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Lava Tubes on the Galapagos Islands

Denes Balazs *

ABSTRACT

The first detailed maps and descriptions are presented of two typical lava tubes (La Cueva de Kübler and La Cueva de Bellavista) on Santa Cruz Island, Galápagos Islands, Ecuador.

Introduction

The "Archipielago de Colón", better known as the Galápagos Islands, consists largely of volcanic rocks. The only sedimentary rocks exposed are some Quaternary littoral deposits. Fifteen to twenty large volcanic complexes rise above sea level. Many hundreds of scoria cones are developed on the sides of the principal peaks.

Most of the islands are covered with alkali-olivine basalt flows of Holocene age. These radiate seaward from the central peaks and have slopes of 3 to 8 per cent. A great many lava tubes occur in these flows. The roofs of the tubes have often collapsed, thus permitting human discovery and exploration of the tubes.

One of the best-known lava tubes is La Cueva de Kübler, the entrance to which lies adjacent to the road connecting Puerto Ayora with Bellavista, on the island of Santa Cruz (Indefatigable Island). Conversations with hunters have revealed the existence of a dozen or so other lava tubes on the island, especially north of Tortuga Bay, around the settlements of Bellavista and Santa Rosa, and at Naranjo (northeast of El Chato). Some of these are flooded. Most, however, are dry. Other lava tubes are said to exist on Floreana (Charles) Island, in the vicinity of Santo Tomás on Isabela (Albemarle) Island, on the north coast of Fernandina Island, and Darwin himself reported some on San Cristobal (Chatham) Island.

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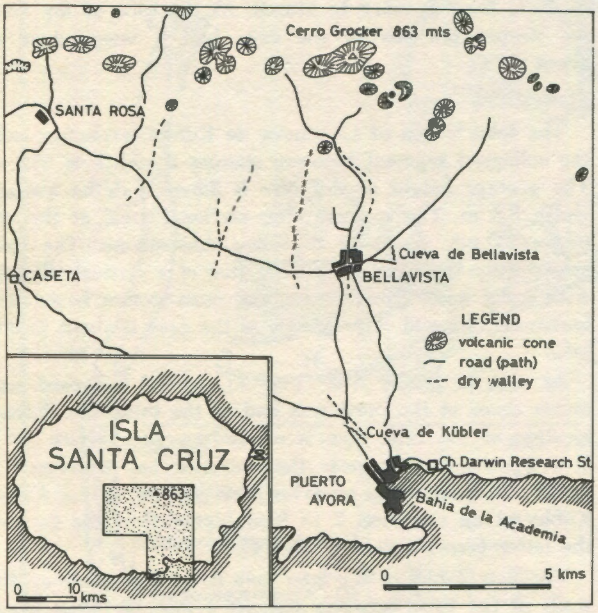

Fig. 1. Map of Isla Santa Cruz, Galápagos Islands, showing the locations of La Cueva de Kübler and La Cueva de Bellavista.

Fig. 2. The smaller entrance to La Cueva de Kübler. Photo by Balázs.

Fig. 3. The larger entrance to La Cueva de Kübler. Photo by Balázs.

Two typical lava tubes on the island of Santa Cruz are described in this paper. Their locations are shown in Fig. 1. Both were surveyed by the author, alone, in 1970, using a two meter-long measuring rod and a compass. The accompanying maps contain a survey error of 2 to 3 per cent.

Cueva de Kübler

Location

La Cueva de Kübler lies about 2.5 km NNW from the center of Puerto Ayora harbor. Along the new road leading northwest and then north to Bellavista, about 20 m before reaching the path which leads north to Caseta and on the same side of the road, is a triangular sinkhole. The opening lies 25 m from the roadway and is 3 m by 4 m by 4 m in size (Fig. 2). Here, it is necessary to use tackle in order to enter the cave. About 40 m to the northwest, however, is a longer collapsed area (Fig. 3), where access to the cave is

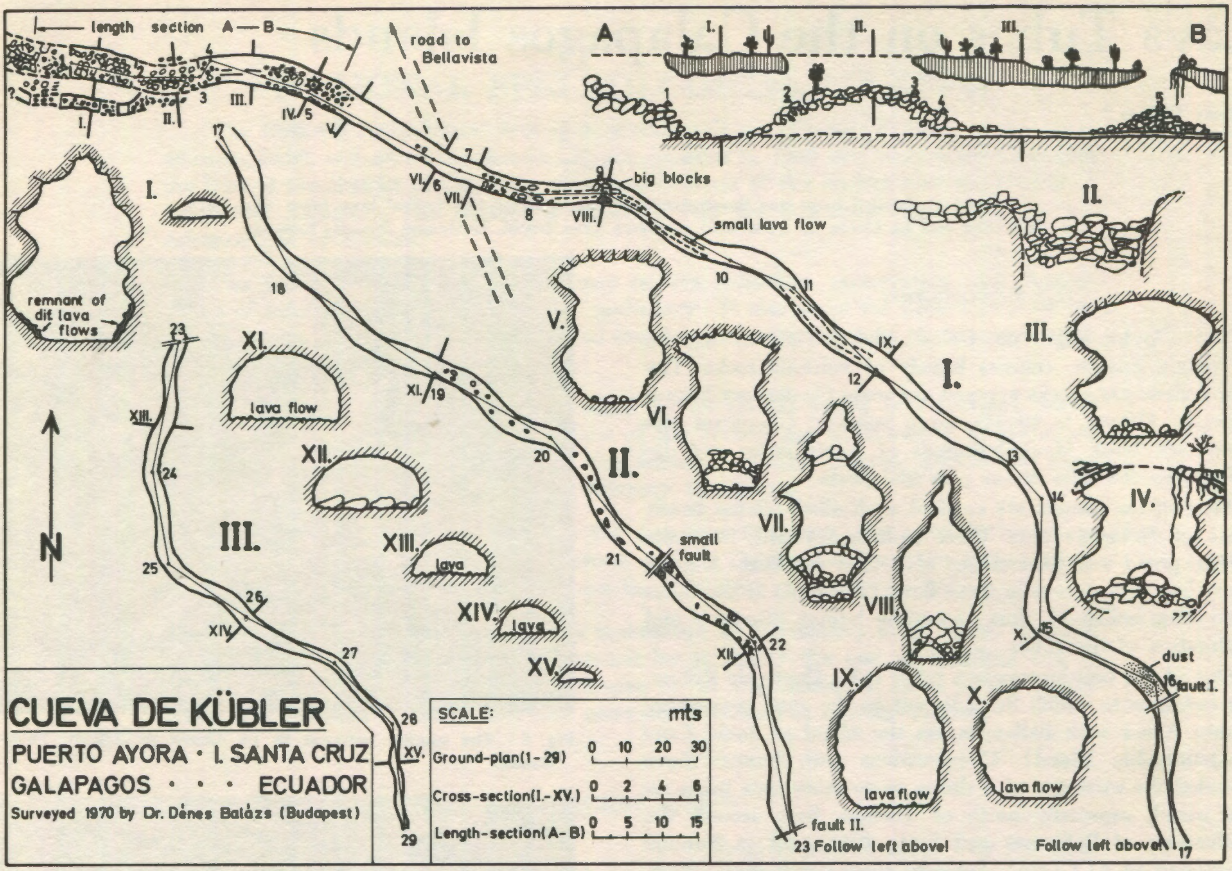

Fig. 4. Map of La Cueva de Kübler, Galápagos Islands.

easy (see longitudinal section A-B on Fig. 4). The entrances are about 80 m above sea level.

