probably due to air currents moving along the ceiling from the Rotunda into the Throne Room. Air flow moves nutrient solutions on the growing tip of the helictite from the windward side to the leeward side where precipitation and offset crystal stacking occur. Near the end of Echo Passage, along the right wall, is a display of aragonite speleothems. One beaded helictite (not well-developed) composed of aragonite can be seen among this display.

Moonmilk. Small patches of moonmilk can be seen at the bottom of the Throne Room as globs of white pasty-looking material on the wall. This material was not analyzed but is most likely calcite or aragonite. The moonmilk occurs near aragonite frostwork.

Cave Pearls. In the Shelf Passage, along the trail, small nests of cave pearls line drip depressions in the sediment or, in one case, line a bird-bath conulite. Quartzitic pebbles (part of the pebble gravel) have been exposed and cleaned by the dripping, and some have acted as nuclei for pearl growth.

Cave Rafts. At the beginning of the Shelf Passage (just past the Thunder Room) cave rafts can be seen floating on the surface of a small pool at a sharp turn in the passage.

Rimstone Dams. Small rimstone dams can be seen along the Entrance Passage crawl in the Anticipation Room. These take the form of small, furled "Chinese walls." Microgours on flowstone, lined with tiny spar crystals, occur in the Shelf Passage and in the Echo Passage. A macrocystalline, microgoured flowstone cascade can also be seen in Red River Passage.

Rims. Rims are located on the "windward" sides of stalagmites where the Rotunda Room emerges into the Balcony of the Throne Room. The rims line the corroded sides of the stalagmites (which face toward the Rotunda Room) and are a condensation type of speleothem.

Shelfstone. Shelfstone occurs in the Anticipation Room, near to the rimstone dams. The shelfstone is of the "crescent" variety, where the crescent shape is produced by "waves" or ripples of pool water radiating out from a drip point and deflecting off the shelfstone.

Shields. Many shields occur in Kartchner Caverns, with the Echo Passage-Strawberry Room-Cul-de-Sac-Overlook section containing the highest density of this

speleothem type. Shields form where water moves under pressure along rock fractures and into the cave, the medial crack of the shield being an extension of the fracture. Kartchner Caverns has many shield speleothems because the bedrock is so highly fractured.

At the Lunch Spot in the Big Room, the top plate of a shield can be seen hanging on the wall while the bottom plate has fallen to the floor underneath the top plate. Horizontal lines, representing once-present water levels within the medial crack of the "Fallen Shield," are visible on the top exposed plate. Some shields in the Lunch Spot are oriented roughly perpendicular to each other and probably developed along perpendicular joint or fracture sets. "The Angel's Wing," in the side passage off the Subway Tunnel, is an especially well-developed, almost pure-white, free-standing shield about 2-3m high and across.

In addition to well-developed palette-shaped shields, there are also many less-well-developed incipient welt-shields which form as small shelves along bedding planes or fractures in the wall rock. A "welt" is a subtype of shield which forms as a planar excrescence along fractures in columns, flowstone, or bedrock. A good example of an extensive welt-shield is at the bottom of the Throne Room, near "The Soda Straw." Welts adorn many small, fractured columns in the cave, typical examples of which exist in the Shelf Passage.

An unusual variety of welt-shield - called "turnips" or "beets" - is found in the Big Room near the Rope Traverse and also directly over the Lunch Spot shield. "Turnip" shields are small bulbous speleothems up to 6 cm or so in diameter which form along vertical or near-vertical fractures in the walls and ceiling. Small amounts of travertine often hang from the bulbous protrusions, creating the turnip- or beet-like appearance. "Turnip: shields are often aligned in a vertical row, probably conforming to a vertical fracture which is partly plugged and partly unplugged. Kartchner is the first cave where this variety of speleothem has been noted and described.

Spar. Phreatic spar, 0.5 cm in length, occurs in vugs in the Throne Room near the "Throne Room Bacon." This spar predates cave development, as the vugs have been truncated by cavern dissolution. Pool spar can be seen in small pools, such as along the Shelf Passage.

Stalactites. Stalactites, stalagmites, and columns are the most common speleothem types in Kartchner Caverns. Stalactites usually occur in rows on the ceiling, corresponding to joints and fractures in the bedrock. Usually these stalactites are small compared to their counterpart stalagmites below.

All stalactites begin their growth as "soda-straws" - straw-like tubes made of monocrystalline calcite. Kartchner Caverns is distinguished in that it has the longest known soda straw in the world - "The Soda Straw" in the Throne Room (Figure 99) measured at 6.45m (21.16 ft) long. This length beats the previous world of 6.24 m (20.47 ft) in a western Australian cave (Hill and Forti, 1986).

A peculiar variety of soda straw in Kartchner Caverns is the "straw-mite." When soda straws drip, they form small stalagmites beneath them; when soda straws grow all the way to the floor, the straw and stalagmite connect to form straw columns. Then, if these fragile columns break, part of the straw can remain adhered to the top of the stalagmite: hence, a "straw-mite." A good example of a "straw-mite" is in the Shelf Passage, overlying the canopy there. The scepter of "The Bishop" stalagmite in the Big Room may be an example of an enlarged "straw-mite."

Other possible "straw-mites" exist in the Rotunda Room along the muddy trail, but more likely most of these are only soda straws which have broken off the ceiling and

have fallen straight down and into the floor mud. Some of the straws are embedded vertically in the mud, some are embedded at an angle, and some lay broken on top of the mud. Some of the fallen straws have helictites along their sides, as do many of the soda straws still attached to the ceiling. The longest three fallen straws are aligned in a row, beneath a straw-lined joint in the ceiling - these may either be "fallen straws" or "straw-mites."

A stalactite variety - "carrot" stalactites - can be seen on the Throne Room Overlook next to the anemolite helictites. The light-orange stalactites (about 30 in number) are elliptical in cross-section, with long axes pointing in the direction that the anemolite helictites point, and with their bulbous masses hanging from thin points of attachment to the ceiling. The carrot stalactites probably began their growth as anemolite helictites; then, when their capillary tubes enlarged, soda straws grew vertically from the helictites, eventually widening and elongating into stalactites. Air flow continued to impart a preferred direction of growth, and elliptical, anemolite carrot stalactites were the final result.

Many of the calcite stalactites in Kartchner, such as at the Y-Junction, display crenulated ("ribbed" or "wrinkled") surfaces where the distance between each rib crest is about 1 cm. The origin of these crenulations is not certain but (as with crenulated icicles) is believed related to thin, slow-flowing films of water. Soda straws and very small stalactites do not display crenulations. It is when calcite builds up substantially on the outside of the stalactite that crenulations begin to appear. Where a slight protrusion develops on the side of the stalactite, it becomes the site of thinner liquid-film layers and greater evaporation and/or carbon dioxide loss. Adjacent to the thinner regions are "hollows" or "troughs" where evaporation and precipitation are less and where thicker water-films tend to accumulate. Just below the "hollows," water films thin out again due to surface tension, and so another horizontal "rib" builds up at these locations, semi-evenly spaced relative to the last rib. Once begun, crenulations perpetuate and become more pronounced as the stalactite increases in mass.

Aragonite spathite stalactites (not well developed) have been found at the end of Echo Passage. The spathites are apparently in the process of forming. At the time of observation, a drop of water was hanging from the "pedal" of one of the better-developed spathites.

Stalagmites. Massive, "broomstick" and "fried-egg" stalagmite varieties occur in Kartchner Caverns. Stalagmites become massive when dripping is rapid and there is not enough time for a ceiling drop to reach equilibrium with its surroundings so as to form a large stalactite. If dripping is very fast, then film-flow deposition takes place along the sides of the stalagmite and it increases in width. If dripping is slower and if there is a uniform, consistent supply of feedwater with uniform solute concentration, then most of the material deposits on the apex of the stalagmite and a tall, thin, "broomstick" variety is formed. Along the trail in the Big Room is an excellent example of a "fried-egg" stalagmite, with a yellow "yolk" center surrounded by a "white" exterior.

Columns form where a stalactite and stalagmite grow together. Kartchner Caverns has the tallest, and probably most massive, column in Arizona - the 17.4m Kubla Khan in the Throne Room (Figure 100).

Nitrates

Nitrocalcite. Nitrocalcite ($Ca(NO_3)2{\cdot}4H_2O$) is a deliquescent mineral, efflorescent only under very low humidity conditions (around 50% or so for a normal range of cave temperatures (Hill and Forti, 1986). Nitrocalcite has been mentioned as being present

in a number of eastern United States caves, but these are pre-1900 citings which are erroneous since eastern caves have relative humidities approaching 100%. Brief mention of nitrocalcite as a cave mineral has been given for one cave in the southwestern United States and one cave in Italy (Hill and Forti, 1986). This is the first authenticated, detailed description of nitrocalcite as a cave mineral.

In Kartchner Caverns, nitrocalcite occurs as cave cotton growing from sediment in scattered areas along the Entrance Passage (e.g. Babbitt Hole, LEM Room) where cold, dry winter air flows into the Entrance Passage from the surface. Mineralization is as efflorescent cotton mats, consisting of colorless to milky-white, silky-to-transparent, slender needle crystals up to 0.5 mm in length and <0.1 mm in width. Birefringence is high: third order yellows, pinks and greens. One optical index measured <1.50, another >1.50. Some of the needle crystals are eaten-away looking along their edges and many have a thin coating of clay on their surfaces. The mineral has a strong, bitter-cool taste.

The growth of nitrocalcite in the Entrance Passage (Figure 103) correlates with episodes of low relative humidity in the winter months. From December 10, 1989 to December 16, 1989, the weather on the surface was unusually dry and cold, with the outside humidity dropping to 23%. The cotton was first noticed on December 12 in front of the Babbitt Hole, two days after the significant drop in surface humidity. Maximum growth was noted on December 12 at Babbitt Hole as a loose mat 1-2 cm thick when the cave humidity and temperature measured 45.3% and 15.5°C, respectively. When both the surface and cave humidity began to rise again, the nitrocalcite slowly deliquesced and disappeared back into the floor sediment. A humidity of 49-50% or below appears to be needed for crystallization, and the humidity needs to remain low before significant cotton can effloresce. This corresponds to a time when the cave is "breathing in" - i.e. when cold, dry air is coming into the cave from the outside. When the cave "breathes out", warm moist cave air quickly causes the mineral to deliquesce and disappear back into the cave sediment.

Interestingly, maximum nitrocalcite growth occurs where sediment in the Entrance Passage had been compacted and smeared with mud by crawling cavers, not in undisturbed dirt off the trail. The cotton seems to grow preferentially along the edges of mud smears. It may be that, where sediment becomes compacted, nitrocalcite cannot crystallize within sediment pore spaces but must crystallize at the surface of the sediment. It has been noted that crystallization obliterates boot and knee-pad marks in the sediment within a few days' time; evidently, sediment particles are forced upward where crystallization occurs within sediment pore spaces. Scattered patches of dark bat guano can be seen all along the Entrance Passage where the trail has not been crawled over. Cave rat trails can also be seen along the walls in this passage. Bat and rat guano could both be possible sources of nitrate for the nitrocalcite mineralization.

Oxides

Hematite. Hematite, Fe_2O_3, has been positively identified from two spots: from the Red River Passage, alternating with greenish-gray illite-clay layers, and as colloidal hematite staining illite and rectorite clay, in the blocky clay unit of the Thunder Room.

Fault zones exposed in the cave are iron-rich and silica-rich, being filled with red/orange clay and quartz veins. The red to orange to yellow to brown coloration of the fault zone material is most likely due to the presence of hematite and/or limonite. Silica and iron (plus other metals) dissolved in hydrothermal water probably ascended

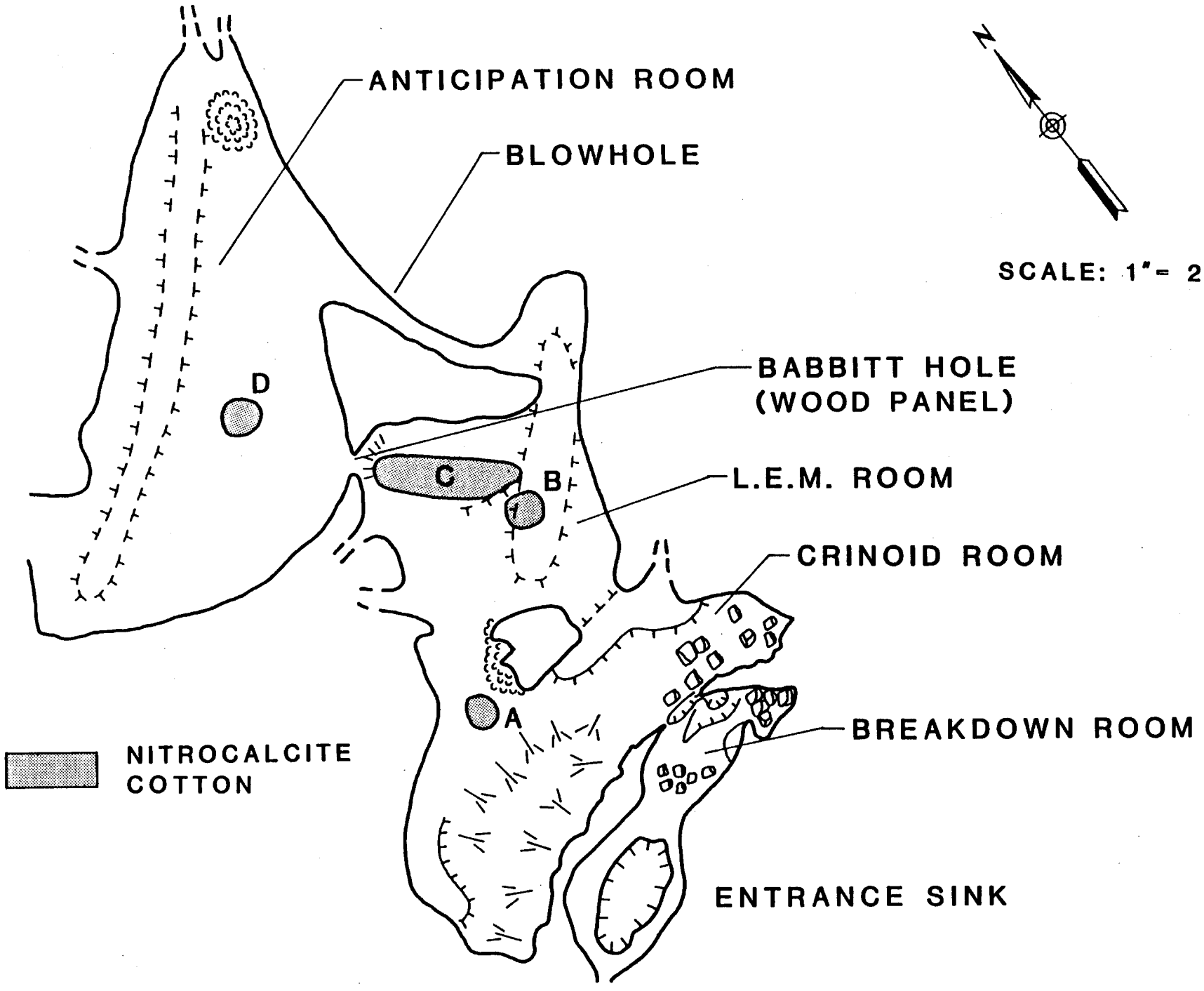


FIGURE 103: LOCATION OF NITROCALCITE IN THE ENTRANCE PASSAGE OF KARTCHNER CAVERNS, DECEMBER, 1989

Arizona Conservation Projects, Inc. 1992

along fault zones from depth and the iron-rich fraction oxidized to hematite. Pyrite has also formed within the fault zones, as can be seen in one surface fault above the cave. Thomson (1990) also reported surface faults stained with hematite.

Phosphates

Two phosphate minerals have been identified in Kartchner Caverns: Brushite, $CaHPO_4 \cdot 2H_2O$, and hydroxylapatite, $Ca_5(PO_4)_3(OH)$. Both are common cave minerals which derive from bat guano (Hill and Forti, 1986). It is probable that other phosphate minerals exist in the cave, but due to limited access to off-the-trail areas, a thorough search has not been made for additional guano minerals. Usually a complex suite of phosphate minerals occurs in altered bat guano and such is probably the case for Kartchner Caverns.

Hydroxylapatite. Hydroxylapatite occurs as a thin (a few mm) crust of orangeish-brown (amber), shiny, resinous material directly overlying limestone bedrock at the Lunch Spot in the Big Room. It is located near (less than 1m from) a decomposed bat guano pile. The hydroxylapatite is the result of the reaction of bat guano with bedrock; the calcium comes from limestone, the phosphate from guano.

Brushite. Brushite occurs in Kartchner Caverns as an ivory-colored, very soft, "moonmilk"-like material beneath fresh bat guano at Bob's Guano Pile in the Big Room. The guano rests on a huge piece of floor breakdown and the brushite occurs between the guano and the surface of the limestone. In other places, brushite "moonmilk" has seeped down over the sides of the breakdown block to form "flowing" masses of creamy material over 2m long, 0.3m wide and 6 cm thick.

Brushite is a phosphate mineral which forms under acidic conditions (pH = 6 or less), where fresh guano reacts with limestone. Above a pH of 6, hydroxylapatite is the stable mineral species. Under low humidity conditions, brushite will dehydrate to the mineral monetite. The high relative humidity at Bob's Guano Pile (>99%; Arizona Conservation Projects, 1991) precludes this transition.

Along the west side of Bob's Guano Pile, a shiny, resinous, dark-brown to black crustal material exists near the brushite mineralization. This resinous material was x-rayed and found to be amorphous. It is probably some organic compound of bat urine.

Silicates

Four silicate minerals have been found in Kartchner Caverns: illite, nontronite, rectorite and quartz. The last of these, quartz, occurs as vein deposits within fault zones or as needle crystals in or near fault zones. The first three are all phyllosilicate $[(Si, Al)_4O_{10}]$ clay minerals which are found as floor sediment or as clay material filling fault zones. The mineralogy of these three minerals will be discussed here but their origin will be discussed later in the sedimentology section.

Clay Minerals

Illite. The name "illite" defines a group of mica-clay minerals of the general formula $(K,H_3O)(Al, Mg, Fe)_2(Si, Al)_4O_{10}[(OH)_2, H_2O]$. Illite has been found as (1) a fissile clay deposit at the end of Red River Passage, (2) a constituent of the blocky clay unit in the Thunder Room, and (3) a minor constituent of a mostly-rectorite clay filling in a fault zone in the Main Corridor. The Red River illite is greenish-gray and thinly layered, alternating with bright red layers of colloidal hematite. The illite is weakly foliated and mimetic, which means that the foliation of the illite happened before the deposition and lamination of the illite clay within the fault zone. The Thunder Room floor illite is about

half altered to rectorite and both clay minerals are stained with colloidal hematite. The illite occurs in radially-disposed domains and may replace feldspar clasts (S. Williams, personal communication, 1991). In the Main Corridor occurrence, the illite has mostly been replaced by rectorite, or at least the illite was one precursor mineral from the rectorite formed (S. Williams, personal communication, 1991).

Nontronite. Nontronite (K, 1/2Ca)$Fe_2^{+3}(Si, Al)_4O_{10}(OH)_2 \cdot nH_20$) is found in Echo Passage where it occurs as a brown, unctuous, floor clay which contains layers, pods and seams of a black, amorphous, manganese-rich material. Layers of this blackish material are interspersed within the nontronite clay mass and are exposed where people have trod through the sticky clay. This black material was probably expelled from the clay mass as it reconstituted into the mineral nontronite.

Rectorite. Rectorite is a mixed-layer clay mineral composed of a 1:1 regular inter-stratification of a dioctahedral mica (pyrophyllite; $Al_2Si_4O_{10}(OH)_2$), and diocta-hedral smectite (vermiculite; (Mg, Fe, Al)3(Al, $Si)_4O_{10}(OH)_2 \cdot 4H_2O$), and water (Newsom, 1978). Rectorite has been identified from two localities in the cave: (1) as a red clay mixed with calcite in the main fault, Main Corridor, that appears to have replaced former illite, and (2) as pure rectorite showing contorted foliation in the Subway Tunnel.

Rectorite is an unusual mineral which forms in but a few known localities, the most renowned being the Jeffrey Quarry just north of Little Rock, Arkansas (Miser and Milton, 1964). The collectable "haystack" quartz occurs with rectorite at Jeffrey Quarry, the quartz having grown within the rectorite, as individual crystals "floating" within the clay mass or as clusters of needles growing outward from quartz veins within the fault zones. Rectorite, in the Arkansas occurrence, is believed to have formed directly from hydrothermal solutions (Newsom, 1978).

Quartz. The mineral quartz occurs in four different modes in Kartchner Caverns: as (1) vein-boxwork, (2) stubby prismatic crystals on boxwork, (3) "birdsnest" needle crystals on cave walls and ceilings, and (4) prismatic crystals replacing limestone bedrock. The location of the known occurrences of quartz are shown in Figure 104. It is likely that more macroscopic and/microscopic quartz will be found on cave walls and ceilings once a thorough search is made. The presence of quartz is an indicator of past hydrothermal activity.

Boxwork. Quartz veins occur in many of the fault zones of Kartchner Caverns. Jagnow (1990) estimated that about one-third of the fault zones are filled with reddish-brown limonite (hematite) and white quartz. The best example of a quartz-filled fault zone is the Quartz Divide. Here, a quartz vein 30 cm wide extends from floor to ceiling and has been left standing while the cave dissolved out around it (i.e., the quartz vein predates the cave). The trail leads through a break in the quartz wall ("The Doorway"), and 1-2m out from the quartz wall on both sides, <1 cm-thick quartz boxwork protrudes 10-30 cm out from the wall. This is probably one of the best localities of quartz cave-boxwork in the world (Hill and Forti, 1986).

Other good examples of quartz boxwork exist in the Crinoid Room, Red River Passage, Subway Passage, Jared's End and Sharon's Saddle. The Sharon's Saddle and Quartz Divide vein-boxwork has been analyzed for fluid-inclusion temperatures: these analyses indicate that the quartz crystallized at temperatures of 125-171°C. The Subway Tunnel boxwork is unusual in that one surface is covered with milky-to-glassy, prismatic quartz crystals up to 0.5 mm long and 0.25 mm wide, while the other surface is a flat bevelled plane, uncrystallized. The crystals grew on the obtuse side of the boxwork fin (where the acute angle makes a 70-75° angle with the ceiling; B. Buecher, personal communication, 1991), and the individual prismatic crystals are oriented in

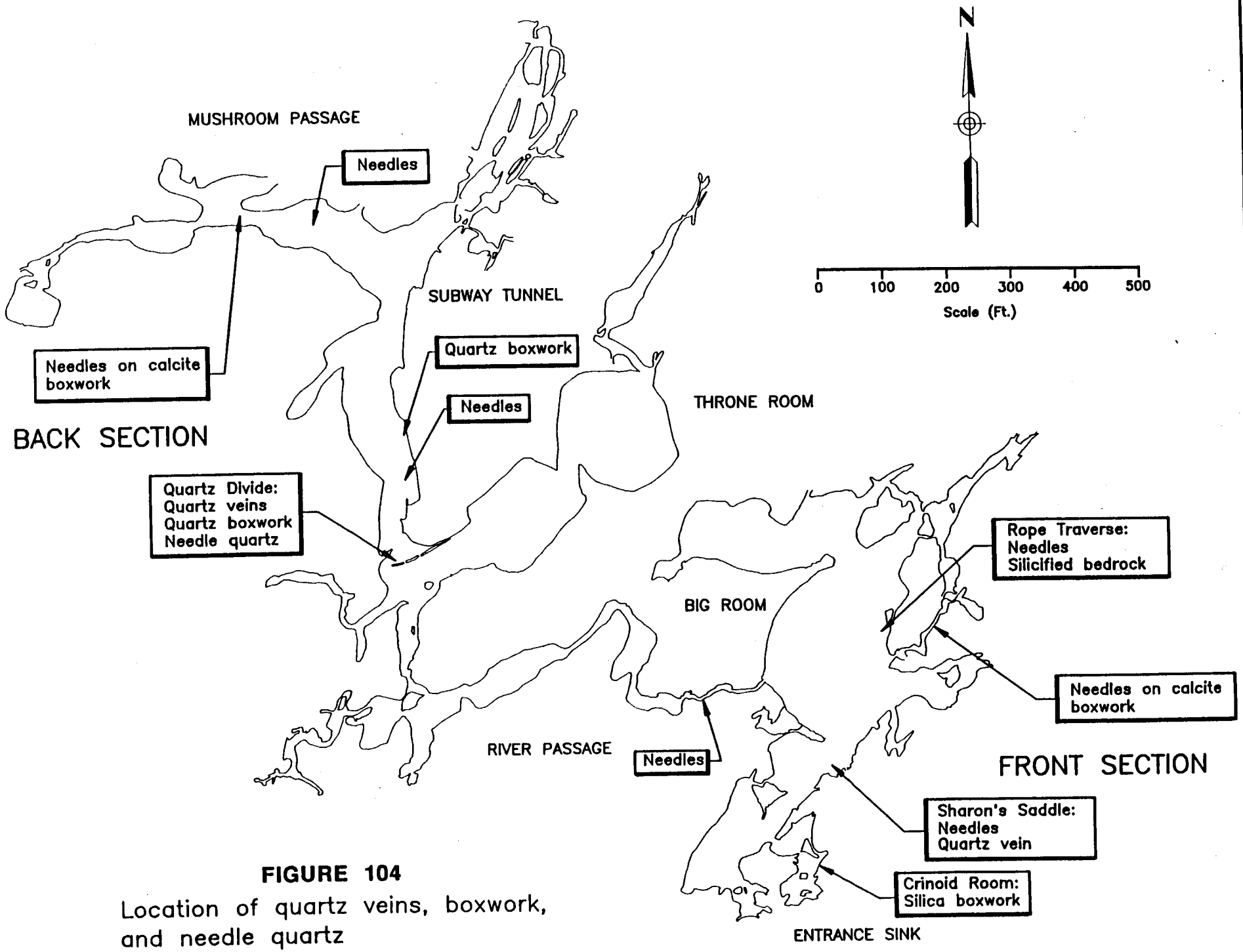


FIGURE 104

Location of quartz veins, boxwork, and needle quartz

all directions on the boxwork fin, from horizontal to vertical. The boxwork fin and crystals on it have been resolutioned. The outward-facing quartz crystal terminations are blunted and the vein part of the fin has been truncated, creating the planar surface.

Needle Quartz. In many locations in Kartchner, the quartz mineralization displays a most curious habit: tiny, slender (high c>a ratio), needle-like, euhedral, prismatic crystals that cluster together in mats. These masses of matted needles look like sticks protruding out at all directions, "birdsnest"-like fashion. Needle length and width can reach about 2 cm and 0.25 cm, respectively, but usually the crystals are smaller than this and many are microscopic in size. This curious needle habit is produced as a function of quartz-crystal twinning (A.Huebler, personal communication, 1991). Aberrant ions (such as can be supplied by mud) poison quartz crystal growth when the crystals are small; this in turn causes twinning (according to the "Japanese twin law") so that another quartz crystal will form with a new c-axis direction. In this way a solid mass of quartz can transform into milk-white baby crystals growing in a hodge-podge, "birdsnest"-like fashion. The elongate c-axis of the needles is caused by crystals growing outward into a saturated silica "soup" - either into a silica-rich solution or into a porous clay medium.

Needle quartz occurs in many locations in the cave. The best locality to see needle quartz is in the Mushroom Passage. Here, clumps of needle mats 3-5 cm in diameter occur, often partly coated with mud. A microscopic examination of bedrock taken from this area reveals a myriad of macroscopic to microscopic quartz needle crystals covering the surface of the bedrock, but not penetrating into the bedrock. Interestingly, major needle-mat growth occurs either on calcite boxwork fins or on the fins of solutional scallops, as if the needles preferred projections as points of crystallization. In the Thunder Room, euhedral needle quartz crystals are actually found intermixed with clay on the floor.

All of the quartz needles (except for the Thunder Room floor needles intermixed with clay) occur on the cave walls or ceiling in or near fault zones. Other less significant trends regarding the quartz needles are: (1) the needles are often associated with quartz boxwork-veins in the fault zones (at least 3 out of 7 occurrences), (2) needles usually occur in muddy, solutional passages, not in collapse passages, (3) the needles do not correspond to any particular limestone stratigraphic unit (they have been found on marker beds 0, 1, 2; see Jagnow, 1990, for a description of stratigraphic marker beds), (4) the crystals appear to be speleothemic; i.e. the "birdsnest" needle clusters either grew into open space or into some porous medium such as clay, and (5) at one location (Rope Traverse in the Big Room) needles exist over rock that has been silicified. Three thin sections were made of this silicified rock. These sections show that the quartz replacing limestone wall rock consists mostly (90-95%) of short, stubby, prismatic crystals. These are not shaped in a needle, "birdsnest"-like fashion and so it seems highly unlikely that the needle mats overlying the limestone are dissolved-out replacement quartz. More likely, the silicification of the cave bedrock was caused by the same hydrothermal silica-rich solutions from which the quartz vein material and needle crystals precipitated.

Sulfates

Two varieties of speleothemic gypsum have been found in Kartchner Caverns and both of these probably derive from bat guano. Gypsum is almost always present with phosphate minerals in bat guano (Hill and Forti, 1986). Phosphatic solutions

generally migrate farther than sulfate solutions, and so gypsum often precipitates close to, or on top of, bat guano.

Gypsum

Cotton. Gypsum cotton occurs as fibrous strands less than 1 cm long overlying guano-rich sediment at the Rope Traverse in the Big Room. The cotton is present in a protected locality, beneath a piece of breakdown just as one starts up the rope. A more extensive (about 1 square meter) occurrence of gypsum cotton can be found in the Kartchner Towers area of the Big Room near the starburst gypsum there. The cotton is less than 1 cm thick and is growing over a layer of dry bat guano.

Starburst Gypsum. Starburst gypsum crust occurs in the Kartchner Towers area of the Big Room. The starbursts consist of crudely-formed stars, about 1-2 cm in diameter which occur as coatings directly over bedrock. These possibly formed as a result of water seeping in from an above-lying guano source on top of the rock.

RELATED FORMS

A "mineral" is defined as an inorganic, homogeneous solid with a definite composition and ordered atomic arrangement. For various reasons, the following cannot be considered as true minerals and so are discussed under the heading of "related forms."

Rootsicles

At the Y-Junction in the Main Corridor and at the north end of the Pirate's Den (on the east side of Crow's Nest Rock) in the Back Section are tree roots covered with travertine - calcified roots or "rootsicles". These are not speleothems in the strictest sense because they contain organic matter. The rootsicles occur where the overburden is shallow and plant roots have grown into the cave in search of water. Calcite has precipitated from saturated water dripping on, or flowing over, the roots.

Vermiculations

Vermiculations are thin, irregular, discontinuous deposits of incoherent material which resemble hieroglyphic writing and which are found on cave walls, ceilings and floors (Hill and Forti, 1986). These are composed of a mixture of mud and clay, not necessarily specific clay minerals. Vermiculations have been found in Kartchner Caverns in low muddy areas but they are not well developed. Leopard-spot vermiculations have been noted at the Quartz Divide and tiger-stripe vermiculations in the Red River Passage.

Amorphous Material

Black material exists as a coating over stream clasts in Grand Central Station, as thin layers in nontronite clay in the Echo Passage, and as a resinous crust near brushite at Bob's Guano Pile in the Big Room. All of these have been x-rayed and have been determined to be amorphous. Since these materials do not contain ordered atomic arrangements and therefore do not display x-ray patterns, they cannot be considered as true mineral species.

SPELEOTHEM DISTRIBUTION PATTERNS

Speleothems are not evenly distributed throughout Kartchner Caverns but have a distribution that depends on a number of factors:

(1) The majority of speleothems are bedding-plane or fracture controlled, not fault-controlled. Graf (1989) noted the same non-correlation of faults, but with respect to the distribution of cave passages rather than speleothems: "faults probably only indirectly influenced the formation of these main cave passages...groundwater appears to have flowed more readily along fractures or joints located within the crest of narrow anticlinal flexures which lie adjacent to the fault surfaces." Faults do not appear to have been the avenue of water descent during the period of cave dissolution or later, during the period of predominant speleothem formation, or even at the present time. When water floods the cave, impermeable clay-filled fault zones act as barriers to horizontal water movement and water rises and descends independently between faulted areas as if separated by a series of locks.

(2) Some of the beds, especially the darker, organic-rich marker beds are more impermeable than other, lighter-colored beds and these can act as perched aquicludes, causing water to form rows of dripstone and cascades of flowstone (D.Jagnow, personal communication, 1991). But even these associations are not markedly apparent. It appears that speleothemic meteoric water routes are indirect and complex.

(3) The "fault shadow" effect has influenced speleothem distribution in some cases. For example, the lack of speleothemic travertine in the area from Lover's Leap to the Bathtub Room may be because faults block the downdip descent of meteoric water in this area.

(4) Aragonite and popcorn exist near the cave entrance or near passage terminations where air flow is more pronounced.

(5) Large masses of travertine (such as "The Wall" and Kubla Khan) exist in larger, upper, breakdown (non-solutional) rooms, rather than in lower solutional passages.

(6) In lower solutional passages, travertine has mainly grown along joint-enlarged, mixture-corrosion recesses where high-CO_2 water is entering along joints and where flooding is less frequent.

(7) Needle quartz preferably occurs on the walls and ceilings of lower solutional passages rather than upper breakdown passages. The exceptions to these rules are at the Rope Traverse in the Big Room and at Sharon's Saddle, Main Corridor. Both of these are breakdown areas, but at the Rope Traverse the quartz actually is found on the solutional surface of a fallen breakdown piece. At Sharon's Saddle, the quartz needles seem to have formed around a former chert(?) nodule prior to collapse of the ceiling. In each case, the needles are located near (few meters from) a fault zone.

(8) Shields are more predominant in the north part of the Front Section, near the Strawberry Room and Echo Passage. It may be that this area is more highly fractured or that the right hydrostatic pressure gradient and input of saturated solutions exist in this part of the cave.

CORROSION OF SPELEOTHEMS

Corrosion of speleothems in Kartchner Caverns may be caused by: (1) bat guano/urine, (2) condensation-corrosion or (3) undersaturated solutions coming in along joints. Corrosion of travertine by bat guano-urine (either in solid, liquid or vapor form) can be seen in the Big Room along the trail west of Bob's Guano Pile. Limestone bedrock has also been corroded in this area and thin pieces of limestone are "peeling" off in layers.

The travertine along the Main Corridor (e.g. draperies) may have been resolutioned by undersaturated water, but more likely they were corroded by

aggressive air (i.e., condensation-corrosion). Corrosion of this type not only affects travertine material but also the bedrock as well, corroding the travertine flush with the bedrock. Condensation-corrosion is related to air flow patterns in a cave (Hill, 1987). Cold, dry evaporative air flows in from the entrance along the floor and causes oriented popcorn and a "popcorn line": above this "line", warm moist air high carbon dioxide flows out of the cave along the ceiling. Water contained in the moist, acidic air condenses on ceiling travertine and bedrock and corrodes them concordant with each other. Pronounced condensation-corrosion can be seen on speleothems facing incoming air flow in the Main Corridor and at Jared's End (3400 ppm CO_2).

COLORATION OF SPELEOTHEMS

Calcite travertine in Kartchner Caverns varies in color from a dark blood-red to red-orange to orangeish-brown to delicate-peach to pure-white. Pure white speleothems can occur next to blood red ones, even within a space of less than a meter. Coloration of speleothems can be caused by many factors: iron group ions substituting for Ca^{++} in the calcite structure; included clay, silt and metal oxides (mostly of iron and manganese) between the calcite crystals; hydrated iron oxide stains along grain boundaries; organic stains incorporated into the growing crystal; differences in crystallinity; and other factors (White, 1981; Hill and Forti, 1986).

Probably much (or most?) of the coloration of Kartchner Caverns' speleothems is due to included insoluble residue (hematitic-clay fault material). Water flowing over fault zones picks up tiny amounts of silt and hematite and this becomes included in the travertine. Mud sealed in by overgrowth calcite can appear to color the entire deposit; although the mud exists only as a minor fraction, it can cause black, gray, brown and red coloration in speleothems (Ford and Williams, 1989). Some of the most vividly colored speleothems in Kartchner Caverns occur along or near fault zones where red-orange clay is exposed - their coloration is most likely due to incorporation of this material. The coloration of the pink crust near the "Throne Room Bacon" is known to be due to included residue: upon dissolution of the calcite with acid, a fine-grained brownish silt was left. The orange-yellow coloration of the coral pipes in the Throne Room may be due to manganese (manganoan calcite) or to included bat guano.

"Fried-egg" stalagmite colors are due to differences in travertine crystallinity: the "yolk" is composed of an optically-continuous, crystalline mass of calcite, whereas the "white" is composed of lots of little, independent calcite crystals which diffract light (Beck, 1978).

Black coatings on stream clasts are deposited from highly oxidized (e.g., turbulent, vadose) water carrying Mn ions. Although the black coatings on stream clasts in Grand Central Station have been analyzed as amorphous, the coloration is probably caused by the relatively high manganese content of the material (Mn = 0.217%).

The coloration samples sent to Will White have not as yet been analyzed.

MACROCYSTALLINE SPELEOTHEMS

Macrocrystalline speleothems are those which display a sparkling surface texture. "Macrocrystalline" textures are where individual crystals can be discerned with the eye as compared to "microcrystalline" where crystals can only be seen under a microscope. Only a few of the speleothems in Kartchner Caverns display macrocrystalline surface textures and most of these occur in Echo Passage. Here, flowstone displays "sugar candy" surfaces and the very-transparent helictites in this passage are reminiscent of the helictite displays in the Caverns of Sonora, Texas. Hill, et al (1989)

related the presence of monocrystalline and macrocrystalline speleothems in the Caverns of Sonora to high carbon dioxide and humidity levels and to the restriction of natural air flow. Under these conditions of continuous high carbon dioxide and humidity, speleothemic solutions take a long time to equilibriate with the cave air and so crystal faces can grow large. The Echo Passage is an area of high carbon dioxide (>3000 ppm) and relative humidity (99.7%) (and also of high radon). These factors may have influenced macrocystalline growth. Some of the macrocrystalline growth in the Echo Passage must be fairly recent as evidenced by clean macrocrystalline flowstone postdating the last flooding event in the passage. This same flooding event covered the "bison" (bear?) bones in the Bison Room with a thin (1 cm or so) layer of mud.

LUMINESCENCE OF SPELEOTHEMS

A few samples of travertine have been flashed to determine their fluorescence. Clear calcite travertine in the Shelf Passage fluoresces green and phosphoresces green with about a 5 second afterglow. Blood-red travertine in the Shelf Passage fluoresces yellow.

RADIOACTIVITY OF SPELEOTHEMS

A geiger counter was taken into the cave to determine the radioactivity of speleothems and other material. Wrucke et al (1983) reported low-grade uranium at Star No. 1 Mine, located in Guindani Canyon about 3.2 km west of Kartchner Caverns and a high radioactivity in the cave might imply a connection between the two areas. Colored, old and young speleothems, mud and bedrock were monitored for radioactivity; none of these measured above background.

The low levels of radioactivity measured with the geiger counter match uranium levels in the travertine material used for age-dating: uranium concentration is less than 1 ppm in all of the samples. It is also reflected in the low level of uranium in limestone bedrock (<10 ppm). This brings up an important question: why are the radon levels in parts of the cave so high (Arizona Conservation Projects, 1991)?

URANIUM-SERIES DATING OF SPELEOTHEMS

Thirty uranium-series dating analyses were made on calcite travertine; out of these, nineteen were successful. Attempts were also made at dating quartz vein and needle material. All dates were performed by Derek Ford, McMaster University. Dating of the calcite travertine was hindered by the fact that: (1) many of the samples are "dirty" (i.e. they have included mud), and (2) the samples were so low in uranium (<1 ppm) that they were very difficult, and took a long time, to date. Due to these factors, a number of the sample dates were "lost." The oldest date obtained on the calcite was around 194,000 YBP (Years Before Present) (stalactite embedded in pebble gravel, on top of blocky clay unit) and the youngest was around 41,000 YBP (travertine associated with bevelled Mushroom, Mushroom Passage).

It was hoped that the "Fallen Stalactite" at Mud Flats in the Big Room would give a very early date, one which might indicate when the water table descended and the cave became air-filled. However, its dates range from about 70,000 to 83,000 YBP, and are much younger than the travertine in Grand Central Station. The oldest travertine event in the cave that has been dated (t1) is the broken stalagmite in the blocky clay which started growing by about 194,000 YBP, and was possibly broken by, and incorporated into, the pebble gravel (pg1) influx at about 110,000 YBP or so. So

all that can be said about the time of cave dissolution is that it happened >200,000 years or so ago.