Name

Karl Kübler, a German settler who immigrated to the island in 1936, was the first to explore the cave. Although sometimes known also as Cueva de Puerto Ayora, El Tunnel, etc., the usual name for it is Cueva de Kübler.

Geology

La Cueva de Kübler is developed in dark gray, porphyritic, olivine basalt. Several successive flows passed through the trunk channel, each leaving a flow ledge on the walls of the tube. The most recent flow, which was very small, formed a smaller tube on the floor of the primary tube. Near the entrance sinkhole, the secondary tube forms a vesicular mound 1 to 1.5 m wide and 0.5 to 1.0 m high. It has collapsed in many places, however.

A joint intersects the tube at Station 16 (see Fig. 4). The joint is 25 to 30 cm wide. Soil washed into the tube through this opening has dried to form a layer of clayey powder 30 to 40 cm in thickness on the floor. A joint opening of comparable size intersects the cave at Station 23 and there is a smaller one at Station 21.

Hydrology

The hydrology of lava tubes, excepting that of a few containing streams, is inconsequential. La Cueva de Kübler is virtually dry, although a few points of seepage are to be found during the rainy season. Yearly rainfall in the area of the cave is very low—not more than 300 to 400 mm.

Temperature

The roof of the tube consists of 3 to 10 m of vesicular lava. The temperature of the cave depends upon the temperature of the enclosing rock mass. Average annual temperature in the area of the cave is about 24°C, reaching a minimum of 21°C from July to October and a maximum of 26°C from January to March. At the time of my visit, the deeper portions of the cave had a temperature of about 24°C.

Morphology

The total length of La Cueva de Kübler, excluding only the collapsed segment between stations 2 and 3, is 852 m. The average height of the cave is 5.9 m and the average width 5.5 m. The average cross-sectional area, at the entrance 27 m^2, gradually decreases downstream. The cave cross-section near the entrance is that of a vertical ellipsoid with a flat base. Downstream, the cross-section becomes a horizontal ellipsoid. The volume of the cave is about 21,000 m^3.

As seen in profile A-B (Fig. 4), several collapsed segments occur at the northwest end of the tube. The former location of the tube now is marked on the surface by a lava trench. Erosion near the entrance has uncovered a smaller tube running more or less parallel to La Cueva Kübler at an elevation 7 to 8 m higher than the floor of the latter (cross-section I, Fig. 4).

The flow ledges of the later lava flows are visible on the walls of the tube between stations 1 and 12. They occur up to 3 m above the floor. The secondary tube on the floor of the cave may also be traced from Station 1 to Station 12.

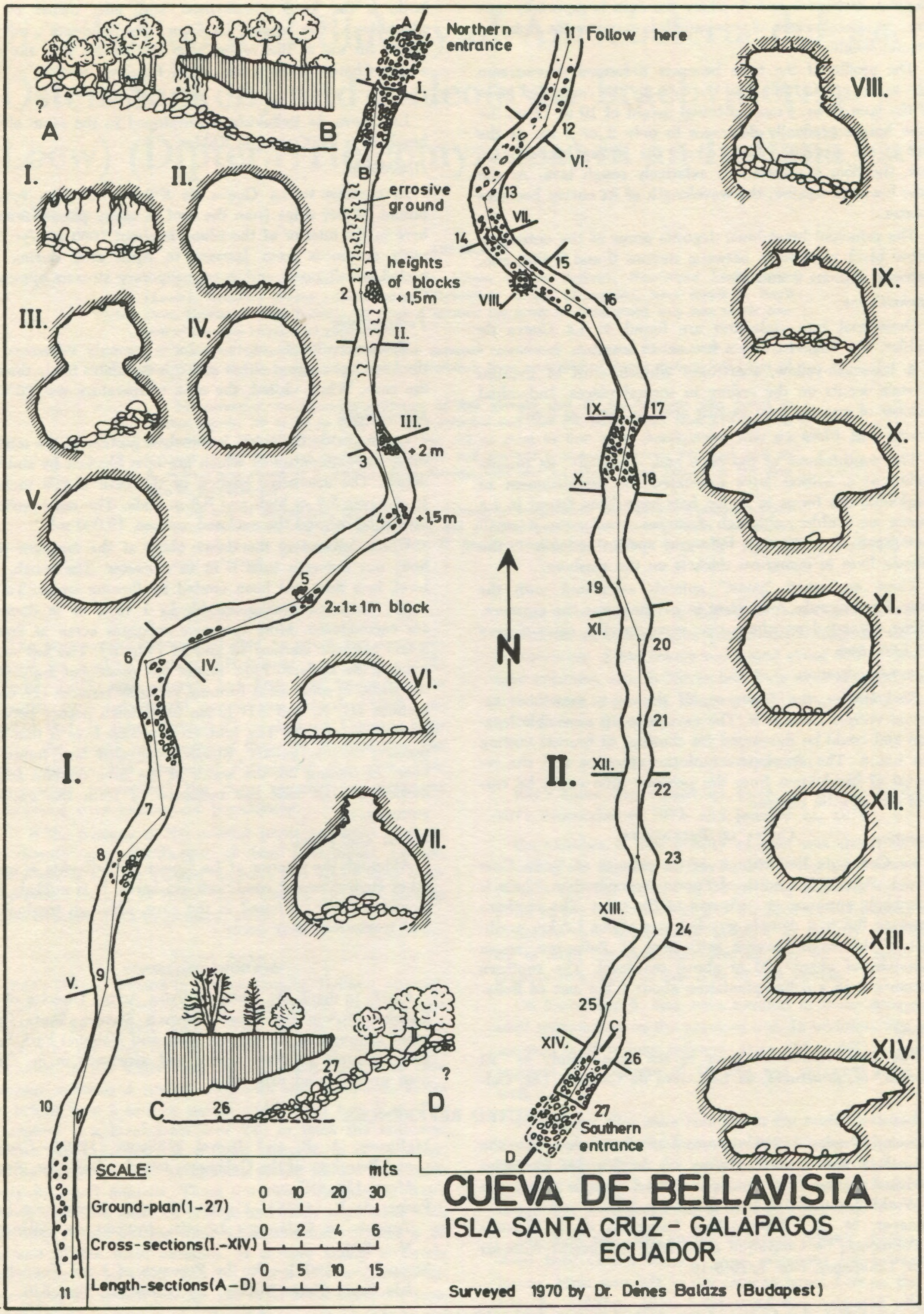

Fig. 5. Map of La Cueva de Bellavista, Galápagos Islands.

Between stations 6 and 7, where the cave is especially narrow, natural bridges of congealed lava span the tube at several heights.

The profile of the tube becomes deformed downstream due to the gradual filling of the tube by the congealed lavas of the later flows. From an initial height of 10 or 12 m, the tube height gradually decreases to only 2 or 3 m. At the end of the accessible cave, where the ceiling becomes too low, the floor is covered by relatively rough lava. As the tube becomes smaller, the wavelength of its curves becomes shorter.

The principal breakdown deposits occur at the entrances. Other block piles occur between stations 6 and 9 and, also, between stations 9 and 22.

Speleothems

Occasional lava stalactites are found in La Cueva de Kübler. The largest is but a few cm in length.

A brownish-yellow, sometimes whitish crust of gypsum crystals occurs on the ceiling in several places. Individual patches of gypsum may encrust areas as large as 2 m^2.

Fauna and Flora

The youthfulness of the cave and, especially, its unsuitability as a habitat have prevented the establishment of troglobitic life forms in it. No bats have been found in La Cueva de Kübler, although *Lasiurus brachyotis*, a small (wingspan 18 to 20 cm), light-gray species endemic to the islands, lives in mangrove thickets on the seashore.