Two ages came as somewhat of a surprise: the age of the flowstone collected in Granite Dells and the bevel-related age in the Mushroom Passage. Three samples were analyzed from the Granite Dells material. Two were too dirty to give reliable dates. The third has a date of around 176,000 YBP, but this date is also suspect because of contamination. Possibly the Granite Dells flowstone formed in the passage before the major influx of granite pebbles and cobbles there, or perhaps the gravels are much older than has been assumed.

It was expected that The Mushroom bevel might be very young, since very little travertine has grown since bevelling. From the date of about 40,000 YBP it appears that the bevelling happened long ago and that even young-looking travertine in Kartchner Caverns may not have formed in the very recent past.

The age of sediments in the cave can be roughly known from the dating of sediment combined with the paleomagnetic dating of sediment. All of the sediments in the cave are paleomagnetically normal, which indicates an age of <730,000 years. From travertine dates at Grand Central Station, the blocky clay unit appears to be > 200,000 years old and the first influx of pebble gravel (pg1) <166,000 years old. There was a time of about 20,000 years (115,000 to 95,000YBP) when travertine (t2) grew over the pebble gravel (pg1) before another influx of pebble gravel (pg2) came into the cave. Finally, the last travertine event occurred at about 115,000-90,000 YBP in Grand Central Station before downcutting of the sediment-travertine series occurred without further vadose-sediment or travertine deposition.

It is not known if the pebble gravels in the Bathtub Room and Shelf Passage are part of the Grand Central Station pg1 or pg2 events, or if these units in different parts of the cave are completely non-correlative (i.e., they came into a different part of the cave at a different time). The pebble gravel, mica sand and blocky clay are at different levels in these areas, so it is probable (but not conclusive) that the sediments are not time correlative. Travertine above the pebble gravel in these two rooms was dated between 78,000 and 119,000; these dates could either indicate a pg1 or pg2 time of origin for the gravels.

Quartz vein material and quartz needle material was also dated. The vein quartz is over 350,000 YBP from direct uranium-series dating and >1,000,000 YBP from $^{234}U/^{238}U$ ratios. This is not unexpected, since the vein material has been exposed by cave dissolution and so is known to be older than the cave passages. From the dates obtained, it can only be said that dissolution of the cave passages happened from >1,000,000 to >200,000 YBP. Attempts are still being made to date the needle quartz, but it may be too "dirty" (included with mud?) to obtain a reliable date. If the date on the needle quartz is old (as is expected) then it will confirm the suspicion that the fault mineralization and cave dissolution events are unrelated time-wise. If, however, the needle quartz turns out to be young (<350,000 YBP) then it would imply that Kartchner Caverns may be - at least in part - a thermal cave (dissolved by hot water).

SPELEOTHEMS AND PLEISTOCENE CLIMATE

The clustering of speleothem dates between about 50,000 YBP to almost 200,000 YBP is very important to the understanding of Pleistocene glaciations and climate. The Kartchner Caverns dates are similar to speleothems in Carlsbad Cavern, New Mexico, another southwestern United States cave. Brook et al (1990) found maximum speleothem growth in Carlsbad Cavern to be during the latter part of the Illinoian glacial (140,000-170,000 YBP), the Sangamon interglacial (70,000-140,000 YBP) and into the Wisconsin glacial. This same trend is displayed by the Kartchner Caverns speleothems: some growth occurred during the Illinoian glacial and some in the Wisconsin glacial, but most occurred during the Sangamon interglacial. The Sangamon must have been characterized by a wet climate throughout the southwestern United States.

A change in climate may be reflected in the Fallen Giant stalactite at Mud Flats in the Big Room. A date of approximately 83,000 YBP was obtained for the macrocrystalline, blocky-calcite center of the stalactite which indicates a period of continuous growth under wet conditions during this time. Then the record changes about 72,000-70,000 YBP to a ringed sequence indicative of intermittent wet-dry climatic conditions. This may indicate a transition from the wetter Sangamon to a drier Wisconsin.

Owen Davis, University of Arizona, will be performing pollen analyses on speleothems dated by Derek Ford in order to correlate speleothem dates with the type of vegetation that grew during this period of the Pleistocene. Also, an attempt will be made to date the 'bison" (bear?) bones collected from the Bison Room. These bones are about 30 cm in circumference and are covered with a thin layer of silt from the last backflooding event in Echo Passage. The bones appear to be very old and decayed and were probably washed into the cave from above, although the route by which they entered the Bison Passage is not now obvious.

SPELEOTHEMS AND TECTONIC ACTIVITY

A recent tectonic event is possibly recorded by broken travertine at the Y-Junction in the Main Corridor and in the River Passage just past Lover's Leap. In each of these areas the ends of stalactites are broken off and 3-6 com of new material has regrown since breakage. Also, a number of fallen soda straws occur in the Rotunda Room. All of these occurrences suggest earthquake activity. While it is not possible to know the absolute age of travertine without dating it, Hill and Forti (1986) give a world-average figure for travertine growth as 2 mm/yr. Using this number, one can speculate that the small amount of travertine breakage in the cave correlates with the 1887 Great Sonoran Earthquake.

SEDIMENTOLOGY

Cave "sedimentology" is the description and interpretation of cave sediments - the clastic deposits within caves. Clastic deposits in Kartchner Caverns were studied with respect to their mineralogy, their relative stratigraphic position, and their absolute ages as determined by paleomagnetic dating and U-series dating of interbedded travertine. The clastic deposits vary in size from large breakdown pieces which have collapsed from the ceiling to the floor, to cobble to pebble to sand to silt to clay-sized particles. The finer-grained particles constitute the muddy floor deposits or fill fault zones exposed in the walls and roof of the cave.

Description of Clastic Deposits

Coarse Deposits

Breakdown. The breakdown in Kartchner Caverns varies in size from large blocks such as at Bob's Guano Pile, Big Room, to smaller pieces where bedrock has been shattered along fault zones. Breakdown can be found within sediment, on top of sediment, or covered by thin layers of sediment deposited under floodwater conditions. The larger upper rooms of the cave are primarily collapse passages, formed when large sections of ceiling collapsed to the floor. Large breakdown pieces from this collapse have blocked lower solutional passages; e.g., the breakdown in the Rotunda Room where it blocks the lower, solutional Triangle Passage.

The Kartchner breakdown seems to be either of the slab or chip variety (White, 1988). The smaller chip breakdown (such as in the Grand Canyon) appears not to be due to solutioning of breakdown, but rather to the shattered nature of the bedrock in this room. The shattered rock has fallen to the floor as small pieces of chip breakdown.

It seems likely that the breakdown process in Kartchner Caverns has been going on during the entire vadose history of the cave. Breakdown falls during the air-filled, vadose stage of cave formation and can be due to the following factors: (1) removal of buoyant support (when the water level lowers below the passage horizon), (2) base-level backflooding, (3) undercutting by free-surface streams, (4) crystal wedging processes, and (5) earthquake activity (White, 1988). All of these factors may have been operative in Kartchner, but (1) was probably the foremost factor.

Pebble gravel. The pebble gravel contains clasts up to 1.2 cm in diameter in a matrix of smaller pebbles, sand, silt and clay. A hand-lens inspection of the pebble gravel indicates that approximately 80% quartz pebbles, 10% quartzite pebbles and 10% sand-,silt- and clay-sized particles make up this unit. The largest clasts are the quartzite pebble.

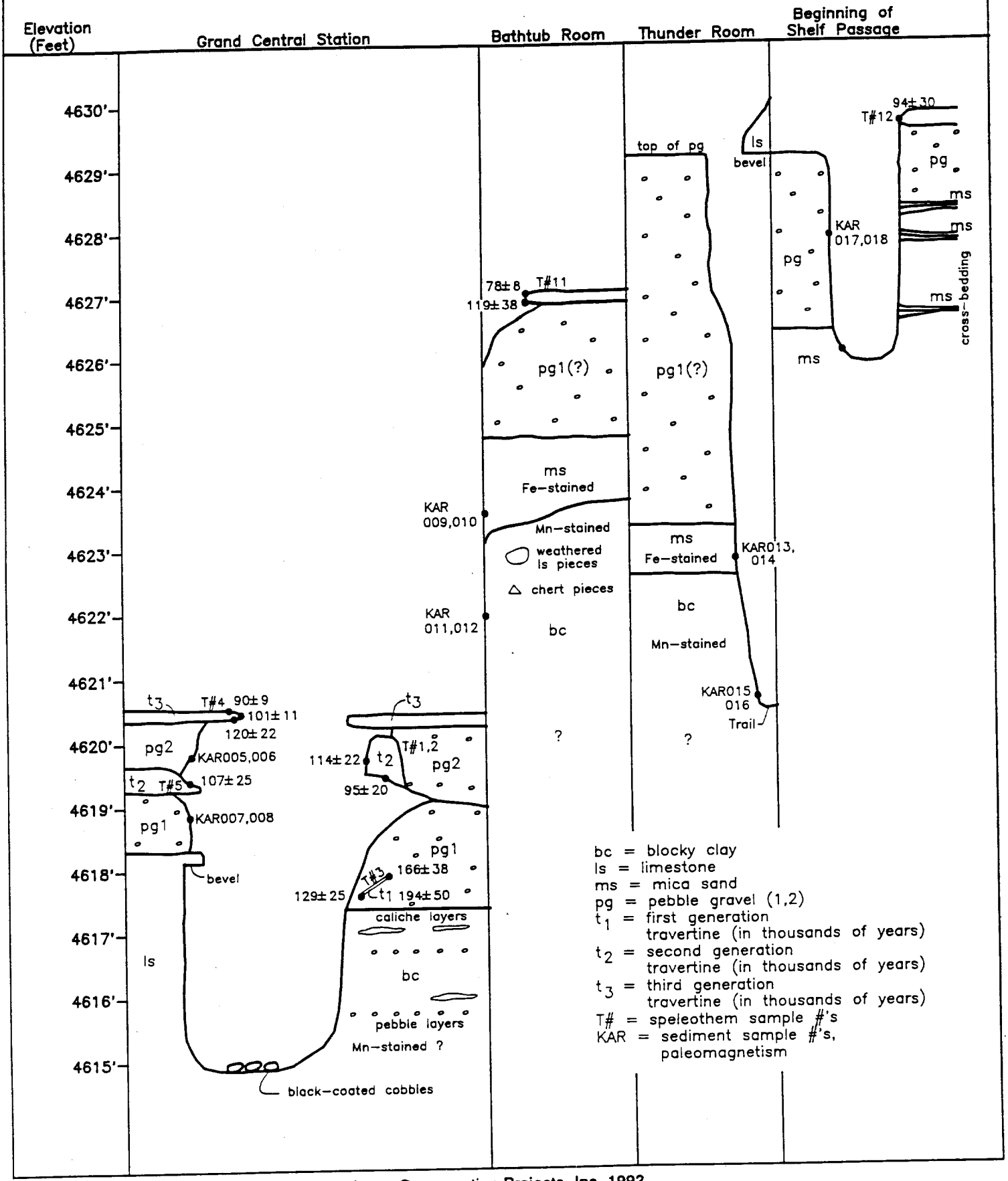
In Grand Central Station, the pebble gravel influxed into the cave in at least two episodes. The oldest pebble gravel (pg1) was covered with a small amount of travertine (t1 = 115,000 to 95,000 YBP or so), and then this travertine was covered by a second influx of pebble gravel (pg2) (Figure 105). Later, more massive travertine (t2 = 110,000 to 90,000 YBP or so) covered pg2. From the closeness of dates on t1, t2 and t3 material and the lack of travertine between the three, it appears as if the pg1 and pg2 pebble gravels were dumped quickly into the cave (perhaps each gravel in single, separate event). Finally, the whole sequence was downcut by late-stage vadose stream activity, and the third generation of travertine (t3) was left as a hanging canopy.

In the Thunder Room-Shelf Passage, the top of the pebble gravel is at the same level as the undercut bevel in the wall limestone: it is suspected that the same backflooded water must have been responsible for both phenomena. In the Shelf Passage, the pebble gravel is graded (coarser at bottom to finer at top), very faintly cross-bedded, and interbedded with mica sand. Slump features show that the sediment slumped towards the center of the passage as the passage was being downcut (i.e., the sediment may have experienced deposition, slumping, and downcutting in the same episode). In Granite Dells, the pebble gravel forms the matrix for large (up to 0.3m in diameter) granite cobbles and boulders.

Surface gravel above Granite Dells resembles the pebble gravel in the cave except that it lacks the fine-grained silt and clay fraction. This is because the surface gravel has been size-sorted by a surface stream and the finer-grained particles have been

FIGURE 105

Correlation: Elevations, Sediment Samples, and Travertine Samples



carried away by the stream. Mica crystals in the granite pieces have a gold-like appearance and are very noticeable; in the cave pebble gravel, the mica is covered with mud but can be seen when the gravel is washed.

Mica sand. Mica sand occurs directly beneath pebble gravel and above the blocky clay in the Bathtub Room and Thunder Room and intermittently in size-sorted pebble gravel at the beginning of the Shelf Passage. It is a laminated sand, the laminae being highlighted in iron-rich sections. Size-wise, it can be classified as a very fine-medium sand (size = 0.1-0.4 mm); it is composed approximately of 95% quartz sand and 5% mica flakes. It is the mica flakes that give the sand its sparkle and its name. The mica sand contains no larger clasts within it.

A sample of mica sand was collected by Scott Gibson for a mica concentrate Rb/Sr analysis in order to determine the source of the mica in the mica sand unit. This study has not been done yet.

Fine-Grained Deposits

Fault clay. The fault zones exposed by the cave are filled with quartz veins and a red to orange hematitic clay matrix. An example of this type of clay is the "red fault clay" collected in the Main Corridor near PP11. The red fault clay is composed of an equal mixture of calcite and rectorite clay. The calcite occurs both as disaggregated fragments and also as scalenohedral crystals, which may mean that some of the calcite was deposited before final movement along the fault zone (the disaggregated fragments), while some formed later, after final movement (the scalenohedrons). The clay mineral rectorite occurs as twisted scales and has formed from, and mostly replaced, illite (S. Williams, personal communication, 1991).

Another occurrence of fault clay may be seen at the end of Red River Passage. This clay is composed of 80% greenish-gray, finely-laminated illite + angular quartz clasts + red colloidal hematite between laminae. The illite is weakly foliated, but the foliation is mimetic - i.e., the foliation occurred before the deposition and lamination of the illite as a sedimentary deposit.

Fault material sloughs off the ceilings and walls of the cave and has accumulated on the floor beneath fault zones in a number of places. Such residue collected near Grand Central Station was classified as a very fine-medium grained silt (0.005-0.02 mm).

Blocky clay. The blocky clay unit is a compacted floor clay composed of various clay minerals plus detrital and organic matter. The blocky clay unit underlies mica silt and the pebble gravel in the Bathtub Room and Thunder Room and pebble gravel (pg1) in Grand Central Station. In Grand Central Station, the Bathtub Room and Thunder Room, its "blocky" segments are covered with thin black coatings. In the Bathtub Room, it encloses angular chert fragments (fallen roof breakdown) and fossiliferous limestone pieces about one-half of their original mass. Harder "caliche" layers occur in sections of blocky clay in Grand Central Station, and there is a possible unconformity between the blocky clay unit and pebble gravel unit.

The composition of the blocky clay unit in the Throne Room contains an equal mix of illite clay (half altered to rectorite) and quartz needles (slender, doubly-terminated prisms). In addition, there is an abundance of organic fiber in the clay. The illite-rectorite clays occur in radially disposed domains and may replace feldspar (S. Williams, personal communication, 1991).

At the Echo Passage-Bison Room junction, a transition can be seen between unconsolidated nontronite clay and compacted blocky clay over a vertical distance of

about 1m. As the clay dried and compacted, it broke up into separate "blocks" and black material migrated to the spaces between the blocks to form thin layers of manganese + metals.

Unconsolidated clay. Mud can be found everywhere in the cave, especially in the Back Section. One crawls through it, wades through it and plods through it. The unconsolidated mud of the Subway Passage is pure rectorite, a pasty, greasy, sticky clay; it is possible that the "mud" in the entire Back Section of the cave is composed - at least partially - of this mineral. The "mud" in Echo Passage is known to be composed of nontronite - a mineral similar in composition to rectorite.

Paleomagnetic Dating of Sediments

All of the sediments, from the blocky clay up to the upper pebble gravel (pg2) are paleomagnetically normal. Since these sediments have been correlated with uranium-series dating of interbedded travertine, it is known that they all date from the Brunhes/Matsuyama normal (<730,000 YBP) rather than from an earlier (>900,000 YBP) normal. All paleomagnetic dating was done by Vic Schmidt, Paleomagnetism Lab, University of Pittsburgh. Locations of paleomagnetic samples are shown in Figure 105.

Interpretation of the Sedimentology

The coarse and fine-grained deposits in Kartchner Caverns have different origins: the coarse deposits are all related to late-stage vadose events in the cave, whereas the fine-grained sediments have a more complex history, one extending back to the time of faulting and one involving the alteration and replacement of clay minerals. Since the fine-grained sediments are older, they will be discussed first.

Fine-Grained Deposits. The origin of the fault clay/silt is speculative. It is known that illite fills the faults and this mineral has altered to rectorite in situ, but what is not known is if there was an even earlier mineral precursor of illite. In other words, did minerals like the feldspars and micas originally fill the faults before altering to illite (and then rectorite), or was the illite clay the original constituent of the faults? Only two clues seem to present themselves in this regard. One clue is the presence of "birdsnest" quartz near or in fault zones. These quartz needles probably grew into a clay matrix during the time that hot, silicifying solutions permeated the fault zones. If feldspar-mica debris did at first fill the fault zones, it must have quickly turned to illite clay so that the quartz needles could grow into the clay.

The second clue in this regard is the illite-filled fault zone at the end of Red River Passage. This illite is thinly laminated and contains angular quartz, much as one would expect of a sedimentary deposit. The illite displays mimetic foliation, which means the foliation was assumed from some precursor mica or feldspar mineral before deposition and lamination of the clay. This opens up the question of whether the Pinal Schist (a foliated rock) might have been the original source of illite to the fault in Red River Passage. Might ascending solutions have carried schistic material up the fault zones and deposited them as a sedimentary deposit within some type of paleokarst cavity? It is not known with certainty how far below the Escabrosa block the Pinal Schist is, but Graf (1989) showed it as less than 30 m; hence it might be a possible source of the illite. The laminated illite in the Red River Passage must be very old. It predates the cave (i.e., is truncated by it) and its beds are tilting northeast to east, not southwest as are the Escabrosa Limestone beds (D. Jagnow, personal communication, 1991). Either the illite was emplaced and tilted before the tilting of the

Escabrosa block, or later movement along the fault zone caused the illite to move in a direction opposite to bedrock tilt. Curiously, the Red River fault cannot be traced to the surface (D. Jagnow, personal communication).

It is uncertain if the blocky clay unit is authochthonous in origin as suggested by Graf (1989), if it is entirely allochthonous - or it it might be a combination of both. In Grand Central Station, the blocky clay has sections of pebble gravel in it, and in the Thunder Room it is mixed with organic matter. These both suggest an allochthonous origin for the blocky clay unit. However, rectorite clay fills the "red fault zone" in the Main Corridor and is also the pure component of the Subway Tunnel "mud," which suggests that this "mud" might be authochthonous fault-derived residue material. Similarly, illite is the main component of the fault clay in Red River Passage and it is also the main mineralogical component of the blocky clay in the Thunder Room. Perhaps then the blocky clay is a combination of allochthonous and authochthonous sediment. Volume considerations favor this interpretation as does the Thunder Room blocky clay which consists of illite and quartz needles (dissolved from the fault zone?) plus feldspar and organic material (brought in as allochthonous debris?).

The same uncertainty exists for the origin of nontronite clay in the Echo Passage. Nontronite is known to derive from granitic terranes where the clay forms from the alteration and breakdown of mica minerals, and it is possible that alaskite and/or Pinal Schist debris could be the source of mica for the nontronite; however, granitic pebble gravels and mica sands do not actually occur within Echo Passage. There is the added problem in that the nontronite and black manganese material expelled from the nontronite is very high in metal. These metal enrichments must involve some kind of hydrothermal activity where the faults acted as conduits for ore fluids, and suggests that the nontronite clay derived from fault zone material as the cave dissolved.

If the clay minerals rectorite and nontronite are allochthonous, then one must ask: under what conditions did they form? Newsom (1978) stated that the rectorite clay associated with "haystack" quartz in Arkansas formed "directly from hydrothermal solutions." In Kartchner, however, it appears to have formed as a late-stage alteration product of illite. Nontronite is known to form under high pH, low Eh conditions. No Eh/pH diagrams have been constructed for rectorite but, considering its mode of occurrence, it is possible that it may form under similar conditions.

The exact paragenesis of the fine-grained clay deposits of Kartchner Caverns is not known with certainty. The following "best-guess" scenario is suggested:

1. Illite was deposited in fault zones by hydrothermal solutions ascending through the Pinal Schist and into the above-lying Escabrosa Limestone. These same solutions brought up silica and iron which deposited along with the illite in the fault zones as quartz veins and hematite.
2. Calcite deposited in fault zones as the temperature decreased. Late movement along the faults disaggregated this calcite and also the vein quartz.
3. Cave dissolution exposed the illitic fault clay and the residue settled to the cave floor.
4. Finally, vadose flood water of high pH and low Eh altered the illite clay to rectorite and nontronite.

Coarse-Grained Deposits. All of the coarse-grained clastic deposits are related to vadose events. As the water table dropped, breakdown collapsed to the floor, blocking earlier dissolved solutional passageways. Later, flood water dumped sand and gravel into the cave where they overlie (unconformably?) the fine-grained clays. The following observations apply to the interpretation of the coarse deposits.

1. The cave pebble-gravel unit is essentially the same as surface gravel above the cave except for the fine-grained fractions. The pebble gravel was thus probably locally derived, having entered the cave during times of heavy storms.

2. The age of the blocky clay, mica sand, and pebble gravel are all >100,000 YBP and <730,000 YBP. The pebble gravel corresponds to the time of greatest travertine growth in the cave - during the Sangamon interglacial, when a much wetter climate probably produced storms capable of carrying surface gravels into the cave.

Using Hjulstrom's diagram for the transportation and deposition of sedimentary particles, it can be estimated that the velocity of the water depositing the pebble gravel must have been <90 cm/sec and >10 cm/sec: either that, or somehow the gravel slumped into place.

4. The Granite Dells cobbles/boulders in a matrix of pebble gravel most likely slumped into place. Granite Dells is very near the surface (see surface-cave map, Arizona Conservation Projects, 1991) and pirated surface runoff probably transported surface sediment into the cave at that location sometime in the past (176,000 YBP?).

5. The mica sand may represent a lateral-fining equivalent of the pebble gravel. The first particles to deposit in a back-wash situation are the large pebbles; then, when the velocity has decreased markedly, the fine-grained fraction (mica flakes, fine sand, silt and clay) settle out. The fine-grained fraction typically grades laterally from the center of passages and are finest-grained in deep recesses (this is called "lateral fining"). Thus, the pebble gravel over mica silt may represent two episodes of flooding, the first less violent or extensive than the second. For example, for the Bathtub Room sediment sequence, Flood Event #1 may have deposited pebble gravel in another part of the cave and mica sand as a laterally-fined sediment. A more violent Flood Event #2 could have brought gravel into the Bathtub Room thus creating the sequence where pebble gravel overlies mica sand. The interbedded graded sequence of pebble gravel-mica sand in the Shelf Passage attests to the probably cyclic and repetitive nature of the sediment-filling process.

SPELEOGENESIS

The term "speleogenesis" refers to the dissolution of cave passages and modification of those passages. An outline of speleogenesis events in Kartchner Caverns, integrated with regional geologic events, is presented in Table 36. Speleogenesis events can be divided into three categories: pre-cave, shallow-phreatic and vadose.

Pre-Cave Events

Pre-cave events started with the deposition of the Mississippian Escabrosa Limestone around 320 Ma ago. It was during this time that the bedrock units now exposed in the cave were deposited. These units - whether they were slightly more or less permeable - influenced later groundwater movement.

The next major event affecting the cave came much later, in the Miocene epoch, during Basin and Range faulting, uplift and heating (Table 36). The Basin and Range event created a graben and horst type of topography in Arizona where disconnected mountain ranges and valleys (such as the Whetstone Mountains and San Pedro Valley) became the predominant topographic features. During this event, the Escabrosa Limestone was faulted and the block of limestone in which Kartchner Caverns is developed was downdropped to its present position. Hydrothermal solutions ascended along fault zones and these became filled with illite clay, quartz veins and hematite (+ metals). Temperatures of these hydrothermal solutions ranged from about 125 to 175°C.

TABLE 36
Proposed Sequence of Geologic Events
Kartchner Caverns and Benson Area

Period	Pre-Cave Events
Mississippian ~320 Ma	Deposition of Escabrosa Limestone
Miocene 10-5 Ma	Basin and Range faulting, uplift; time of heating. Influx of hydrothermal solutions along fault zones; solutions enriched in Si, Fe and other metals. Illite clay from underlying Pinal Schist fills fault zones? Quartz veins precipitate in fault zones; T = 125-171°C "Birdsnest" quartz needles grow from hot solutions into illite clay matrix. Minor paleokarst development along fault zones?
Miocene to Pleistocene	Time of cooling Calcite precipitates as vein material within limestone T = 30-40°C
	Shallow Phreatic Events
Pleistocene ~730,000 YBP	Deposition of St. David Formation; upper part <730,000 YBP Time of maximum valley filling.
~200,000 YBP	Water table stable (in St. David Formation?) at about 4625' elevation;cave passages dissolve along water table Illite clay residue from fault zones settles to cave floor
	Vadose Events
Illinoian Glaciation 170,000-120,000YBP	"Granite Wash" unit deposits on erosional surface of St. David Formation. Cave becomes air-filled. Travertine growth begins.
Sangamon Interglacial 120,000-70,000 YBP	Downcutting of valley fill; development of Whetstone Terrace across San Pedro Valley Warm, humid climate (forested?) Major time of speleothem growth Alteration of illite clay floor residue and in fault zone to rectorite and nontronite under high H, low Eh, stagnant-water conditions; blocky clay unit forms. Back-up flood water entering from downcutting Guindani Wash creates vadose solution bevels.

Period	Vadose Events (continued)
	Erosion of Granite Wash unit;Granite Wash debris washed into cave-becomes pebble gravels (pg1,pg2), mica sand.
Wisconsin Glacial	San Pedro River cuts down through Whetstone Terrace; Pleistocene lake in San Pedro Valley, 30,000-10,000 YBP Travertine growth declines. "Bison" (bear?) bones wash into cave? Bats begin to inhabit cave?
Present 10,000 YBP-present	Downcutting of San Pedro River to present level. Wetter climate replaced by dry desert climate. Travertine growth continues to decline; deliquescent nitrocalcite can grow in low-humidity entrance area. Minor earthquake activity causes speleothem damage. Temporary flooding of cave.

During this time, the processes of cooling corrosion and thermal mixing corrosion (Bogli, 1980) may have dissolved some karstic cavities along the fault zones. Minor paleokarst development is suggested by the following:

1. The laminated illite clay filling the fault zone at the end of Red River Passage looks like it formed as a sedimentary deposit before it was impregnated with hematite and tilted (opposite to the direction of bedrock tilting). The void which the illite fills may actually be a paleokarst cavity formed along the fault zone and exposed by the cave (but not on the surface).
2. Surface exposures of vein quartz may widen to 15m or more and then thin to only a few centimeters (Thomson, 1990, his map). The wide, bulbous masses of quartz may represent filled paleokarst developed along the faults. These intruded masses of quartz appear to have chemically brecciated host limestone rock around the veins (e.g., the River Passage Fault).
3. "Birdsnest" needle quartz has preferentially deposited along boxwork fins and solutional fins in or near fault zones. If paleokarst cavities developed along the fault zones, then the "speleothemic" appearance of this quartz is explainable (i.e., the needle clusters had to grow into open space or at least into a cavity filled with porous mud). Otherwise, one must invoke speleogenesis by thermal water to explain the "birdsnest" quartz. Such a late state (late Pleistocene) heating event in the Benson area does not seem compatible with the timing of other known regional geologic events.

After the Basin and Range thermal event, solutions cooled and calcite deposited as vein material within the host limestone and along faults. Carbon-oxygen isotope values for calcite boxwork plot in the same regime as known thermal spar in other areas and calculations of calcite deposition temperatures based on oxygen isotopes range between 30-40°C. Late-stage movement along faults could have produced the disaggregation or pulverizing of calcite and also of pre-existing quartz veins.

Shallow-Phreatic Events

Phreatic domes, ceiling channels and anastomoses can be seen in the Hill Room, between the Mushroom Passage and Sue's Room and elsewhere in the cave. This is

evidence for at least some cave dissolution below the water table. Since no deep-phreatic pits or other bathyphreatic features are known to be present (as indicated by the gravitimetric survey of Art Lange), the phreatic regime of cave development was probably shallow. Phreatic scallops in the Mud Flats area of the Big Room measure 0.3-0.6m in diameter. The velocity of water movement corresponding to this scallop size is approximately 1.2 cm/sec (Sweeting, 1973). Cave development appears to be along joints rather than along faults. This is not unusual: it is comparatively rare to find an entire system of conduits that is directed primarily by faults or contained within them (Ford and Williams, 1989).

Solutional cave passages cut across bedding and are essentially horizontal, even where bedding dips at high angles. This indicates strong water-table control on cavern dissolution. This water table must have been stable at one level for a long period of time, and it must have been aggressive in order for it to cut across bedrock, impermeable fault zone gouge, and quartz veins alike. Cave dissolution at or near the water table by cold, meteoric water as suggested by Jagnow (1990) is probably more likely than thermal-water dissolution, although low-temperature (<100°C) geothermal water still exists in the Benson area (Witcher et al, 1982).

Time of cave dissolution was probably around 200,000 YBP. This time may correlate with water table development in the St. David Formation, whose upper layers are known to be <730,000 YBP (Graf, 1989). It is not known if the St. David Formation ever extended as high as the cave, but if it did, it could have provided the regional water table necessary for cave dissolution at the 4620-4630' level.

Vadose Events

Some vadose scalloping occurs on travertine material in the Angel's Wing side passage off the Subway Passage and on bedrock elsewhere in the cave. The size and asymmetry of these scallops record direction and velocity of vadose flow; these have been plotted by Jagnow (1990). Also, vadose activity is recorded by the presence of vadose sediment and the downcutting of this sediment in Grand Central Station, the Shelf Passage, Grand Canyon and elsewhere. The presence of black-coated stream clasts in downcut channels is further evidence for late vadose stream flow.

POTENTIAL CAVE ACCESS POINTS

INTRODUCTION

At the present time there is only one entrance into Kartchner Caverns, the original discovery entrance. To reach the main rooms of the cave, one must crawl for several hundred feet through small passages. In order to develop the cave for public viewing, a new entrance will need to be constructed or the existing entrance passages enlarged. Introducing new access points into the cave should not be taken lightly because we must insure that they will not adversely affect the microclimate of the cave. The overall goal of these studies is to identify the location which will have the smallest impact on the conditions in the cave. Furthermore, we would also like to identify the site which appears to be the most practical from the standpoint of developing the cave for the public.

To date, all previously developed caves have been developed with little initial regard for preserving the microclimate of the cave. This has resulted in retroactive attempts to reduce the impact of the changes and to restore the original microclimate. Maintaining the microclimate has been found to be much more critical for Kartchner Caverns because it is located in an arid environment and improper development could lead to rapid drying of the cave. The approach being used in the entrance selection process for Kartchner Caverns is a multi-step process. First, we have evaluated the potential threats to preserving the microclimate of the cave, based on data collected during the cave climate studies. Second, a large number of potential entrance sites were identified and analyzed for suitability based on several criteria. Those potential entrances which offer the smallest impact or which minimize the impacts on the conditions and features of the cave were selected for additional study. Additionally, by examining each entrance location in some detail, those with serious problems were identified. The result of this analysis was presented in the Interim Report which recommended that three locations be investigated in greater detail. The third step has been the geologic investigation of the recommended sites and final entrance selection.

The first two steps of the process are detailed in the Interim Report (ACPI, 1991). That process is briefly reviewed here. At the beginning of our study, a number of possible sites for the development of a new entrance were initially located by identifying portions of the cave close to the surface and which may have been former and now-collapsed entrances. These potential entrance sites became the focus for the on-going microclimate monitoring. Each potential location was then evaluated to determine the likelihood for disrupting the cave microclimate. An additional set of criteria was used to evaluate each location for the ease of development.

For each potential entrance we are concerned with two broad questions: What is the impact on the cave resource? and: Is this a practical location for bringing people into the cave? The first question requires an assessment of the relative merits of the various entrances based on the potential impact to cave features and microclimate. This assessment is primarily related to preserving the cave resource. The second deals with those factors which influence the ease or suitability of each entrance in regard to developing the cave. This assessment is primarily related to the suitability of the entrance to meeting the needs and expectations of the viewing public.

A number of general assumptions were made to provide a uniform framework for comparing entrance sites:

- In-cave tour of approximately one hour.
- Length of tour route 3000' to 5000'.
- Connecting tunnel from Cul-de-Sac to Throne/Rotunda Room.
- Tour party size of 20-30 people if guided tours are used.
- Visitor's Center will be located so as to minimize the distance to the cave entrance.

A number of items specifically not considered are:

- A particular tour route.
- A fixed number of entrances or combinations of entrances.
- Cost.
- Number of visitors.
- Means of moving visitors through the cave (walking or mechanical transport)
- Effectiveness of methods to mitigate negative impacts.

A total of 10 different sites for constructing a new entrance into the cave were investigated. See Figure 106 for a map showing the locations of each site. For each location, three different approaches were used to create access into the cave:

- A ramp or sloping tunnel suitable for wheelchair access (15:1 slope).
- Stairs in a more steeply sloping tunnel - the stairs would not be handicap-accessible
- An elevator and a short (75' minimum) length of tunnel to accommodate approximately 50 people (2 tours).

For each of these 30 combinations, an assessment was made of the potential for disrupting the microclimate of the cave. Based on the microclimate study, the potential for increasing airflow through the cave was considered to be the most important issue to be addressed. Other items considered in the assessment were the impact on the supply of moisture to the cave and impacts on the biota. The biota is not only an important feature of the cave but also provides a sensitive indicator of the conditions within the cave.

A major concern in the evaluation of the biota is the potential impact on the bats which inhabit the cave during the summer. Bats roost in the Big Room from May to September. The bats have been identified as Myotis Velifer. The cave is used as a maternity site by approximately 1000 to 2000 bats. These bats appear to be easily disturbed by human activity. It is unlikely that they would remain in the cave if the roost area was developed. The impact on the bats of developing other portions of the Big Room is not known. It is also unlikely that the bats can be encouraged to move to another part of the cave. The area around Sharon's Saddle and the fly-way to the natural entrance is of critical importance to the bats.

Each potential entrance site was also evaluated to assess the practicality of each entrance in developing a suitable tour of the cave. Those factors which were identified as influencing the ease of development are:

Access Tunnel. Length of tunnel, elevation difference and geologic hazards that may be encountered along the tunnel route.

Interior Trail. The distance from the entry point to major features of the cave (Throne, Big and Rotunda Rooms) was rated. Distance to a room suitably large

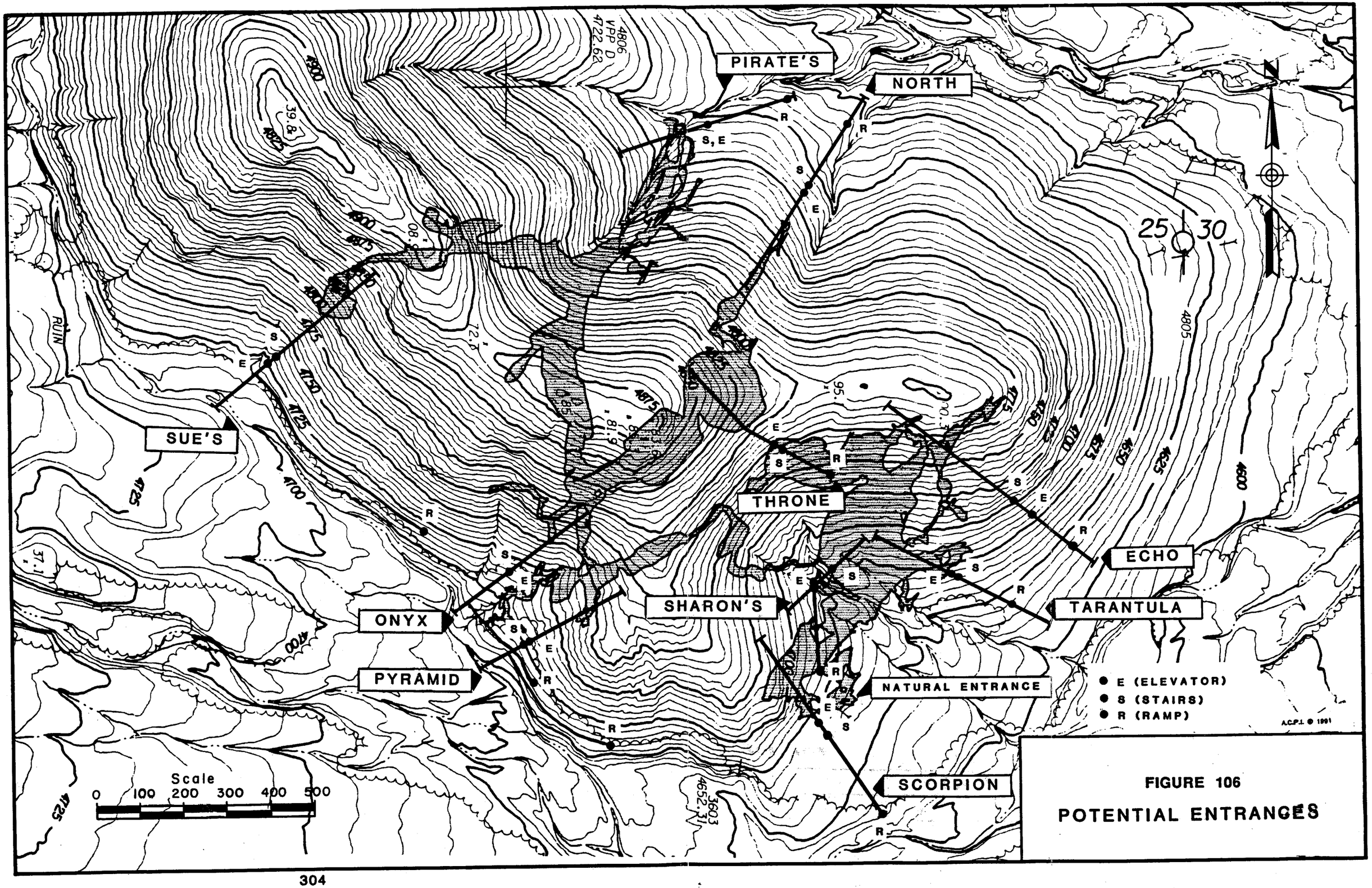


FIGURE 106

POTENTIAL ENTRANCES

enough to assemble a tour of 20 people for orientation to the cave. Availability of alternate trail routes. The combined distance to major features and length of the entrance tunnel. Potential for area to flood.

Surface Trails. The distance the visitor must travel between the Visitor's Center and the starting point of the tour was also considered. Distance from the most favorably located Visitor's Center to the proposed entrance. The elevation differential from the lowest point along the route to the potential entrance.

One result of the assessment of the potential entrances has been the identification of severe impacts which would have a dramatic effect on the cave. These severe impacts compromise the integrity of the cave resource or the ability to develop the cave. These impacts are associated with a particular entrance configuration which would jeopardize the integrity of the cave if that entrance were constructed. An example of a severe impact is frequent flooding of an area which would disrupt trails across the area. Potential entrances or individual options for which severe impacts were identified were excluded from further consideration.

The results of the Interim Report analysis is given in Table 37. Potential entrances which have severe impacts are eliminated from further consideration. Only 3 of the 10 original sites are left for consideration: Tarantula Room, Echo Passage,Throne Room.

In the Interim report, the North Passage was also considered but determined to be less suitable than the three recommended locations and was dropped from further consideration. An additional drawback to the North Passage was later found in the spring of 1991. The North Passage was found to flood. This would be considered to be a severe impact which would prevent the use of the North Passage as an entrance.