There are many "guest" animals associated with the cave. For example, owls roost in cavities near the entrance. These suggested an alternative name for the cave—Cueva de Lechuzas.

Commercialization

Karl Kübler, the discoverer of the cave, sometimes escorted visitors through it. The cave is in an accessible location and could be developed for showing to tourists visiting the island. The development of the entrance and the removal of breakdown from the primary tube could be carried out at little expense.

Cueva de Bellavista

Location

La Cueva de Bellavista is in the interior of Santa Cruz Island, about 7 km north of Puerto Ayora harbor. There is a sinkhole entrance at each end of the tube. The northern entrance lies in a densely wooded area about 1.2 km northeast of the small farming settlement of Bellavista, at an elevation of about 300 m above sea level. The southern entrance is in a coffee plantation about 1 km east of Bellavista.

Name

The local inhabitants refer to the cave simply as "El Tunnel" or, sometimes, as La Cueva de Gallardo (Sr. Gallardo is the local schoolmaster and, also, owner of the plantation). The name, "La Cueva de Bellavista", was selected for use in this report after discussions with the staff at the Charles Darwin Biological Research Station.

Geology

La Cueva de Bellavista is developed in the same olivine basalt as is La Cueva de Kübler.

Hydrology

In contrast to La Cueva de Kübler, this lava tube is humid. Water drips from the roof in many places. Rainfall here in the interior of the island is about 1000 mm/yr. The rainy season is from January to April and, during this period, small pools and even temporary streams appear in the cave.

Temperature

The microclimate of the tube is strongly influenced by the large openings at either end. Air circulates freely through the cave. When visited, the cave temperature was 23°C.

Morphology

La Cueva de Bellavista is merely a portion of the original tube, the extremities of which are now blocked by sinkhole debris. The accessible portion of the cave is 669 m long. It averages 5.6 m high and 6.6 m wide. The cross-sectional area is 29 m^2 and the enclosed volume, 19,000 m^3.

Upon descending the debris slope at the northern sinkhole, one enters a tube 6 m in diameter. The rough, but level, lava floor has been eroded by flowing water. To the south, scattered breakdown blocks 1 to 2 m in diameter are encountered. More extensive collapses occur at Station 3 and between stations 13 and 14 (Fig. 5). The last nearly reaches the surface. Flow ledges are prominent features of the walls, in some areas forming veritable terraces (cf. cross-sections III, X, and XIV). No breakdown occurs between stations 20 and 26. The tube cross-section here is that of a regular, circular gallery. Rough, congealed lava forms the floor. At Station 26, the width of the tube doubles and at Station 27 the roof has collapsed to form the southern entrance.

Fauna and Flora

Although the interior of La Cueva de Bellavista is moist, other environmental conditions are harsh. It is unlikely that troglobites will be found in the cave, although troglophiles and trogloxenes may occur.

Acknowledgements

I wish to thank Mr. Tjitte de Vries, Acting Director of the Charles Darwin Biological Research Station, Santa Cruz, other members of the Station staff, and National Park Service employees for their advice and assistance to my "one-man underground expedition."

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We regret that, due to loss of the original manuscript, publication of this paper was delayed.

Distribution and Biology of Amoebaleria defessa (Osten Sacken) and Heleomyza brachypterna (Loew) (Diptera: Heleomyzidea) in an Indiana Cave

John Busacca *

ABSTRACT

Four heleomyzid species, *Amoebaleria defessa* (Osten Sacken), *Heleomyza brachypterna* (Loew), *Aecothea specus* (Aldrich), and *Heleomyza serrata* (Linnaeus), were found in Ray's Cave, Greene County, Indiana. Of these 4 species, the latter two composed only two to six percent of the cave heleomyzid population.

The area 40 to 50 m from the cave entrance consistently contained the greatest density of flies. There was no statistically significant variance from an expected equal male/female ratio of flies.

In November, an extensive collection of flies showed that *H. brachypterna* was found in greatest density 30 to 80 m from the cave entrance and was not found more than 210 m from the entrance. The density of *A. defessa* was not as great as that of *H. brachypterna* near the entrance of the cave, but increased gradually and reached a plateau between 120 and 210 m. *A. defessa* was found at a fairly uniform density, with one exception, much deeper in the cave than *H. brachypterna*.

Flies moved further into the cave with extremes in temperature and relative humidity outside the cave. *A defessa* migrated sooner than did *H. brachypterna*. In January, both heleomyzid species were found deep in the cave, with *H. brachypterna* being found as far as 750 m from the cave entrance.

Introduction

The presence of heleomyzid flies in caves has been reported by various authors (Holsinger and Peck, 1971; Vandel, 1965; and others), but little has been done to quantify cave heleomyzid populations. Marsh (1969) reported that, in John Rodgers Cave, Jackson County, Kentucky, the density of heleomyzid flies was greatest near the cave entrance and decreased throughout the cave. This observation represented the most quantitative statement concerning cave heleomyzid populations.

It is the purpose of the present paper to report changes in density and distribution of two heleomyzid species, *Amoebaleria defessa* (Osten Sacken) and *Heleomyza brachypterna* (Loew), in Ray's Cave, Greene County, Indiana from October, 1971 to January, 1972.

Study Area

Ray's Cave is located in Greene County, Indiana, approximately 18 miles southwest of Bloomington, near Indiana Highway 54 (Powell, 1961). The cave is about 2000 m in length; the first 750 m inward from the entrance are included in the study area. In the study area, the cave passage contains a stream and, with one exception, varies in height from 2 to 5 m and in width from 1 to 5 m. The exception is a breakdown area 240 m from the entrance. Above this breakdown is a dome about 6 m in diameter, at the top of which is an opening to the surface penetrable only by small animals. There are two entrances to Ray's Cave. The main entrance is large and easily negotiable, with the cave stream flowing from it. The second entrance is 35 m east of the main entrance. It is very small, is barely negotiable by an adult, and leads to a narrow passage intersecting the stream passage 150 m from the main entrance.

Bats were observed in the dome immediately above the breakdown in October and sporadically throughout the cave in November. A bat colony was found about 650 m from the cave entrance, also in November. Bats were found throughout the cave in January. Their greatest concentration was 40 to 50 m from the entrance.

Methods and Materials

Ray's Cave was visited on three occasions: October 9, 1971, November 6, 1971, and January 21, 1972.

On October 9, the density of flies was determined by counting the number of flies in 10 m-long segments of the passage for 150 m and in 30 m long segments from that point to the breakdown at 240 m. Because the density data indicated that the area of greatest fly density was 40 to 50 m from the cave entrance, all flies on the south wall were collected in the first 5 m of this section.

On November 6, flies were counted in these same measured segments as on the previous trip. In addition, flies were counted in 30 m-long segments from 240 to 420 m. In each segment, a maximum of 15 flies was collected from each wall.

In January, flies were counted in the same measured segments as on the previous trip. Heleomyzids were then sought 650 to 750 m from the main entrance. Solitary flies were collected at 720 and 750 m from the main entrance. Collected flies were preserved in 70% ethyl alcohol.

On each trip, bat guano, decaying organic matter, and dead bats (when found) were examined for heleomyzid larvae. Meat was left in the cave as larval bait on the first trip. In addition, adult heleomyzid flies captured alive in October were kept in the laboratory.

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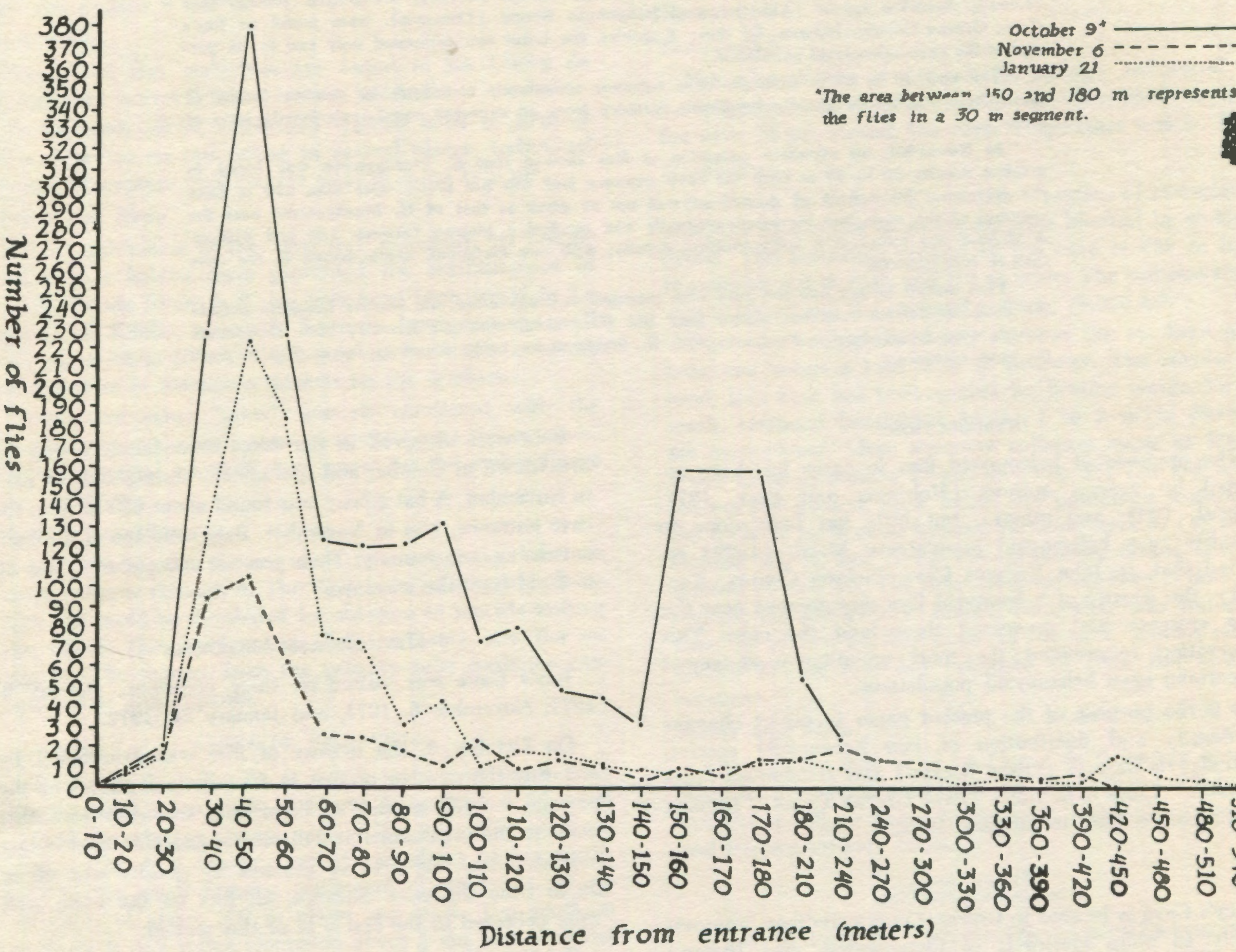
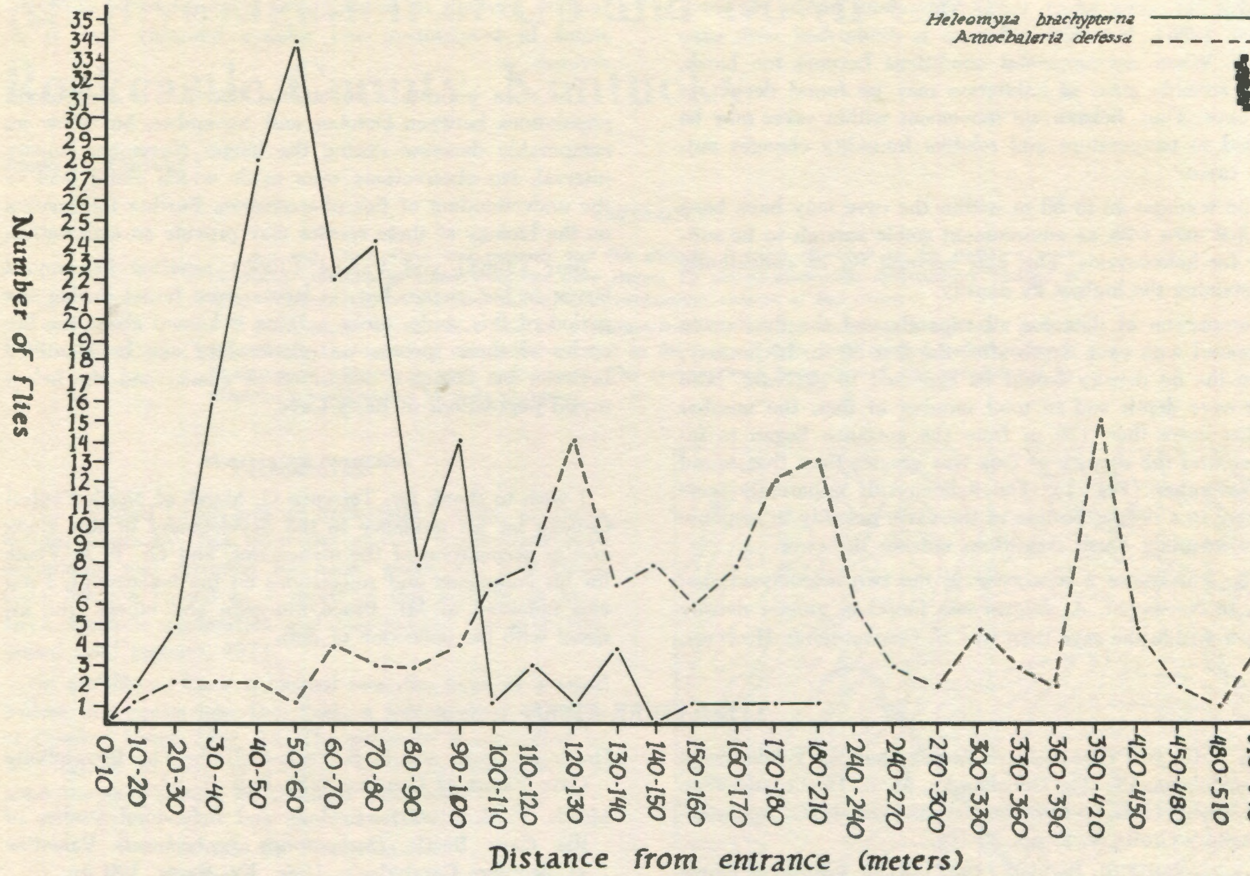

October 9*
November 6
January 21
*The area between 150 and 180 m represents the flies in a 30 m segment.
Number of flies
Distance from entrance (meters)



Results

Heleomyzid density on all trips was greatest in the segment 40 to 50 m from the entrance. Density was very low outward from this segment and gradually decreased inward from it (Fig. 1).

The October 9 collection from the area 40 to 50 m into the cave showed *H. brachypterna* and *A. defessa* to be represented in almost equal numbers, 40 and 38, respectively.