A fourth entrance site was added to the three examined in the Interim Report. The fourth location would enter the cave in the Throne Room at the same location as the proposed Throne Room entrance. The new option would be an alternate tunnel alignment. However, this tunnel would slope up into the cave rather than down as in the original proposal. This reduces the difference in elevation between the natural entrance and tunnel entrance and would induce less airflow. Because the tunnel slopes upward into the cave, it is less likely that gravity or density airflow could enter the cave through the tunnel. It also reduces the elevation which the visitor must climb from the visitor's center to the entrance. An additional advantage is that this tunnel alignment avoids crossing over known cave passages.

The four sites recommended for further study are:

Throne Room
Throne Room Tunnel alternative
Tarantula Room
Echo Passage

Detailed studies of the geology were done at each of these locations by David Jagnow.

GEOLOGIC EVALUATION OF PROPOSED ENTRANCES

Purpose of Study

This geologic study was conducted to provide geological engineering information critical to the evaluation of potential visitor access points. It also provides geological interpretations essential for the understanding of how meteoric water enters the cave: along faults, fractures, and as perched aquifers on top of impermeable marker beds. This understanding should ultimately allow better management of the delicate cave resources.

TABLE 37
POTENTIAL ENTRANCES FINAL RANKING

POTENTIAL ENTRANCE	ACCESS Type	CAVE IMPACTS			ACCESS TUNNEL		INTERIOR TRAIL			SURFACE TRAIL		TOTAL SCORE	Severe Impacts
		Raw Point Total	WEIGHT 6	Severe Impacts	Raw Point Total	WEIGHT 1	Raw Point Total	WEIGHT 2	Severe Impacts	Raw Point Total	WEIGHT 1		
Tarantula Room	**Ramp**	**21**	**20**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**3**	**23**	**0**
Tarantula Room	**Elevator**	**21**	**20**	**0**	**0**	**0**	**0**	**0**	**0**	**3**	**4**	**25**	**0**
Echo Passage	**Ramp**	**18**	**17**	**0**	**1**	**3**	**1**	**2**	**0**	**3**	**4**	**26**	**0**
Echo Passage	**Stairs**	**18**	**17**	**0**	**1**	**3**	**1**	**2**	**0**	**3**	**4**	**26**	**0**
Tarantula Room	**Stairs**	**21**	**20**	**0**	**1**	**3**	**0**	**0**	**0**	**3**	**4**	**27**	**0**
Echo Passage	**Elevator**	**22**	**21**	**0**	**0**	**0**	**1**	**2**	**0**	**3**	**4**	**28**	**0**
Throne Room	**Stairs**	**15**	**15**	**0**	**1**	**3**	**5**	**10**	**0**	**2**	**3**	**30**	**0**
Throne Room Alt.	**Ramp**	**15**	**15**	**0**	**1**	**3**	**5**	**10**	**0**	**2**	**3**	**31**	**0**
Throne Room	**Ramp**	**15**	**15**	**0**	**2**	**5**	**5**	**10**	**0**	**2**	**3**	**32**	**0**
Throne Room	**Elevator**	**25**	**24**	**0**	**0**	**0**	**5**	**10**	**0**	**3**	**4**	**38**	**0**
Pirate's Den	Ramp	8	8	0	0	0	6	12	1	4	6	25	1
Pirate's Den	Stairs	8	8	0	1	3	6	12	1	5	7	29	1
Pirate's Den	Elevator	12	12	0	2	5	7	14	1	1	1	32	1
Scorpion Passages	Elevator	21	20	1	0	0	2	4	0	7	10	34	1
North Passage	Ramp	8	8	0	0	0	10	20	1	5	7	35	1
Scorpion Passages	Stairs	21	20	1	1	3	2	4	0	7	10	37	1
North Passage	Stairs	12	12	0	1	3	10	20	1	6	9	43	1
North Passage	Elevator	18	17	0	0	0	10	20	1	6	9	46	1
Onyx Passage	Stairs	33	32	0	1	3	6	12	1	2	3	49	1
Scorpion Passages	Ramp	37	36	1	1	3	2	4	0	6	9	51	1
Sharon's Saddle	Ramp	46	45	1	1	3	3	6	0	2	3	56	1
Sharon's Saddle	Elevator	62	60	1	0	0	3	6	0	4	6	72	1
Onyx Passage	Elevator	60	58	0	0	0	6	12	1	2	3	73	1
Sharon's Saddle	Stairs	62	60	1	2	5	3	6	0	4	6	77	1
Pyramid Room	Stairs	33	32	1	1	3	6	12	1	1	1	48	2
Pyramid Room	Ramp	38	37	1	0	0	5	10	1	5	7	54	2
Pyramid Room	Elevator	38	37	1	2	5	6	12	1	1	1	55	2
Sue's Room	Stairs	30	29	1	2	5	10	20	1	2	3	57	2
Sue's Room	Elevator	40	39	1	1	3	10	20	1	2	3	64	2
Onyx Passage	Ramp	55	53	1	1	3	6	12	1	2	3	71	2
Sue's Room	Ramp	45	44	1	4	10	10	20	1	2	3	76	2

Geologic evaluation of the potential entrances has been carried out in two phases. The first part has focused on the detailed geology above the cave. The second part was construction of detailed geologic cross-sections at each proposed entrance.

Detailed Surface Geology Map

The detailed surface geology mapping of various subdivisions within the Escabrosa Limestone has provided several useful benefits. The identical dark marker beds that were mapped in Kartchner Caverns in 1990 were located on the surface and mapped in detail for this study. The Detailed Surface Geology - Potential Entrances Map (Figure 107 in the map pocket at the end of this report) and its structural interpretation have provided the necessary data for geologic cross-sections at proposed entrances (Echo Passage, Tarantula Room, and Throne Room). This most recent mapping has also provided a detailed composite Stratigraphic Section (Figure 108) for the Escabrosa section exposed in the Kartchner Hills.

The low carbonate hills overlying Kartchner Caverns generally dip to the southwest at 15° to 35°. Dr. Kenneth C. Thomson mapped Kartchner Caverns State Park in more detail as part of the study by Arizona Conservation Projects, Inc.(Thomson, 1990). The present study focuses in greater detail on the subdivisions within the Escabrosa Limestone block that contains Kartchner Caverns.

Area of Detailed Mapping. Kartchner Caverns is contained entirely within a highly faulted and fractured block of Escabrosa Limestone. This "Kartchner Block", otherwise known as South Hill, is bounded on the west by the West Boundary Fault; on the north by the South Valley Fault; and on the east and south by deposits of Quaternary alluvium that lap onto the Escabrosa Formation. The southwest corner of the Kartchner Block contains a downdropped triangular wedge of Horquilla Formation that was not mapped in detail. The detailed mapping focused on the key marker beds within the Escabrosa Formation, and the associated structures.

The mapping of the Quaternary alluvium deposits that surround the Kartchner Block was taken directly from Ken Thomson's map with only minor revision.

Mapping Methods and Procedures. The key stratigraphic marker beds that were previously mapped in Kartchner Caverns as part of the Subsurface Geology Map (Jagnow, 1990) were projected to the surface and located on the surface during this study. The dark marker beds and faults that are so obviously displayed inside the cave are much more difficult to recognize on the surface. Measured traverses along the network of geophysical stakes, permanent survey stations and temporary survey stakes over proposed entrances provided excellent control for the mapping. Black and white aerial photographs, along with color aerial photographs, were used extensively to provide stereo coverage of the geology. In general, the stratigraphy and faulting are depicted as solid lines where mapping is relatively certain, and shown as dashed or dotted lines where projected or inferred.

Structural Geology Overview

The Basin and Range faulting of the Whetstone Mountains probably occurred during Late Miocene and Early Pliocene time, about 10 to 5 million years ago (Steve Reynolds, Arizona State Geological Survey, and Hill). The placement of the Kartchner Hills fault block occurred during this time, accompanied by faulting, fracturing, quartz vein-fillings and iron mineralization.

The present study has identified no less than 60 faults that cut or bound the Kartchner Block. The vast majority of these faults are high-angle normal faults that

trend northeast. Where the displacement and dip of the fault plane is known, there are only five known high-angle reverse faults. There are three low-angle faults (dipping 40° to 45°), of which two are normal, and the third shows reverse displacement. There do not appear to be any true thrust faults cutting the Kartchner Block.

The most complexly faulted portion of the Kartchner Block is directly over the Big Room. The high concentration of faults in this area is probably responsible for the increased solubility that formed the Big Room. The majority of faults cutting Kartchner Caverns are high-angle normal faults that trend northeast from 20° to 60°. Most of these faults are either vertical or dip steeply to the southeast from 90° to 75°. The displacement on these faults is usually less than 10', being down-thrown on the southeast side--a typical normal fault. There are two reverse faults where the fault plane is dipping to the southeast, yet the southeast side is upthrown.

One of the most important low-angle faults is the Big Room Cross Fault. This fault cuts across the west end of Echo Ridge, dipping about 45° to the east. The hanging wall of the fault is offset downward by at least 40'. Where this fault crosses the Big Room, it dips about 50° to the northeast, and displays about 55' of offset. This fault appears to form the southwest termination of the massive Wall of stalagmites and columns that has developed beneath a northeast-trending reverse fault in the Big Room.

The Cul-de-Sac Fault shows the greatest displacement (other than the bounding faults). The Cul-de-Sac Fault cuts Echo Ridge just west of the Big Room Cross Fault and part way up onto Throne Ridge. To the northeast, the fault has about 165' of displacement. To the southwest, the fault bifurcates into two faults of lesser displacements. These two faults cut the western end of the Cul-de-Sac Passage, dipping 53°to 57° to the east, and forming a highly brecciated hematite-stained zone between the two faults.

The low-angle (40° to 45°) and intermediate-angle (50° to 60°) faults appear to have produced the major offsets in the Kartchner Block - probably during its initial emplacement during Basin and Range faulting. Many of the high-angle northeast-trending faults cut the low-angle faults, indicating these faults formed at a later date - probably associated with a later settling and adjusting of the Kartchner Block. The emplacement of silica and other mineralization along the faults appears to be associated more with this later period of faulting.

The faults are highly variable. They curve, change dip, bifurcate and merge with one another. The approximate amount of displacement and the orientation of the fault plane is shown on the map, if known. Most of the faults are marked by an abundance of reddish-brown hematite (iron-oxide) staining. About 1/3 of the fault zones are also filled with white quartz.

Stratigraphic Section

Initial observations throughout Kartchner Caverns revealed a series of "black beds" (actually dark gray) that can be traced throughout the entire cave. These prominent dark beds are easily spotted by the general public, and have been mapped as "key stratigraphic marker beds", designated by numbers zero (0) through five (5) in ascending order. Although very similar in appearance, each bed has its own distinctive lithology and fossil assemblage, with distinctive intervening sequences. These six beds provided the keys for mapping the entire cave. These same key marker beds have been projected to the surface and mapped in detail in this study. Although much more difficult to map on the surface, these dark beds once again are distinctively different from the surrounding mass of gray carbonates. They have

provided an excellent means of subdividing the Escabrosa Formation. The detailed lithologic descriptions are provided in the Stratigraphic Section (Figure 108). All of these units appear very dark gray or nearly black in the field due to a high percentage of organic matter. When broken, the rock yields a "fetid odor," smelling faintly like oil. On the surface, these units are more easily eroded, forming slopes between the adjacent cliff-forming limestones. Most of these dark beds are relatively impermeable and serve as perched aquifers. Water seeps into the cave along the top of each bed, commonly forming rows of stalactites where the bed intersects the cave. Mapping the six marker beds plus the sandstone and horn coral beds provides eight nicely-spaced stratigraphic markers throughout the 425' of Escabrosa Formation. Some of the bed and interval thicknesses vary slightly, especially from the front section to the back section of the cave. This suggests there may be significant strike-slip movement on the main Cul-de-Sac Fault that separates the two halves of Kartchner Caverns.

Potential Entrance Geologic Cross-Sections

The three potential entrances were subjected to a detailed geologic study. The locations of these proposed entrances are illustrated in Figure 107 in the map pocket at the end of this report. All three proposed entrances are located on the south or southeast-facing slopes of Escabrosa Formation, and are located within 600' of one another.

Detailed geologic mapping of the three proposed entrances, from both inside and outside Kartchner Caverns, was conducted the last week in April and first week of May 1991. Additional refinement was accomplished during detail surface geology mapping over the cave in July 1991. The enclosed geologic cross-sections, at a scale of 1"=20', summarize the geology at each of the proposed entrances. A fourth geologic cross-section illustrating an alternate tunnel sloping upward to the Throne Room has been added to the original three locations.

Throne Room Entrance

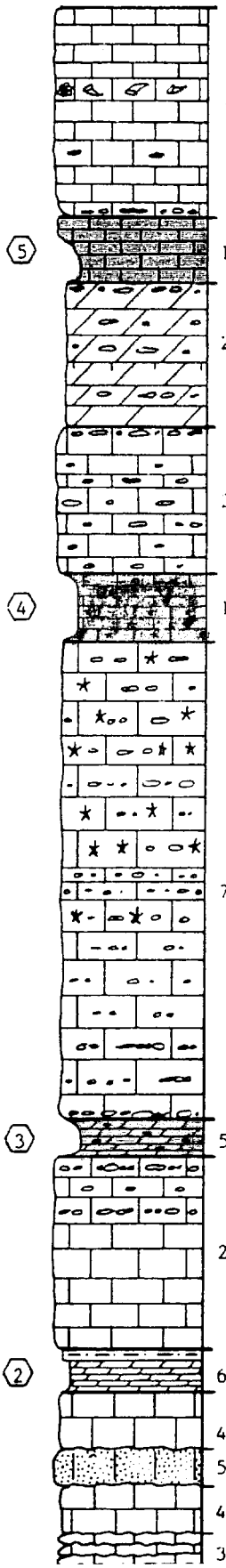
The Throne Room Entrance Cross-Section (Figure 109 in back pocket of this report) is probably the most complicated of the entrance cross-sections in terms of lithology and faulting. Yet the geology and structure are well controlled and believed to be well understood.

The geologic control points for this section are very secure. The measured surface section located marker bed 4 above the proposed tunnel entrance, with marker bed 5 at the proposed stairs entrance. Marker beds 4 and 5 are repeated farther up the hillside in a separate fault block. The two low-angle faults that cut the Cul-de-Sac are marked by an extensive breccia and silicified zone immediately north of the line of section. Marker bed 4 is repeated again near the crest of the hill. Inside the Throne Room and Cul-de-Sac Passage, there is excellent control on marker bed 1, the overlying triplet beds, the overlying sandstone, and marker bed 2. Each of these units is beautifully exposed in the cave, and the deepest portion of the Throne Room penetrates to the top of marker bed 0 (at the entrance to the North Passage).
The Throne Room Entrance Cross-Section shows a variety of apparent dips resulting from different fault blocks, and the fact that the section turns a corner just east of the Throne Room (Turn Line). The line of cross-section across the Throne Room trends 316.5°. Strike and dips measured in the cave give a slight apparent dip to the SE. The beds along the southeast side of the Throne Room show increasing dip (fault drag) as they approach the main Cul-de-Sac Fault. Dr. Thomson's measured surface

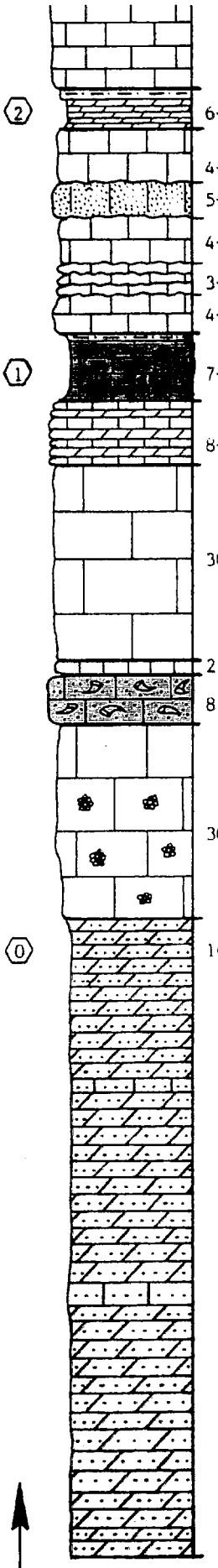
FIGURE 108

KARTCHNER CAVERNS STRATIGRAPHIC SECTION
by David H. Jagnow

425' of Escabrosa Formation



	30'	Limestone, lt.gray, coarsely crystalline, sparry, cherty near base with occasional beds of abundant colonial corals and very large horn corals.
(5)	10'	Limestone, dk.gray, dense, faintly laminated, fractured, upper portion more resistant. Color varies to medium chocolate brown.
	22'	Dolomite, lt.gray, weathers buff, with abundant dk. gray chert nodules. Occasional dk.gray limestone stringers with chert nodules.
	21'	Limestone, lt.gray, cherty, with abundant chert boudins at top.
(4)	10–13'	Limestone, dk.gray, sparry, dense, with abundant small crinoids.
	70'	Limestone, lt.gray, dense, coarsely crystalline, with pink to gray chert nodules throughout and abundant large crinoids in upper 2/3s.
(3)	5'	Dolomite, v.dk.gray, highly fractured with red hematite-stained calcite in fractures, fetid odor.
	23–28'	Limestone, lt.gray to lt.tan, massive, sparry micrite with chert in upper portion and pinkish color in lower portion.
(2)	6–8'	Dolomite, v.dk.gray, thinly laminated, fetid odor, white calcite fracture fillings, siltstone at top.
	4–8'	Limestone, v.lt.tan, pinkish, micrite, calcite fractures.
	5–8'	Sandstone or sandy limestone, red-brown, frosted ss.grns.
	4–7'	Limestone, lt.tan to med.gray, wavy bedded.
	3–4'	Limestone, reddish, tan, & reddish, mottled, wavy.



micrite with chert in upper portion and pinkish color in lower portion.

(2) 6-8' Dolomite, v.dk.gray, thinly laminated, fetid odor, white calcite fracture fillings, siltstone at top.

4-8' Limestone, v.lt.tan, pinkish, micrite, calcite fractures.

5-8' Sandstone or sandy limestone, red-brown, frosted ss.grns.

4-7' Limestone, lt.tan to med.gray, wavy bedded.

3-4' Limestone, reddish, tan, & reddish, mottled, wavy.

4-12' Limestone, lt.tan to med.gray.

(1) 7-11' Limestone, dk.gray, banded, sparry micrite with fetid odor, abundant horn & colonial corals. Locally altered to dolomite. Siltstone bed at top.

8-10' Limestone and dolomite, med.to lt.gray, thinly bedded, some beds pinkish hematite-stained.

30' Limestone, massive, lt.to med.gray, sparry micrite, highly fractured with siliceous vein-fillings.

2' Limestone, med.gray, distinct bed.

8' Limestone, sandy, reddish lt.gray, resistant, with abundant horn corals.

30' Limestone, massive, recrystallized sparry micrite. Common colonial corals in lower 2/3s.

(0) 100' Dolomite, dk.gray to pinkish gray, sandy, fine-grained, finely laminated with occasional limestone beds. Interval may be as much as 200' thick at east end of outcrop immediately above Martin Formation.

KEY STRATIGRAPHIC MARKER BEDS

SCALE: 1" = 25'

strikes in this area average 316°, so the apparent dip is essentially flat along the line of section over the Throne Room.

Additional strikes and dips were measured on the surface above the Cul-de-Sac portion of the cross-section. This portion of the cross-section calculates to an apparent dip of 6° to the SW. The faults are labeled A, B, and C for discussion purposes. Fault A is the Echo Passage Fault shown where it cuts into the Big Room. The 13' of displacement was estimated from marker bed 2, a little north of the line of section. It is interesting to note that about half of marker bed 2 lies on top of a massive breakdown block along the west wall of the Big Room. Marker Bed 2 tends to part along a shaley unit right in the middle of the bed. This characteristic is also visible in the Throne Room. Fault B is a small normal fault that strikes to the northeast between the Strawberry Room and Pool Room with approximately 10 feet of displacement.

Fault C dips to the NW and there appears to be about 5' of offsets (down to the NW) where the fault cuts marker bed 0 (north of the line of section). The fault appears to be contained in the fault block above fault D, as it does not appear to cut the Cul-de-Sac Passage. Fault D is a major low-angle normal fault that dips 45° to the east, and has about 44' of displacement along the fault plane. This fault cuts across the entrance to the Cul-de-Sac Passage and appears to form the western boundary of the Big Room. The termination and offset of marker beds on the surface help define the fault plane.