The collection of flies taken November 6 showed *H. brachypterna* to be present in greatest numbers 30 to 80 m from the cave entrance and absent beyond 210 m (Fig. 2). The density of *A. defessa* was lower than that of H. *brachypterna* nearer the cave entrance, but increased gradually until it was consistently greater than that of *H. brachypterna* more than 100 m within the cave. With one exception (390 to 420 m), *A. defessa* was found in fairly uniform density beyond the breakdown area at 240 m.

Table 1

Heleomyzid Flies from Ray's Cave
(January 21, 1972 Collection)

Distance from entrance (meters)	*Amoebaleria defessa*	*Heleomyza brachypterna*
40–50	2	6
160–170	11	—
210–240	6	1
720	—	1
750	—	1

By January, *H. brachypterna* had moved deeper into the cave (Table 1). The two flies at 720 m and 740 m from the entrance represent the furthest penetration by either heleomyzid species in the study area. These flies, also, were the only flies observed in the area 650 to 750 m from the cave entrance.

The number of flies present in the cave decreased sharply from 1883 in October to 945 in November. During the November-January interval, there was no great population decrease. If the number of flies collected in November (323) were added to the January total of 575, the fly population in those months is almost equal.

A chi-square test showed no significant deviation from an expected equal male/female sex ratio for either species, as reflected by all collections.

Two other heleomyzid species, *Aecothea specus* (Aldrich) and *Heleomyza serrata* (Linnaeus), also were found in Ray's Cave on all trips. In November, *H. serrata* was collected as far as 240 m and *A. specus* as far as 540 m from the main entrance. Together, these species total only 2 to 6 percent of the flies collected during the three trips.

Neither the bat guano nor the decaying organic matter contained any larvae. The dead bats and meat bait attracted many larvae, but these produced only sphaerocerids (Diptera: Sphaeroceridae). Adult heleomyzids kept in the laboratory producted no eggs.

Discussion

Differences in fly density and distribution indicate heleomyzid flies are active within the cave at different times of the year. Fluctuations in temperature or relative humidity outside the cave affect the environment inside the cave (Barr, 1968), but their influence is diminished with cave depth. When environmental conditions become too harsh, more suitable areas of habitation may be found deeper in the cave. Thus, heleomyzid movement within caves may be related to temperature and relative humidity changes outside caves.

The segment 40 to 50 m within the cave may have been the first area with an environment stable enough to be suitable for heleomyzids. This may account for its consistently maintaining the highest fly density.

Comparison of data for all trips showed the fly density decreased with cave depth after the first 50 m. In January, when the fly density would be expected to decrease, both with cave depth and in total number of flies, the number of flies more than 170 m from the entrance began to increase and the density of flies was greater than that found in November (Fig. 1). The heleomyzids apparently were moving to a deeper portion of the cave, possibly in response to increasingly harsh conditions outside the cave.

Fig. 2 indicates a separation of the two heleomyzid species. In November, *A. defessa* was found in greater density deeper within the cave than was *H. brachypterna*. However, *H. brachypterna* was found very deep within the cave in January. Perhaps *H. brachypterna* is more tolerant of fluctuations in temperature and relative humidity than is *A. defessa*.

The data indicate a substantial decrease in heleomyzid populations between October and November, but show no comparable decrease during the longer November-January interval. No observations were made which could lead to the understanding of this phenomenon. Further information on the biology of these species may provide an explanation.

Barr (1968) and Vandel (1965) reported heleomyzid larvae in bat guano, but no larvae were found during the period of this study. Since nothing is known about the life cycles of these species, no relationships can be identified between bat colonies, deposition of guano, and the heleomyzid populations in Ray's Cave.

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An Investigation of Up and Down Cave, Rockcastle County, Kentucky

James C. Currens *

ABSTRACT

Up and Down Cave was mapped and the geologic features observed in the passages were described. Analyses of water from the cave stream by atomic-absorption spectrometry yielded a rough determination of the total calcium and magnesium content of the water.

Development of the cave has been characterized by the formation of recessional gorges. Waterfalls retreating along channels developed at the tops of shale beds created vadose canyons in alignment with one or more major joints. The canyons have been divided into pseudolevels by breakdown bridging and by shale plugging.

Introduction

The Crooked Creek area of Rockcastle County, in southeastern Kentucky, has been the site of intermittent cave exploration and mapping for many years. Up and Down Cave became known as a result of this activity in May, 1971. Sporadic exploration and mapping of the cave continued until January, 1973.

Up and Down Cave is located near the head of a small hollow that opens into Dry Fork, a wet-weather tributary of Crooked Creek (Fig. 1). The property is controlled by Mr. Nathan Mullens of Climax, Kentucky. Permission to enter the cave should be obtained from him.

Method of Investigation

The mapping of Up and Down Cave was done with a Silva Ranger compass, an Abney clinometer, and homemade survey tapes. Two compass readings were taken at each station in the main passages. The compass was read to the nearest half degree and the tapes to the nearest centimeter, or twentieth of a foot. The raw survey data was reduced to Cartesian coördinates with a Fortran program on an IBM 360 computer.

Other work included measuring the stratigraphic section within the cave, describing the gross lithologic characteristics of the section, and correlating the section with the surface stratigraphy. Also, the absolute calcium and magnesium content of the stream flowing through the cave was measured by atomic-absorption spectrometry.

Geologic Setting

Up and Down Cave has been developed in the Upper member of the Newman limestone of late Mississippian age. Most caves near Up and Down Cave are found in the lower Newman (the Ste. Geneviève and St. Louis limestones), although vertical shafts are common in the Upper member.

The Upper member varies in thickness from 0 to 140 ft. This unit is composed of microcrystalline to coarsely crystalline, gray, fossiliferous limestones and green-gray shales. There are thin beds of coarsely crystalline limestone in some of the shale beds.

Immediately above the Upper member of the Newman is the Pennington formation, a dark olive-green, silty shale. This unit is approximately 17 ft thick at the entrance to

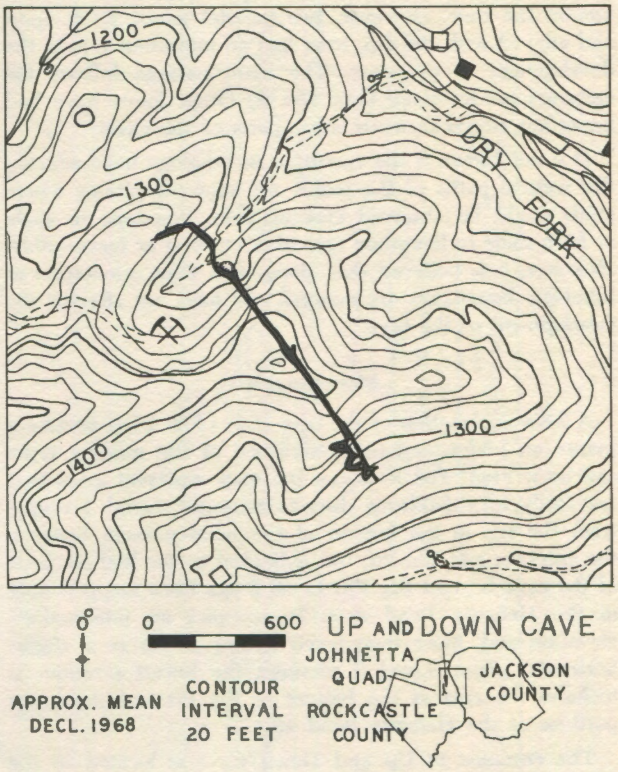

Fig. 1. A portion of the Johnetta 7½ minute quadrangle, showing the location of Up and Down Cave and the relationship of its passages to the land surface above. Note the sink northwest of the entrance and the two springs.

Up and Down Cave. Overlying the Pennington is the Lee formation. This is a thick series of sandstones, shales, and coals. At the entrance site, a 2-ft thick outcrop of coal occurs less than 50 ft above the base of the Lee (Gualtieri, 1968). The entrance sink begins at the base of the Lee, penetrates the Pennington, and ends in the first limestone bed of the Upper member of the Newman.

The alternating series of shales and limestones of the Upper member is one of the major controlling factors in the development of Up and Down Cave. The first limestone unit of the Upper member, 28.5 ft thick, lies directly below the Pennington and forms the roof of the cave. Passage development generally is below this unit. The first shale unit, 9.6 ft thick, occurs next. Much of the cave passage is

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in the first shale. Below the first shale is the second limestone, 12.6 ft thick, followed by the second shale (3.0 ft), the third limestone (5.1 ft), and the third shale (3.8 ft). Passages also are found in these shale beds, but they are not extensive. The remainder of the rock exposed in the cave consists of the fourth limestone (25.4 ft) and the fourth shale (2.6 ft). Passages also occur in the lowest shale bed. Below the last shale bed is an undetermined thickness of limestone. A maximum of 10 ft of this basal limestone are exposed in the cave. A total of about 70 ft of rock is exposed within the cave.

Structures in the area are very simple. Part of the Cincinnati arch, the rocks dip gently to the southeast at about 3 degrees. Faulting and folding are nearly nonexistent. The northeastern end of the Mount Vernon fault does extend into the southern part of the Johnetta quadrangle area (Gualtieri, 1968), but it is too distant to have affected the area around the cave. However, two parallel joints, 20 ft apart and aligned with the dip, have had an important rôle in the development of the cave. The main passage follows the eastern joint for more than 800 ft. Other joints have had important effects in many other parts of the cave.

It is not known if the variations in lithology have affected the vertical paths of the joints. All known locations where joints might be observed crossing from limestone to shale or from shale to limestone are either covered or inaccessible. However, it is believed that changes in joint orientation at lithologic boundaries are minimal and have not affected the development of the cave.

Morphology

A brief explanation of the cave map (Fig. 2) is necessary before an understandable description of the passage types can be written. The levels on the map represent areas that are easily identifiable as discrete passages. Level 1 ranges from the top to the bottom of the main passage between the entrance and Big Pit, but is limited to the highest parts of the cave beyond Big Pit. Level 2 has been mapped only in the Helictite Bend area. It occupies an intermediate elevation and, more than levels 1 and 3, lies in a single, horizontal plane. Level 3 occupies the lowest position. It includes the area at the bottom of Big Pit and the lower portions of the Helictite Bend area.

The entrance to Up and Down Cave is located in the south end of a sink near the head of a small hollow. An intermittant stream carries coal chips and other debris from an abandoned strip mine above the cave into the sink and the cave.

Inside the entrance, two passages can be seen. Penny Passage, to the right, curves around the breakdown from the sink, then trends up-valley for a short distance, beneath the ridge on the northwest side of the hollow. The main stream of the cave enters at the end of this passage.

Directly ahead, leading into the ridge on the southeast side of the hollow, is the main passage of the cave. This passage continues in nearly a straight line until it approaches the far side of the ridge. At this point, several passages depart from the previous trend. None reaches the surface, but the cave stream emerges in the adjacent hollow, approximately 1500 ft southeast of the entrance. Coal chips occur in the gravel at the spring. According to Gualtieri (1968), no coal crops out in this hollow and, therefore, a fairly certain correlation between the spring and the cave stream can be made.

The main passage of Up and Down Cave is a large vadose canyon. The passage is approximately 70 ft high and may be as much as 30 ft wide, although it commonly is much narrower. The canyon passage is partially filled and divided into levels by slumped shale and by limestone breakdown. The only sign of solution under pipe-full conditions is on the ceiling. Here, a prominent joint has been enlarged to form a small ceiling channel.

The levels formed by the shale and breakdown are termed "pseudolevels". The pseudolevels are supported either by large blocks of breakdown, or by shale that has slumped into a narrow part of the canyon. The regions floored by breakdown tend to be very short and of varied elevations. Most of the blocks parted from the walls after the shale under them slumped and removed their support. The passages with shale floors have developed along levels parallel to and just below the shale beds. A limestone bed, cut by a trench, lies below the shale. Where the trench is narrow, the shale plugs it and forms a floor (see Fig. 3). This type of passage occurs for 100 ft on the entrance side of Big Pit and in the Caver Traps area. On level 3, stream gravel, bedrock, and piles of breakdown and shale form the floor. The deepest pits in the higher levels have bottoms on level 3.

At the entrance to the Helictite Bend section, a zone of incompetent rock has caused the enlargement of a portion of level 1. Rock bounded on each side of the passage by joints collapsed at this point when the supporting shale was removed. Levels 2 and 3 here are blocked by breakdown. At the end of this breakdown room, level 1 departs from the trend of the main joint.

The passages in the Helictite Bend area differ greatly from those in the remainder of the cave. These passages are of the same type, but are not restricted to alignment along one joint. One of the passages appears to be a continuation of the main trend of the cave, but it, also, departs from perfect alignment with the main joint.

Portions of Penny Passage are similar to the main passage. The passage bends nearly 180° around the collapse at the entrance sink before coming back into alignment with the joint observed in the main passage. After following the joint for less than 75 ft, the passage makes a sharp turn to the west and ends within 250 ft. In this area, phreatic solution and collapse have enlarged the passage upward into the first limestone. One feature present throughout the cave that is best seen in Penny Passage is a layer of gravel and clay on top of the first shale and at the base of the first limestone. This type of fill occurs in many other caves of the region.

Features of the surface also offer clues about the morphology of the cave. Several feet above the resurgence are seeps. These are swampy areas at elevations approximately equal to those of the shale beds in the cave. Also, a sinkhole (see Fig. 1) similar to the one at the entrance to Up and Down Cave and aligned with the trend of the main joint occurs nearby in a hollow north of the entrance. This demonstrates the importance to groundwater movement of the joint that extends the length of the main passage.

Hydrology

The main stream enters the cave at the end of Penny Passage, at the contact of the first limestone with the first shale. Most of the passage is in the first shale bed, and the