Fault E is a narrow fault zone consisting of two faults that cut the end of the Cul-de-Sac Passage. At the end of the Cul-de-Sac, the zone between the faults is so highly fractured and discolored by limonite staining that the bedding orientation and various marker beds are unrecognizable. Both faults are relatively low angle (50 to 60 degree dip) normal faults. They are visible at the surface, diverging slightly to the SW, and merging to the NE with a large breccia and silicified zone. The surface bedrock between these faults is less highly fractured than in the cave, but it is still highly fractured. It appears that the fault farthest northwest has the greatest displacement, but the actual displacement in this contorted fault block is hard to calculate.

Fault F is the Throne Room Fault. This fault was previously thought to be the highly silicified fault trace at E. It now appears that the small displacement Throne Room Fault is probably truncated beneath the major Cul-de-Sac Fault. Major brecciation and silica zones are more commonly associated with the faults of major displacement.

Fault G is the Quartz Divide Fault, and high-angle normal fault with about 10' of displacement. The displacement is difficult to discern in the Throne Room where it is covered with flowstone. However, on the surface, marker bed 4 is offset 35 feet. With a dip of 15°, this gives a vertical offset of 10 feet. The fault is marked by a 1'-thick vein of silica at the Quarts Divide in the cave.

Tunnel: The proposed tunnel entrance is 244' in length. It has a vertical descent of 16' over a true horizontal distance of 243' (15:1). The tunnel essentially follows the slight dip of the bedding. It will penetrate about 110' of thick-bedded light gray, cherty and crinoidal limestone following the base of marker bed 4. At 110', the tunnel should penetrate Fault D and excavate 88' of similar limestone between marked beds 3 and 4 before penetrating Fault Zone E. This highly fractured zone should be about 19' thick. The brecciation and silicification will probably increase in close proximity to the northwest edge of this fault block. After penetrating Fault Zone E, the remaining 27' will be the upper portion of marker bed 2, a very dark gray thin-bedded dolomite, and the overlying limestone bed.

The tunnel should be easily excavated. The bulk of the stratigraphy will consist of very competent limestone. Localized nodules and boudins of chert may provide some

difficulty both due to the hardness of the silica, and the variable nature while excavating. The main concern is in excavating the highly fractured zone between the two Cul-de-Sac Faults (Fault Zone E). This interval, where exposed at the end of the Cul-de-Sac, appears to be cemented with flowstone and limonite to give a fair degree of competence.

Elevator: The 55' elevator shaft is proposed at a distance of 75' from the Throne Room point of entry. The vertical shaft would spud in about 6' above marker bed 4, penetrate about 12' of marker bed 4, and continue downward through another 37' of thick-bedded light gray cherty and crinoidal limestone in the interval between marker beds 3 and 4. The entire bedrock interval is very competent for a vertical shaft. A small diameter test hole or preferably core hole should be drilled first in the center of the proposed shaft to search for unknown voids and to analyze the structural conditions.

Stairs: The proposed stairway would be 118' in length. It has a vertical descent of 48' over a true horizontal distance of 108'. The stairway excavation would start in marker bed 5 and descend 13' before crossing Fault D. The next 70' between Faults D and E will consist of competent cherty crinoidal limestone in marker bed 4 and immediately below. The Cul-de-Sac Fault Zone (E) should be encountered at about 83' into the stairwell. This highly fractured zone should be about 15' thick and be cemented by flowstone and limonite with some silica near the faults. The last 25' will consist of limestone units overlying marker bed 2. Once again, the main concern is in excavating the highly fractured zone between the two Cul-de-Sac Faults. This interval will pose only minor problems.

Alternate Throne Room Entrance Tunnel

The second geologic cross-section (Figure 110 in the map pocket at the end of this report) shows an alternate tunnel entrance that slopes upward to the Throne Room and takes better advantage of the surface topography. Fault designations on this cross-section refer to the same faults as shown on Figure 109. The alternate tunnel trends 328°. There were good strike and dip measurements directly along the cross-section - striking 330°, dipping 25° SW. This gives an apparent dip of only 1° to the NW on the Alternate Tunnel Cross-Section.

The alternate tunnel entrance is 284' in length. It has a vertical rise of 19' over a true horizontal distance of 284 (15:1). The tunnel gradually climbs stratigraphically through the interval between marker beds 3 and 4. It will penetrate about 232' of thick-bedded light gray cherty and crinoidal limestone in this interval before penetrating the Cul-de-Sac Fault Zone (E). The highly fractured fault zone will be about 19'. The brecciation and silicification will probably increase in close proximity to the main fault. After penetrating Fault Zone E, the remaining 32' will be the upper portion of marker bed 2, a very dark gray thin-bedded dolomite, and the overlying limestone bed.

The alternate tunnel penetrates fewer faults and provides several distinct advantages.

Recommendations: The entire Throne Room Entrance section consists mostly of very competent geology. The main concern is the fractured nature of the Cul-de-Sac Fault Zone (E). All four options for both alignments are equally viable. The alternate tunnel appears to have the following advantages:

1. The alternate tunnel crosses the fewest number of faults.
2. The alternate tunnel overlies only a small portion of the Cul-de-Sac.
3. It has the least effect on water infiltrating down dip into the cave.

Tarantula Entrance

The Tarantula Entrance Cross-Section is more complicated in terms of lithology and faulting (Figure 111 in the map pocket at the end of this report). The faulting depicted on both the cross-section and the map of the cave have been simplified for clarity. In reality, there are swarms of small faults and fractures that branch from the faults that are shown. Some of these small faults are parallel to the line of section and can't be shown. Displacement along these faults is very difficult to determine because some of the key dark marker beds are altered to white and tan in the cave by unusual weathering in this portion of the cave. These factors combine to make the interpretation of this cross-section the most difficult of the three locations. As a result, less confidence should be placed on the geologic interpretation of this cross-section.

Identification of marker beds outcropping on the surface is very limited on this section because loose alluvium covers the southeastern half of the entire section up to the proposed stairway entrance. Marker bed 2 and the underlying sandstone outcrop near the northwest end of the cross-section. Inside the Tarantula Room, the horn coral bed outcrops at stream level near the entrance to Red River Passage. But once you cross the fault swarm from Sharon's Saddle, the rock is highly fractured and control is not obvious. It appears the horn coral bed is down-dropped about 10' based on the offset of marker bed 1 farther out in the Big Room. The best strike and dip data was again provided by Dr. Ken Thomson's surface mapping. Three sets of strikes and dips directly over the Tarantula Room measure 336°, dipping 11° SW; 326°, dipping 14° SW; and 336°, dipping 15° SW. The average of all three measurements gives a strike of 333°, dipping 13.3° SW.

The Tarantula Entrance Cross-Section trends 297°, so the apparent dip along the line of section is 8°--used along the entire section. This dip correlates well with what is seen in the cave. The faults are again labeled A, B, and C for discussion purposes. These are <u>not</u> the same A, B, and C faults on the previous Throne Room section! (Faults for each cross-section are independently identified.) Fault A forms a flowstone-covered wall in the upper portion of the Tarantula Room. It appears to be a near-vertical fault plane, but the flowstone cover makes it impossible to see the amount of offset. A small normal fault offset of 2' down to the SE has been assumed. This fault could not be located on the surface because of the highly fractured nature of the rock. The location of the fault in the cave is well known, and it ties quite nicely to an inferred fault mapped by Ken Thomson above and northeast of the Tarantula Room. Fault A is the continuation of the fault mapped as Fault B on the Echo section, but the displacement is different.

Fault B is a normal fault with about 2' of displacement down to the SE. Two faults from the Y-Junction area merge into a single fault right at the line of section. The displacement along these faults appears to increase to the southwest. This fault is obvious in the cave, but difficult to locate in the fractured rock at the surface, and therefore dashed. It probably continues to the north-east under the alluvium. Fault C is very apparent both in the cave and on the surface. Three of the faults from Sharon's Saddle merge to the northeast into this single, highly-brecciated, vertical fault zone with 10' of displacement down to the southeast. Fault C can be seen along the north wall of the Tarantula Room, with highly brecciated rock adjacent to the fault. The same brecciated rock is visible on the surface.

<u>Tunnel</u>: The proposed tunnel is about 240' in length (266' to the endpoint farther down the slope). It has a vertical descent of 18' over a true horizontal distance of 265' (15:1). It begins in an estimated 4' to 6' of alluvium, and the entire tunnel remains in

the interval at and immediately above the horn coral bed. The horn coral bed consists of about 8' of sandy, reddish light gray limestone with abundant horn corals. The northwest end of the tunnel will climb stratigraphically into the overlying massive light to medium gray limestone. Both units are very competent. However, the northwest end of the tunnel will need to penetrate approximately 70' of unstable collapse material that gave the Tarantula Room its origin. The Tarantula Room collapse zone probably collapsed into an underlying cave passage. So, it is quite likely that the tunnel may also penetrate unknown cave passages or voids associated with the collapse cone.

Elevator: The 43' elevator shaft is proposed at a distance of 78' from the Tarantula Room endpoint. The vertical shaft would begin about 6' above Marker bed 1. Within 15', the shaft would probably enter the unstable collapse zone (cave breakdown). The bedrock is highly fractured at the elevator location. The fracturing, combined with the underlying collapse breccia, would not provide a structurally stable shaft. If any consideration is given to this alternative, a small diameter test hole or preferably core hole should be drilled first in the center of the proposed shaft to analyze the structural conditions.

Stairs: The proposed stairway would be 87' in length. It has a vertical descent of 43' over a true horizontal distance of 99'. Stairway excavation would start out immediately above marker bed 1. Less than 20' of excavation is needed to enter the cave, and the closest point is only 12' (via tunnel) to the surface. The stairway would following the existing slope of the collapse cone. Portions of the ceiling (and preferably floor) would be easily excavated to allow ample headroom. The entire tunnel should be concrete lined with ample steel and concrete structures to support any fractured blocks in the ceiling.

Recommendations: The Tarantula Room owes its existence to the collapse zone pictured in the cross-section (Figure 111). The elevator and tunnel entrances must be heavily discounted due to the necessity to penetrate this unstable collapse zone. However, the Tarantula Room is a good location for the stairwell for the following reasons:

1. The collapse zone is judged too unstable to structurally support either the tunnel or elevator shaft.
2. The collapse zone can be adequately stabilized to provide firm foundation for the stairway.
3. The stairway avoids the unstable collapse zone below.
4. The stairway requires minimal excavation (12'-20').
5. The stairway makes full use of the existing sloping passage.

Echo Entrance Alignment

The Echo alignment cross-section is probably the least complicated in terms of lithology and faulting (see Figure 112 in the map pocket at the end of this report.). As with each of these sections, the survey stakes on the surface indicate the location of the center of the tunnel, elevator, stairs, and endpoint - which is directly over the entry point into the cave passage. The geologic control points for this section are very secure. The horn coral bed outcrops on the surface at the location of the proposed stair entrance, and marker bed 1 is found further up the hill. Marker bed 2 was found on the surface directly above the point of entry into the cave, and the prominent sandstone bed is located a few feet below. The surface location of marker bed 0 has

been projected from other data, as an unknown thickness of alluvium covers both the elevator and tunnel locations. Inside the Echo Passage, the location of marker bed 0 is also well known. The southeast wall of Echo at the point of entry is about 24' below the top of marker bed 0. The best strike and dip data was that of Dr. Ken Thomson. He had two measurements in the immediate vicinity. Both strikes measured 340°. The measured dips were 22° SW (measured at marker bed 1 on the line of section), and 15° SW (measured slightly SW of the line of section). The shallower dip of 15° provided the best fit with the known geology. The Echo Alignment profile trends 306°. Therefore, the 15° true dip gives an apparent dip along the line of section of 8° - which is shown on the entire section.

As a general rule, the majority of faults in the cave are easy to map. The major faults are relatively easy to map on the surface, but the smaller faults with only a few feet of displacement are often very difficult to map accurately on the surface. Therefore, the fault interpretation is usually the weakest aspect of each of the geologic cross-sections. The faults are again labeled A, B, and C for discussion purposes. These are not the same A, B, and C faults on the previous Tarantula section! (Faults for each cross-section are independently identified.) Fault A is a normal fault dipping steeply to the east. An offset of 8' was measured on the horn coral bed near the proposed stairway entrance. The fault can be traced to the north, but to the south it is immediately obscured beneath the alluvial cover. Fault B is a near-vertical fault projected as a continuation of the fault across the end of the Tarantula Room. It was mapped in part by Ken Thomson northeast of the Tarantula Room, but is difficult to spot near marker bed 1 - and therefore dashed. The displacement is also uncertain, although marker bed 1 is not repeated, so it appears to be slightly upthrown on the southeast side - an estimated 5 feet. Faults C and D are both well documented in the cave. Fault C is the Echo Passage Fault, a normal fault that dips about 75 to 85 degrees to the SE in the cave, and has about 13' of displacement in the Big Room. Fault D appears to be a small reverse fault that forms the SW wall of the Echo Passage and extends to the SSE very close to the terminus of the Red River Room, the deepest point in Kartchner Caverns. Beds within marker bed 0 are deformed adjacent to the fault, documenting the sense of movement by the fault drag. Even though faults C and D are quite different and strike completely different directions, they appear relatively similar on this line of section.

Tunnel: The proposed tunnel is 405' in length at its base. It has a vertical descent of 25' over a true horizontal distance of 404' (16:1). It begins in an estimated 4' to 5' of alluvium, and the entire tunnel remains in marker bed 0. The tunnel should start out about 47' below the top of marker bed 0, and will slowly climb up section, ending about 24' below the top of marker bed 0. The tunnel will cross two known faults (A and B) which appear to pose no unusual problems. Marker bed 0 is a dense, competent dolomite, dark gray to pinkish gray, sandy, fine-grained, massive with fine laminations. This lithology is excellent structurally and the massive nature should provide very controlled construction unless unknown voids are encountered.

The Echo Tunnel Entrance is the most likely of all the proposed tunnels to encounter unknown cave passages. Much of the tunnel will be excavated near the main level of cavern development. The possibility does exist to encounter passages that are not connected to the main cave. During excavation, the central drill hole should be drilled several feet deeper than the surrounding blasting holes in order to probe for any unknown cavities. Blasting charges can be decreased or eliminated if cave passage is detected ahead of the excavation.

Elevator: The 55' elevator shaft is proposed at a distance of 247' from Echo Passage. The vertical shaft would start in an estimated 2' of loose alluvium, then penetrate about 17' of massive medium gray limestone, before encountering the upper 35' of marker bed 0. The entire bedrock interval is very competent for a vertical shaft. Fault A is sufficiently distant from the shaft to pose no structural problems. A small diameter test hole or preferably core hole should be drilled first in the center of the proposed shaft to search for unknown voids.

Stairs: The proposed stairway would be 221' in length. It has a vertical descent of 89' over a true horizontal distance of 202'. The stairway would start out in the horn coral bed and descend section to 24' below the top of marker bed 0. The massive limestones and dolomites of this interval are very competent and excellent for tunnel construction. The stairway crosses one known fault (B) which should pose no structural problem.

Recommendation: The entire Echo Entrance section consists of very competent geology, broken by only two known small faults. All three options (tunnel, elevator and stairs) are equally viable from a geologic standpoint. A tunnel is preferred for the following reasons:

1. The entire tunnel would be in the same lithology (marker bed 0).
2. It would have the least effect on water infiltrating down dip into cave

Additional Recommended Geological Studies

The detailed structure and stratigraphy of the Kartchner Block is surely more complex than the current map indicates. Additional mapping can be performed to verify many of the dashed faults and outcrops.

It is especially important to allow detailed mapping of the stratigraphy and faults exposed in any future entrance tunnels prior to cementing over the geology. These excavated exposures will provide additional points of control to the complex geologic picture.

FINAL ENTRANCE SITE SELECTION

The Interim Report narrowed down the number of potential entrance sites from 10 to 4. The final phase of this study has looked at the geologic suitability of each of these four locations in greater detail. All of the proposed locations, with the exception of the Tarantula Room Ramp and Elevator, have few geologic problems. The Tarantula Room entrance is located on the edge of a collapsed zone which the ramp and elevator shaft would have to cross. Attempting to construct an entrance tunnel through this collapsed zone would be very difficult. This makes these two options unfeasible from a geologic standpoint.

Three options have been considered for each entrance location: a ramped tunnel, stairway and elevator. The ramped tunnel and elevator have the advantage of providing handicapped access to the cave. The type of elevator recommended is a hydraulic lift elevator. This has the advantage that it is moved up and down on top of a hydraulic piston rather than being raised and lowered by overhead cables. This results in a smaller building being needed on the surface but an additional depth of shaft is needed to house the piston and hydraulic machinery below the cave level. Also, unlike the ramp and stairway, the elevator needs a source of power in order to function. This is a consideration during construction when utilities may not be available yet and also, after development, when a power failure or mechanical failure

could close down the cave for an extended period of time. Elevators have been found to cause damaging air exchange in several other caves, most notably Carlsbad Caverns. The cost of operating an elevator is roughly estimated to be $20,000 a year in power and maintenance costs. This annual cost is equivalent to an initial cost of about $140,000. An elevator would be economically justified only if it would save construction of more than 150 feet of tunnel. From Figures 109, 111 and 112, the length of tunnel saved for each location can be found. The Tarantula Elevator would save 150 feet of tunnel, the Echo Elevator would save 130 feet of tunnel and the Throne Elevator would save 140 feet of tunnel. This indicates that elevators are marginal from a purely economic analysis.

Elevators are not recommended for the following reasons:

- They are dependent on a reliable source of power.
- They may be a source of damaging air exchange if not properly constructed.
- They require specialized maintenance.
- They limit the movement of materials into the cave during construction.
- They are not economically justified.
- They require locating hydraulic machinery within the cave, with a potential for leaks.

Elevators appear to have no unique benefits and have many undesirable characteristics. Elevators are not considered to be a viable option and are dropped from consideration. The two configurations at the Tarantula Room are also excluded for geologic reasons. This leaves six entrance configurations.

Location	Type	Point Ranking
Echo	Ramp	26
Echo	Stairs	26
Tarantula	Stairs	27
Throne	Stairs	30
Throne Alt.	Ramp	31
Throne	Ramp	32

A desirable goal for the development of the cave is to allow access to the handicapped. Much of the interior of the cave is relatively flat and trails should be designed for handicapped access. It remains to be seen if it will be possible to design the entire interior trail system to accommodate the handicapped. Use of stairways on the new entrance would limit the use of the cave by the handicapped. Under the assumption that State Parks intends to provide handicapped access, if possible, the stair options can be eliminated. (It may be possible to incorporate some form of inclined elevator system into a stair design, but this has not been considered in this study.)

The remaining options are: Ramp tunnels into the Echo Passage and into the Throne Room using the Alternate tunnel alignment. The remaining option of a downward sloping tunnel into the Throne Room is clearly inferior to the new alternate alignment and is not considered further.

RECOMMENDED ENTRANCE

The original goal has been to narrow the selection down to a single new entrance location. The best location for a new entrance is a ramped tunnel into the Echo Passage. The location is shown in Figure 107 and Figure 112 shows the profile of the

proposed ramped tunnel. The tunnel would approximately 400 feet long and slope down into the cave at a slope of 15:1. It would provide handicapped access to the cave.

If a second entrance was found to be needed, the alternate tunnel alignment into the Throne Room would be the second choice. This could also be used as an exit portal if the cave were designed as a one-way through-trip.

CONSTRUCTION IMPACTS AND MITIGATION

During the exploration and scientific study of Kartchner Caverns, great care was taken to preserve the pristine nature of the cave. Many of the features in the cave are very fragile or are dependent upon the stable environment found in the cave. These resources need continued protection during the construction phase of the project. Potentially, the construction phase of the project can be the most damaging to the cave. While it is certainly the goal of Arizona State Parks to protect the cave, a contractor will be primarily interested in completing the work. It will be necessary to insure that the contractor understands the reasons for certain approaches and the necessity of protecting the cave features.

AIR EXCHANGE MITIGATION METHODS

The control of air exchange and subsequent evaporation within the developed cave is one of the most important considerations in the design of the underground facilities. With proper attention to the initial design, the inevitable increase in air exchange and evaporation can be held to a minimum.

Tunnels into the cave are less likely to create increased air exchange if airlocks are included. Airlocks can be any type of door which will provide a good airtight seal against a small pressure differential. An airlock does not need to be absolutely air tight, but it should prevent significant amounts of airflow from occurring. A system of three airlocks would provide good control: one airlock at the surface, another along the tunnel and a final airlock at the entry into the cave. Airlocks should be spaced sufficiently far apart to allow the whole tour group to collect before opening the next airlock. A distance of 75 feet between airlocks would seem sufficient. Three airlocks will insure that at least one airlock will remain closed at all times.

One type of airlock door which seems to be particularly appropriate is a turnstile type door similar to the one used at Carlsbad Caverns, New Mexico. This design does not impede visitor movement and still appears to offer an adequate amount of air control.

Care should also be exercised in the design of the entrance portal. A poorly designed building or the presence of high walls near the portal can greatly increase the amount of air exchange by creating localized areas of low air pressure.

In the discussion of potential entrances, it was assumed that control of air exchange would be ineffective or more difficult for certain types of entrances. Historically, this has been the case at caves which use elevators or which have large elevation differences between entrances. This has also occurred because the problem was not recognized until after the facilities had been built. If controlling air exchange is a primary design consideration, then it can be effectively integrated into facilities. An important point which should not be overlooked is that the <u>air exchange control must be completed prior to any connection into the cave</u>. Before the final few feet of rock are removed, the air control devices must be in place. The drying potential

of outside air is so great that irreparable damage can be done in only a few days' time without proper air exchange control devices.

Controlled air exchange will also be an important consideration during the construction of facilities within the cave. Workers who are unfamiliar with the reasons for controlling air exchange will be tempted to leave doors open to speed the movement of materials or to bring in hoses and wires. A primary consideration in the design of airlock doors should be the ability to accommodate the flow of construction materials and workers. It may be found to be more practical to use one design during the construction phase and a different design for the public. The standards of the "construction" air control should be as high or even higher than those of the final design. The "construction" air control should be of the highest quality as we cannot anticipate the exact requirements for air control. If a design is inadequate, the damage will already be done before changes can be made. Experience gained in the use and fabrication of the "construction" air control may show that less stringent devices are adequate.

CONSTRUCTION PROBLEMS

1. Blasting. Blasting of cave entrances can potentially damage speleothems. Example: blasting into the Throne Room might cause the World's Longest Known Soda Straw to fall and shatter.

2. Trail Construction Damage. Trail construction or careless construction workers might cause irreparable damage to certain speleothems and minerals. Example: a rare speleothem called a "conulite" occurs in floor mud at the Lunch Spot in the Big Room in a location that makes it very vulnerable to being trampled upon. Example: one of the world's most outstanding occurrences of brushite moonmilk is located at Bob's Guano Pile in the Big Room. Construction workers might mistake this for easily-dug trail fill. Example: the exquisitely delicate helictites in the Echo Passage could be easily "plucked" off the wall by visitors if the trail is constructed too close to the helictites.

RECOMMENDATIONS:

1. The engineer in charge of entrance construction should be fully aware of the trade-offs involved with entrance location, damage potential of failure to control air exchange and the irreplaceable nature of speleothems and other cave features.
2. Prior to beginning construction on any tunnel into the cave, the contractor should be shown the features requiring protection and extra care. Preferably this should be done by someone familiar with cave minerals.
3. During and prior to trail construction, trail routes should be inspected and significant speleothems and features marked by an individual trained in recognizing their features. The process would be similar to obtaining an archaeological clearance on the surface.

Summary of Construction Impacts

The construction phase of the development can potentially cause the greatest amount of damage to the cave. This can occur in several ways.

FINAL REPORT

ENVIRONMENTAL AND GEOLOGIC STUDIES

FOR

KARTCHNER CAVERNS STATE PARK

Volume I

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cave will likely contain unwanted organic debris and viable seeds. No method of sterilizing surface materials should be used which would leave a residue which would destroy the cave organisms. Outside materials will also need to be brought up to cave moisture levels prior to entering the cave. Areas where materials are stockpiled in the cave should have a layer of plastic placed over the floor before materials are placed. This will help in recognizing the original floor surface once the stockpile is removed.

- Inadvertent destruction of important features through a lack of recognition.
- Intentional destruction of cave features by workers.
- Accumulation of dust from construction activities.
- Maintaining the quality of air entering the cave. During the winter, surface air is drawn into the cave at the natural entrance. Construction activities should take place far enough from the entrance to insure that fumes and dust are not drawn into the cave.

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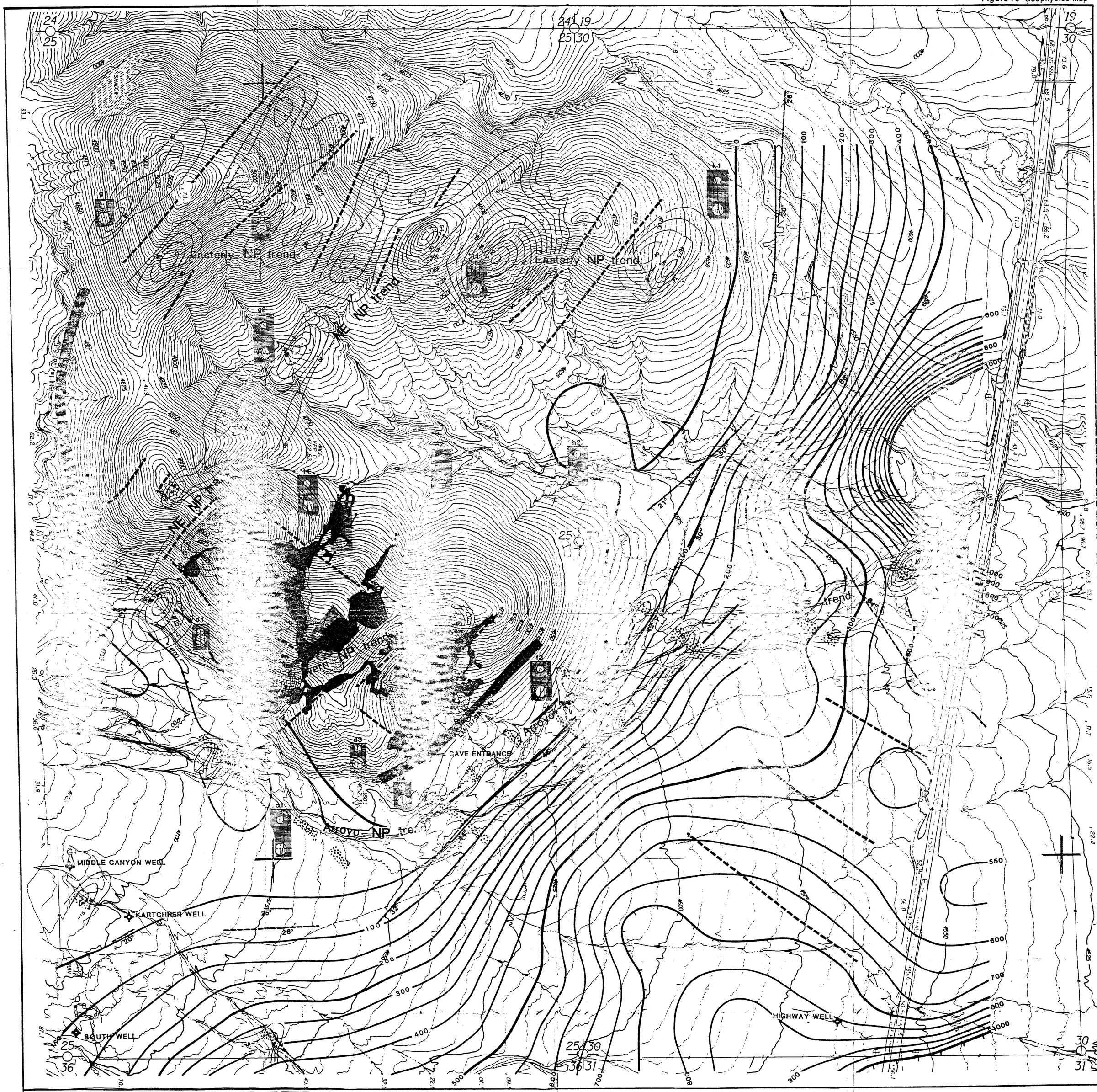
GLOSSARY OF TERMS

Boudin - a sausage-shaped segment of rock.
Boxwork - intersecting mineral blades, usually calcite, projecting from the walls or ceiling of a cave.
Column - a speleothem formed by the joining of a stalactite and a stalagmite.
Coralloid - any of a number of nodular, globular, or coral-like speleothems.
Drapery - a folded or furled speleothem which hangs down from inclined walls or ceilings with a curtain-like appearance.
Dripstone - any sort of speleothem formed by dripping water (e.g., stalactites and stalagmites.
Flowstone - a smooth, sheet-like speleothem formed by films of flowing water.
Helictite - a twisted, usually worm-like speleothem which grows via a small capillary channel.
Pearl, Cave - a spheroidal, polished carbonate concretion which forms in shallow cave pools.
Shield, Cave - a disc-shaped speleothem composed of two parallel hemispherical plates separated by a medial crack. Like the helictite, it is believed to have formed under capillary pressure.
Soda Straw - a tubular stalactite which resembles a drinking straw.
Speleothem - a secondary mineral deposit formed in caves.
Stalactite - a vertically-hanging speleothem formed by dripping water and generally having a tube or remnant of a tube at its center.
Stalagmite - a vertically-oriented convex floor deposit formed by water dripping down from above.



Key

- NP infiltration anomaly
- NP low & high
- NP boundary
- alternative solutions to a gravity low (15 & 30ft-radius passage)
- 200FT
- cave cross-section (Line E)
- EM-deduced boundary
- well
- fault trace from gravity dip (downside)
- minimum depth contours to bedrock in feet, based on 0.20g/cm³ density contrast (carbonates=2.67)

11½° 1989

0 200 400 600 800 FEET

0 100 200 300 METERS

FIGURE 75

KARTCHNER CAVERNS STATE PARK
Geophysical Investigations
Interpretive map

The Geophysics Group for
ARIZONA CONSERVATION PROJECTS Inc.
& ARIZONA STATE PARKS DEPT
15 March 1990

South Wash

Windmill Wash

Guindani Canyon

Saddle Wash

106 Ac. Q_{100} = 505 cfs

105 Ac. Q_{100} = 497 cfs

2157 Ac. Q_{100} = 6367 cfs

3.8 Ac. Q_{100} = 20.3 cfs

172 Ac. Q_{100} = 851 cfs

6.2 Ac. Q_{100} = 35.2 cfs

Park Boundary

16.6 Ac. Q_{100} = 104 cfs

15.8 Ac. Q_{100} = 88.3 cfs

5.4 Ac. Q_{100} = 33.4 cfs

3.7 Ac. Q_{100} = 20 cfs

changes in channel alignments create flooding hazards in this area

Potential channel shift of Guindani Wash in this area.

800 Ac. Q_{100} = 888 cfs

119 Ac. Q_{100} = 524 cfs

5.0 Ac. Q_{100} = 59.1 cfs

low flow directed by road

high flows cross road

2375 Ac. Q_{100} = 6724 cfs

7.2 Ac. Q_{100} = 38.4 cfs

2.9 Ac. Q_{100} = 15.3 cfs

35+00

entrance

Kartchner Caverns

30+00

25+00

29.8 Ac. Q_{100} = 122 cfs $d_1 + d_2$ overflow

Setbacks not shown upstream of this point

Center Wash

5.0 Ac. Q_{100} = 26.8 cfs

Middle Canyon

Possible flooding & erosion along S. Park boundary of unknown extent

Park Boundary

North Wash

205 Ac. Q_{100} = 779 cfs

143 Ac. Q_{100} = 550 cfs

2473 Ac. Q_{100} = 9105 cfs

207 Ac. Q_{100} = 778 cfs

Ricketts Wash

4-10'x7' Bridge

Box Culvert 1-8'x3' 45° Wingwalls

1-36" C.M.P. No Hdwl.

2428 Ac. Q_{100} = 5885 cfs

411.2 Ac. Q_{100} = 1158 cfs ($f + d_2$ diverted)

0.9 Ac. Q_{100} = 4.8 cfs

SR 90

2-36" C.M.P. No Hdwl.

18" C.M.P.

Overflow Weir Section

13.1 Ac. Q_{100} = 70.3 cfs

21.5 Ac. Q_{100} = 94.0 cfs

14.9 Ac. Q_{100} = 72.0 cfs

Box Culvert 1-10'x10' 45° Wingwall

Park Boundary

24" C.M.P. L. Headwall

Box Culvert 1-9'10"x8' 45° Wingwalls

2.1 Ac. Q_{100} = 11.3 cfs

29.9 Ac. Q_{100} = 184 cfs

29.3 Ac. Q_{100} = 99.3 cfs

3.0 Ac. Q_{100} = 19.3 cfs

4.8 Ac. Q_{100} = 25.9 cfs

231 Ac. Q_{100} = 823 cfs

Scale: 1" = 200'

LEGEND

- C — Q_{100} Width — Single Point Channel Rating
- Recommended Erosion Setbacks
- Potential Bank Erosion Areas
- Guindani Wash Erosion Setbacks
- Guindani Wash 100-Yr. Flood Plain
- (b) Drainage Area Designation
- Drainage Area Boundaries
- Flood Hazard Area
- 4560 — 100-Year Water Surface Elevation

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DCB/1990

FIGURE 76

DRAINAGE MAP

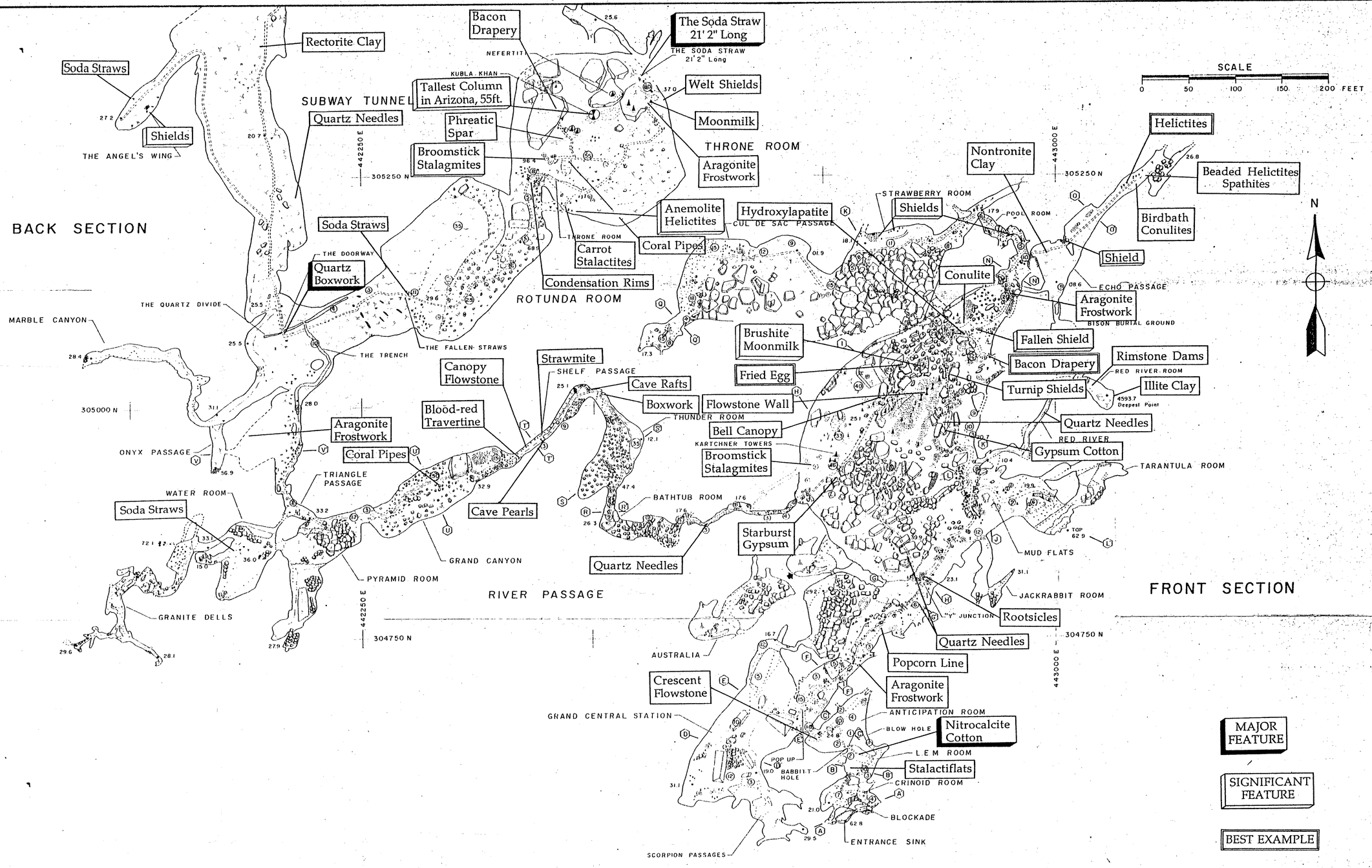


FIGURE 101

MINERAL MAP OF KARTCHNER CAVERNS

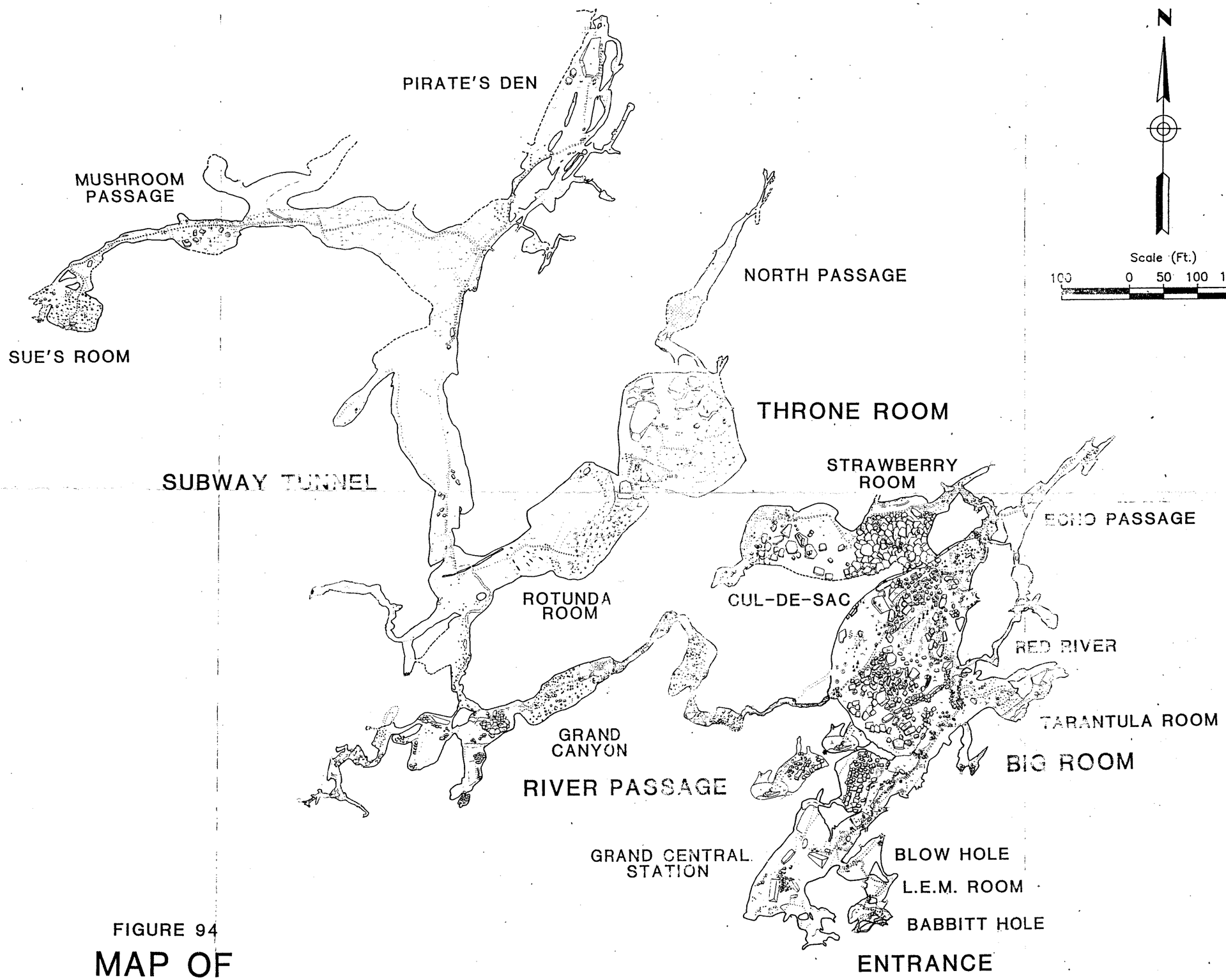
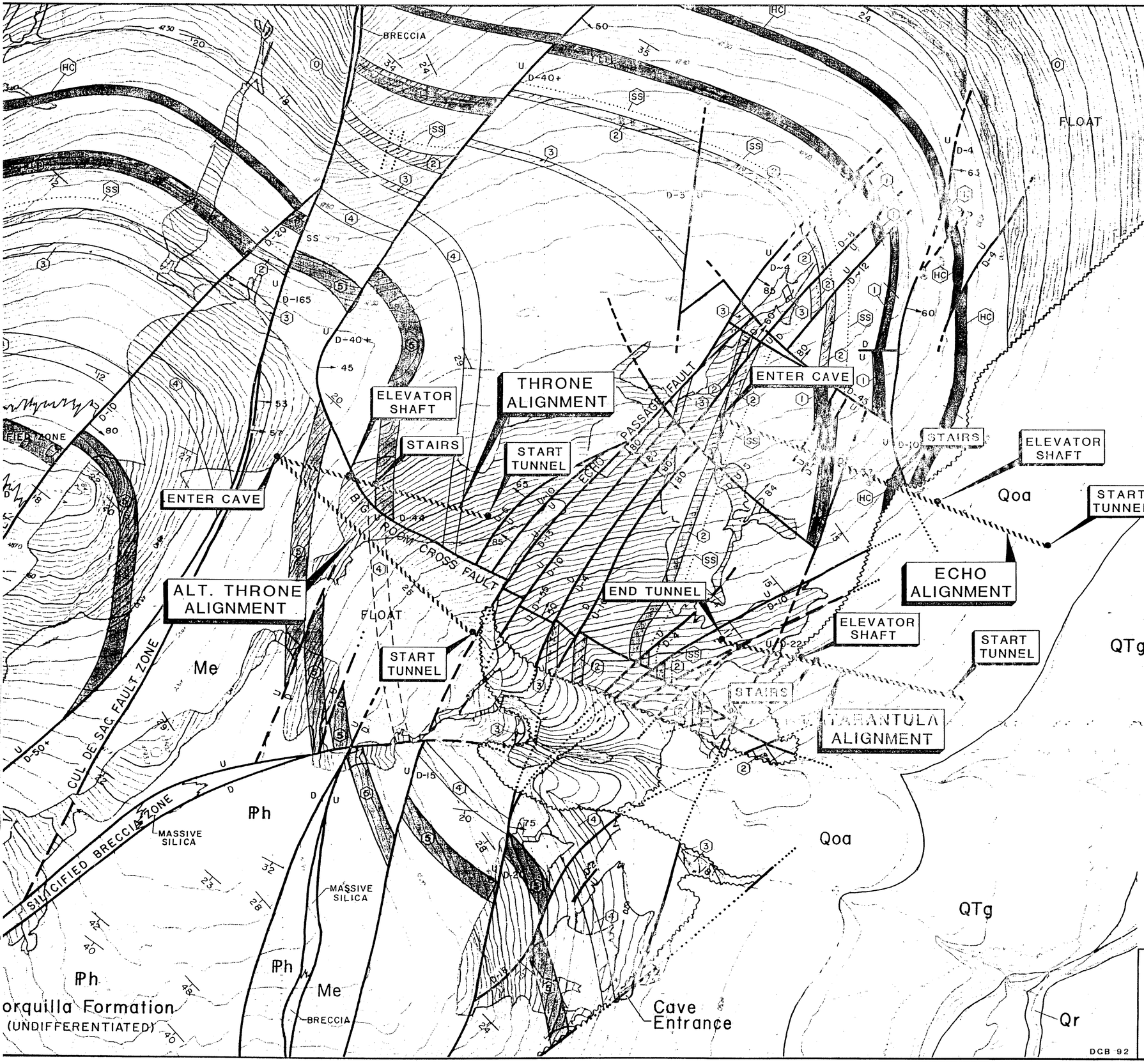