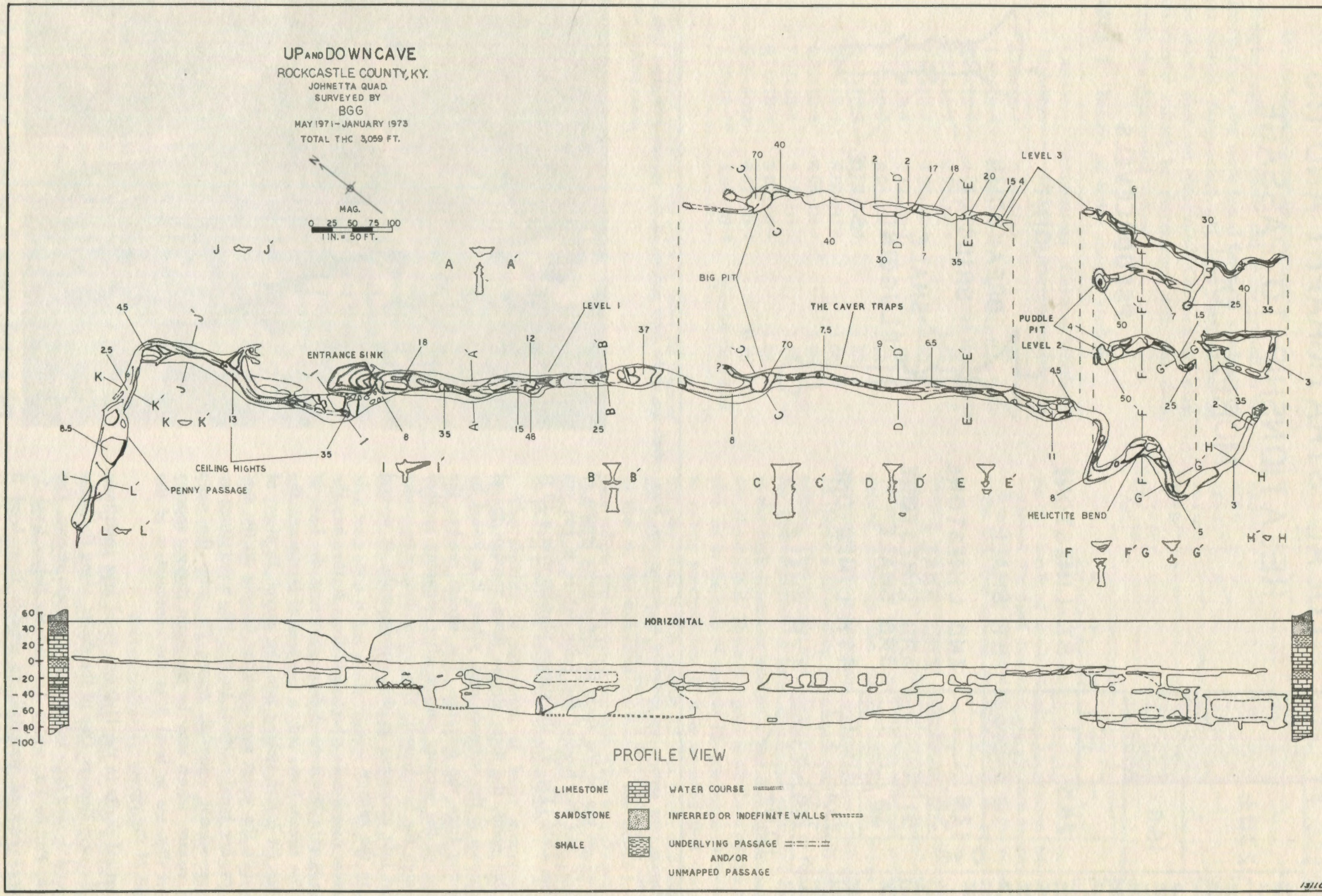

Fig. 2. Map of Up and Down Cave.

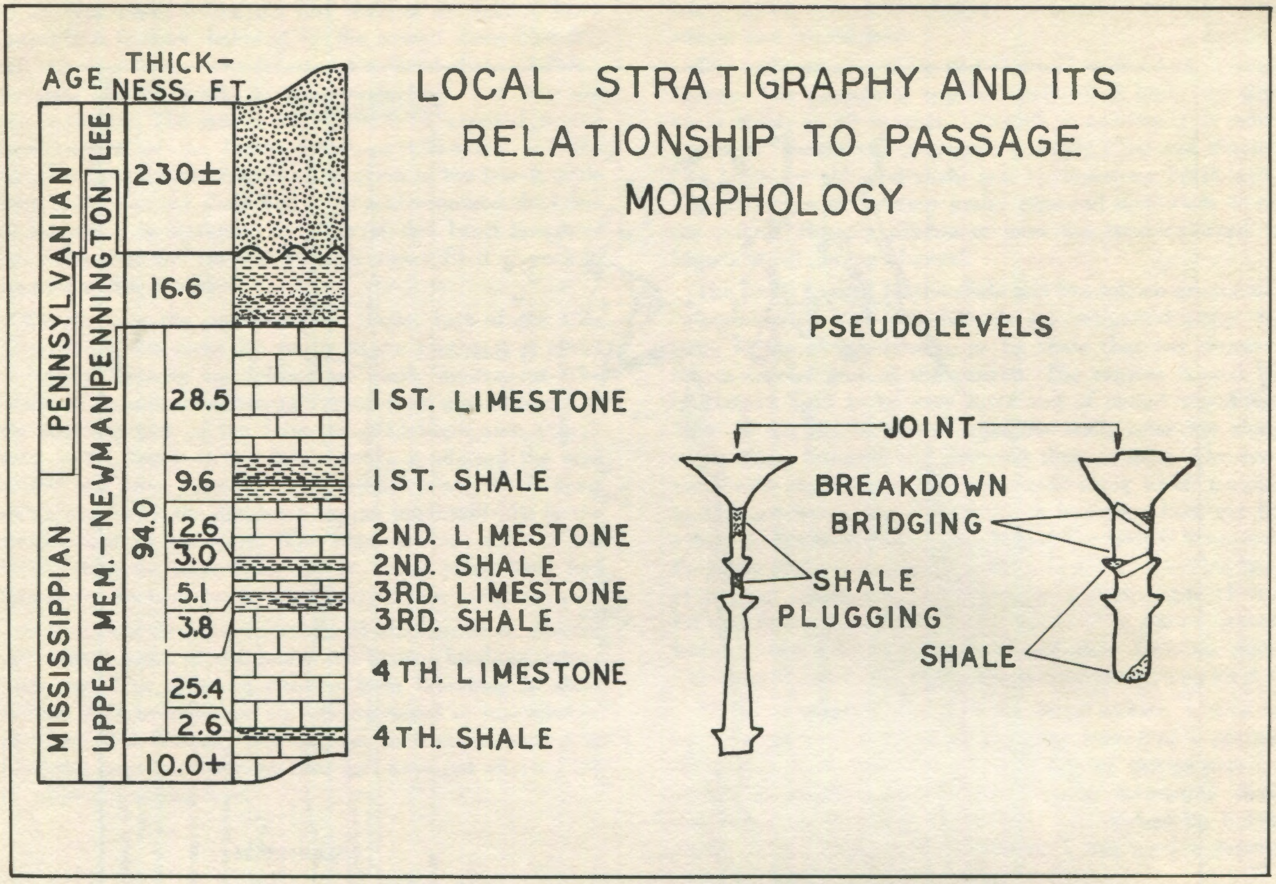

Fig. 3. Passage cross sections are controlled by stratigraphy. Note correlation of the wide portions of the passage with shale beds and of the floors of the pseudolevels with limestone beds.

stream flows on top of the shale for the greater length of the passage. Not far beyond the point where it has cut through the shale (Fig. 4), the stream plunges over a 15 ft waterfall.

From this point, the main stream flows through gravel and breakdown to the entrance area, where it is joined by water coming from the entrance. The stream reaches the gravel floor of the primary canyon after dropping another 30 ft through the breakdown. The water disappears under debris and into undercuts in the canyon walls at several locations in the canyon.

The stream passes over other small drops further into the cave. One is at a limestone-shale contact near the base of Big Pit. The stream flows only a few tens of feet across the floor of Big Pit before sinking into the gravel. In times of heavy rainfall, the water may continue flowing on the surface for another hundred feet. In Big Pit, water from an adjacent recessional waterfall, Annex Pit, joins the main stream. A stream, which may be the main stream, appears for a short distance in level 3 in the continuation of the main trend of the cave.