FIGURE 94

MAP OF KARTCHNER CAVERNS



MAP UNITS

Qr	Recent Alluvial Deposits — Sand and gravel found in stream channels
Qal	Alluvium Deposits — Sediments occuring in main stream channels. Older than Qr.
Qoa	Older Alluvium — Sediments deposited earlier, currently dissected by modern streams.
Qf	Fan-like Deposits formed on steeper hill slopes.
Qaf	Alluvial Fan Deposits — Derived from the Whetstone Mountains to the west.
Float	Soil and sediment cover which conceal rock units.
QTg	Terrace Gravels — Pediment gravels of the Whetstone surface.
Ph	Horquilla Formation
Me	Escabrosa Formation
pЄp	Pinal Schist

LEGEND

- CROSS SECTION
- FAULT — Solid line where located, short dashed where inferred, dotted where concealed
- 22 — DIP OF FAULT
- U / D-4 — DIRECTION AND OFFSET OF FAULT
- 15 — STRIKE AND DIP OF INCLINED BEDDING
- LIMITS OF BEDROCK
- (2) — NUMBER OF MARKER BED
- (HC) — HORN CORAL MARKER BED
- (SS) — SANDSTONE MARKER BED

NOTE:
Stratigraphic section, structural mapping, detailed marker bed mapping, cross sections and geologic interpretations by David H. Jagnow.

Strike and dip measurements, and differentiation of geologic units by Kenneth C. Thomson.

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FIGURE 107

DETAILED SURFACE GEOLOGY POTENTIAL ENTRANCES

BY DAVID H. JAGNOW 8/91

FIGURE 110

THRONE ROOM ALTERNATE TUNNEL CROSS SECTION

BY DAVID H. JAGNOW 8/91

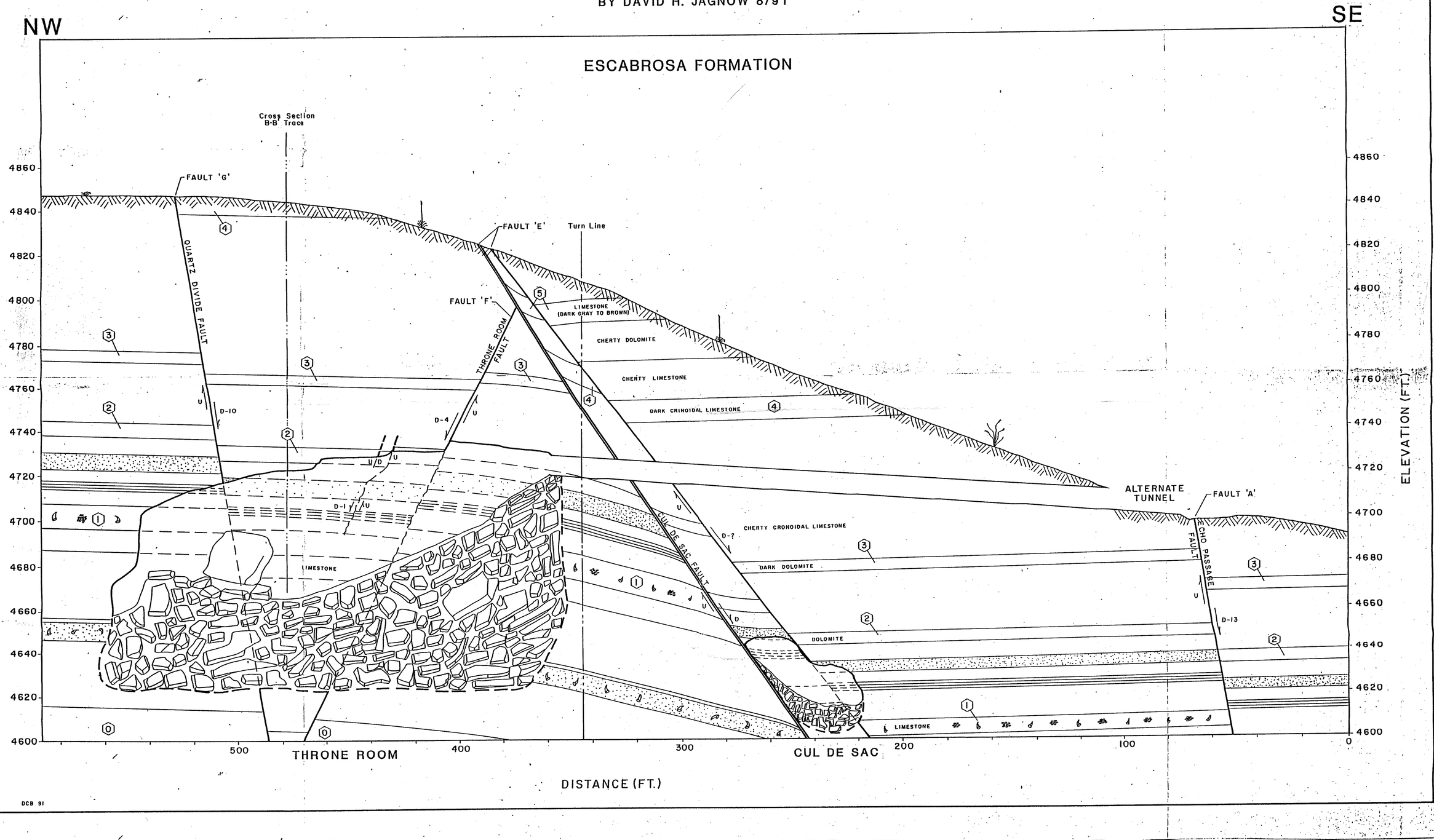

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FIGURE 111

TARANTULA ENTRANCE CROSS SECTION

BY DAVID H. JAGNOW 8/91

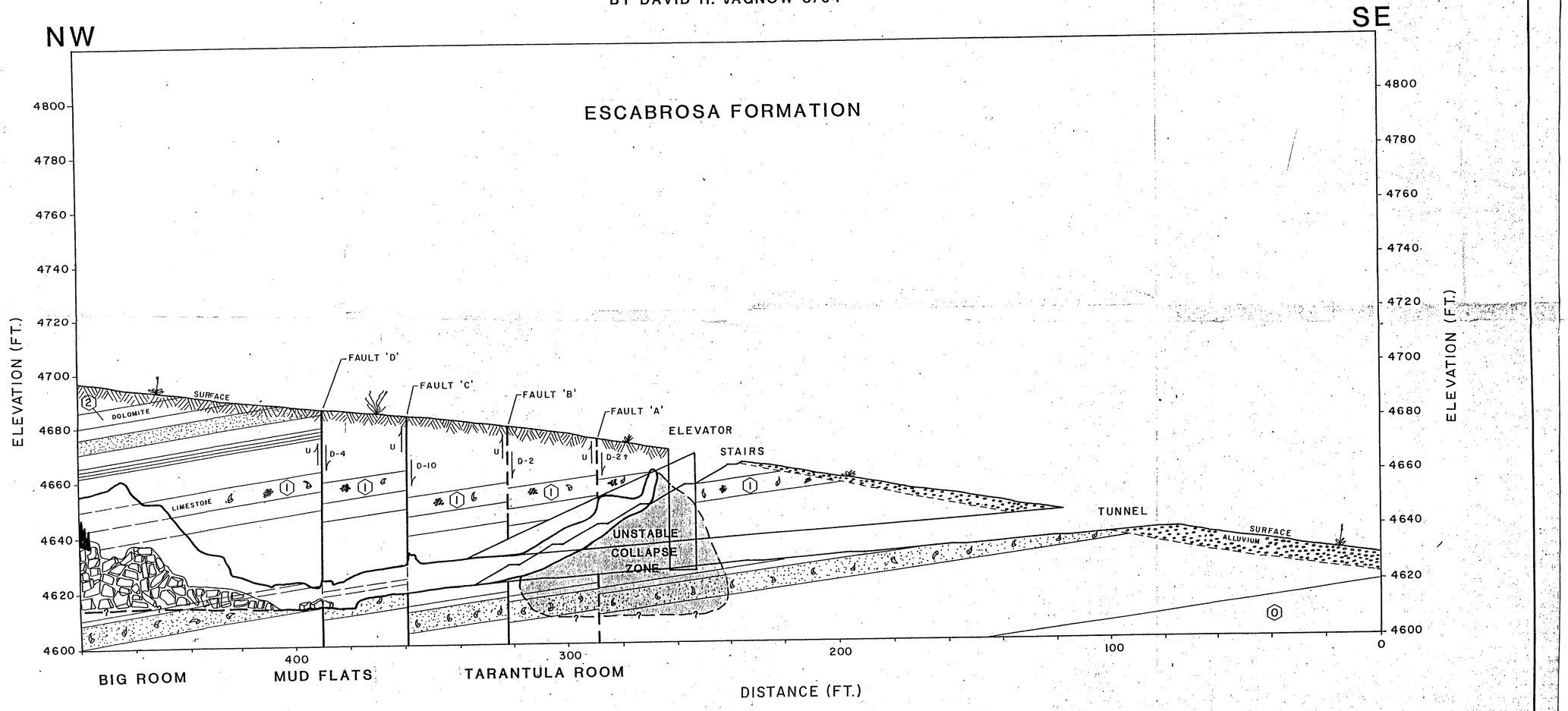

FIGURE 112

ECHO ENTRANCE CROSS SECTION

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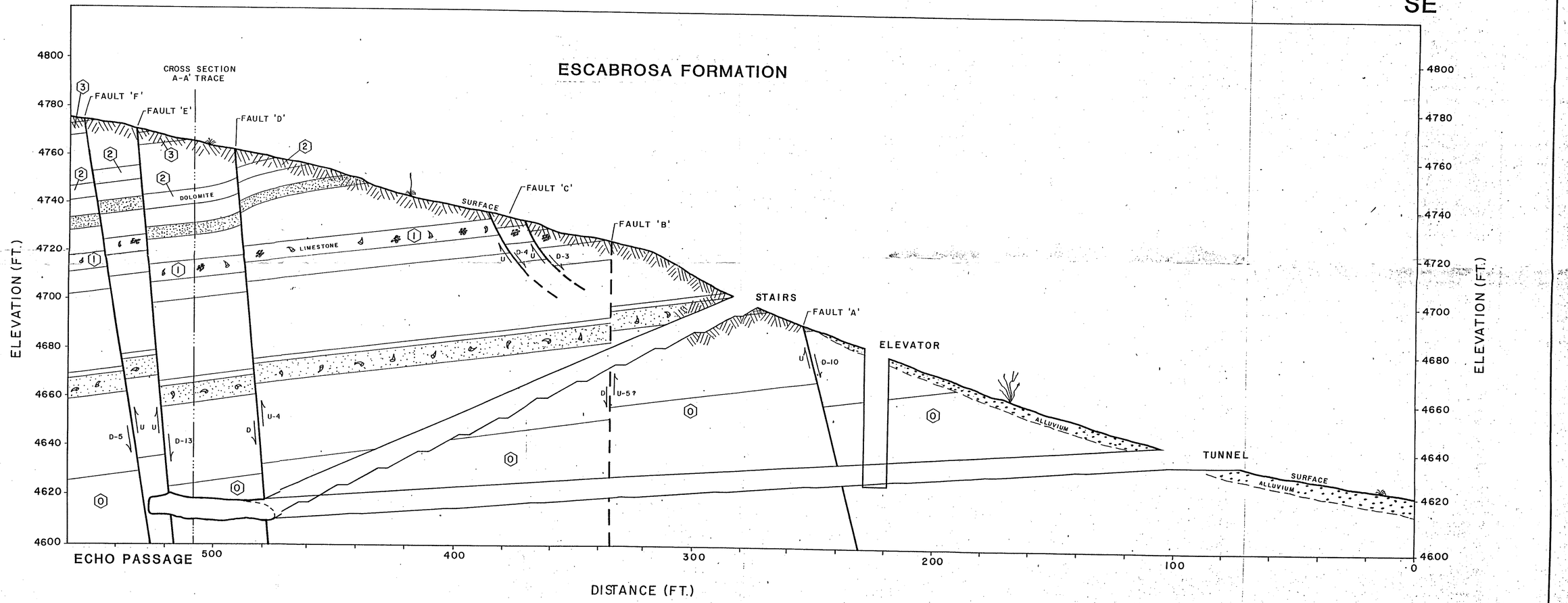

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SCALE

0 50 100 150 200 FEET

N

BACK SECTION

Quartz Needles

Soda Straws

Flowstone Mushroom

MUSHROOM PASSAGE

Aragonite Frostwork

SUE'S ROOM

HILL ROOM

Quartz Needles

Rectorite Clay

SNAIL TRAIL

Soda Straws

Rootsicles

Aragonite Frostwork

JARED'S END

CROW'S NEST ROCK

PIRATE'S DEN

Boxwork

BOXWORK MAZE

Soda Straws

THE NORTH PASSAGE

441750 E

305500 N

442500 E

305750 N

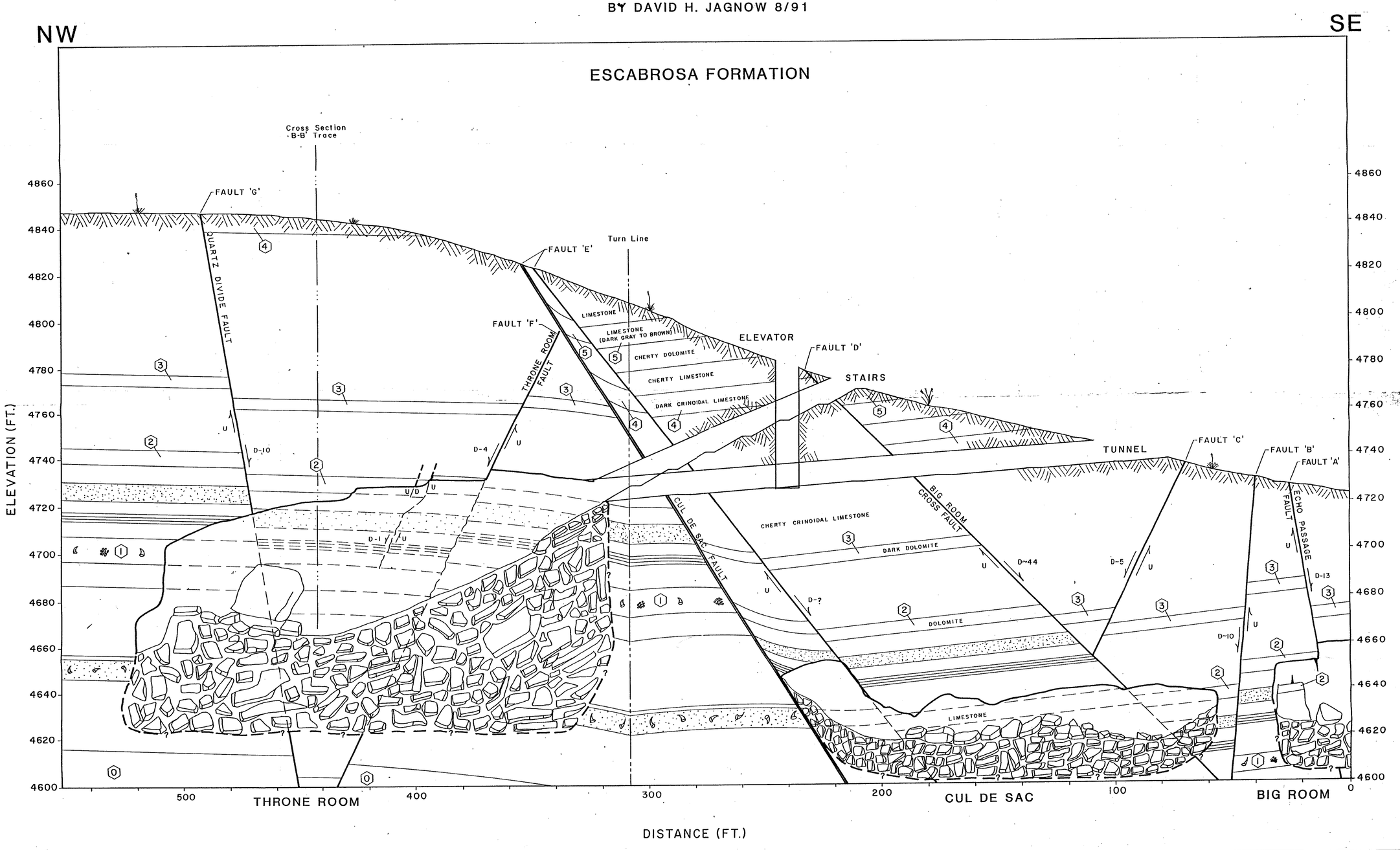
FIGURE 101A

MINERAL MAP OF KARTCHNER CAVERNS

FIGURE 109

THRONE ROOM ENTRANCE CROSS SECTION

BY DAVID H. JAGNOW 8/91



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