Two vertical shafts in the Helictite Bend area contribute water to the cave streams. One of the shafts, along the main trend in level 3, may be a tributary of the main stream. The other shaft, Puddle Pit, which lies directly below level 1, is another recessional waterfall. It extends from level 3 nearly to level 1, from which its top is accessible via a small pit. A small stream enters Puddle Pit below level 1

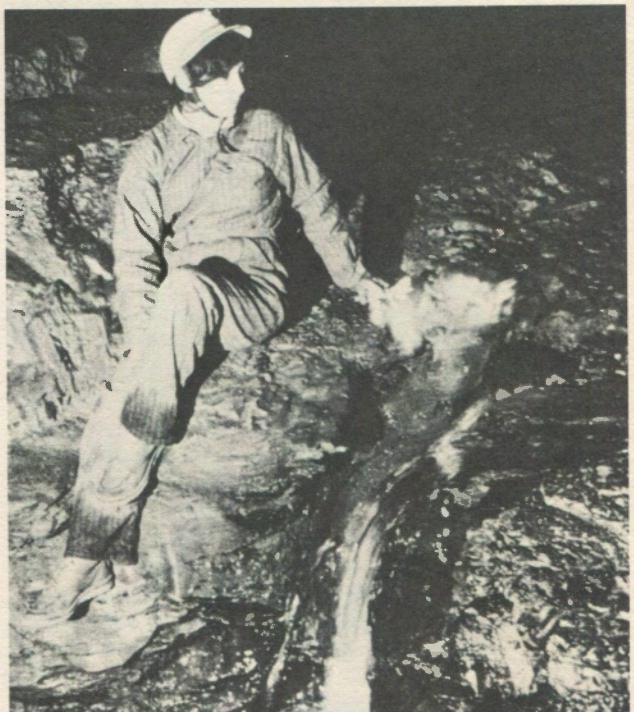

Fig. 4. Penny Passage at the contact of the first shale with the second limestone. The contact is approximately at the level of the person's left foot.

and is ponded at the base of the dome. The pool extends under a low ledge, but water movement caused by draining is not detectable.

Atomic-Absorption Spectrometry

Water samples taken both above and below ground in the Up and Down Cave area were tested for total calcium and magnesium content. Temperature, pH, pCO_2, and additional cations and anions were not considered. Calcium and magnesium saturations cannot be determined with this data. Table 1 gives the determined values.

TABLE 1. Results of water sample analysis.

Sample No.	Calcium Molality	Magnesium Molality	Calcium Molality/ Magnesium Molality
1	5.99×10^{-4}	6.58×10^{-4}	0.91
2	1.85×10^{-4}	2.06×10^{-5}*	greater than 9.00
3	6.29×10^{-4}	2.06×10^{-5}*	greater than 30.05
4	6.94×10^{-4}	6.17×10^{-4}	1.12
5	7.58×10^{-4}	6.36×10^{-4}	1.19
6	6.79×10^{-4}	6.17×10^{-4}	1.10
7	6.79×10^{-4}	6.05×10^{-4}	1.12
8	7.43×10^{-4}	6.05×10^{-4}	1.23
9	6.29×10^{-4}	6.05×10^{-4}	1.04
10	6.59×10^{-4}	6.05×10^{-4}	1.09
11	7.43×10^{-4}	5.76×10^{-4}	1.29
12	6.19×10^{-4}	5.97×10^{-4}	1.04
13	5.39×10^{-4}	6.17×10^{-4}	0.88
20	1.25×10^{-3}*	4.94×10^{-4}	greater than 2.64

* Indicates the instrument readings were above or below the range of the bracketing standard solutions. Estimates were made by extrapolating the working curve.

Fig. 5 shows the approximate locations of the sample sites and the calcium and magnesium values. Samples 2 and 3 were taken from the stream running into the entrance. Sample 2 was taken from water flowing over sandstone and soil. It shows a very low magnesium value and a relatively high calcium value. Sample 3 was taken from water flowing on Pennington shale downstream. It, also, shows low magnesium, but it has an even higher calcium content. These results may be due, in part, to the cementing material of the sandstone and acidic water from the strip mine.

Samples 4 through 12 were taken at random intervals in Penny Passage. The stream in this passage is believed to be nearly isolated from other streams and from seepage through the ceiling during much of the year. This was the case on the sampling day and the effects of dilution and mixing should be minimal. The calcium content of the water flowing over the shale in this passage fluctuates greatly from sample site to sample site, while the magnesium content rises slightly downstream, then declines to a nearly constant level. The increase in calcium in samples 5 and 8 may be attributed to changes in unmeasured factors, such as pCO_2. Other possible causes include stream impingement against the limestone walls, solution of blocks of limestone lying in the stream, and the water penetrating to the underlying limestone along partings and fractures where the shale is very thin.

Samples 9, 10, and 11 were taken from water flowing over limestone bedrock. Sample 9 was taken about 10 ft downstream from the shale-limestone contact and sample 10 twenty feet downstream from the contact. Sample 11 was taken just above the 15-ft recessional waterfall. These 3 samples show a steady increase in calcium content downstream, although the values initially are below those of sample 8. The magnesium content drops gradually. Sample 12 shows a large drop in calcium and a small rise in magnesium. This sample was taken from a pool at the bottom of the 15-ft waterfall. A small recessional waterfall also occurs at the shale-limestone contact a few feet upstream from the site of sample 9. There is a pool at the base of this waterfall, also. As in the case of sample 12, pooling may be conducive to calcite precipitation. If it is assumed that the pCO_2 in the pool from which sample 12 was taken and also that in the pool above the site of sample 9 were reduced (relative to that in the turbulent portions of the stream), then the data follow the expected pattern. That is, calcite concentration rises when direct contact of the water with the limestone occurs and low values are due to temporary changes in pCO_2, resulting in calcite precipitation.

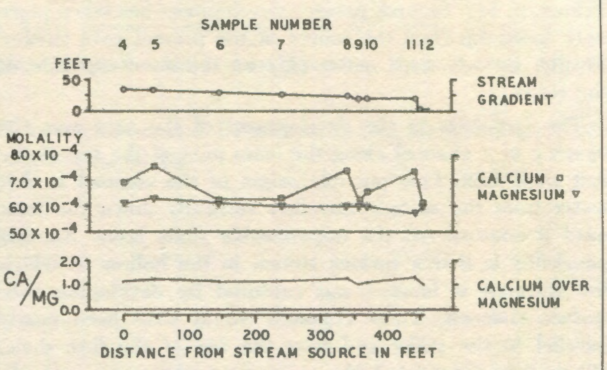

Fig. 5. Results of atomic-absorption spectrometry related to stream gradient. The small drop in stream elevation between sample sites 8 and 9 is at the contact of the first shale and the second limestone. The large drop between sites 11 and 12 is the recessional waterfall.

The rapidity of saturation of karst groundwater with respect to calcite has been discussed by several authors. Beiter (1970, p. 41) showed that saturation may be approached by karst waters in as short a distance as 200 m (656 ft) in the Cave Hollow cave system. However, Miotke and Palmer (1972, p. 64) concluded that groundwater in the Mammoth-Flint Ridge cave system can remain aggressive long after it has made contact with the limestone. The short distance over which the rise in calcium concentration between sample 9 and sample 11 occurred indicates rapid solution of the limestone.

The incomplete data require that any conclusions be speculative. It seems that Up and Down Cave is continuing to be enlarged at a rapid rate. The geologic and hydrologic conditions at the cave offer an ideal site for study of the rate of limestone solution.

Developmental History

Up and Down Cave, unlike most of the caves in its area, offers a large variety of clues about its history. A speculative chronological sequence of events based upon these clues is presented below:

The premise that groundwater movement in the area frequently has been down dip on top of the shale units is based on three observations. The first is that the regional dip has remained constant since the early Pleistocene (Miotke and Palmer, p. 14). Second, passage development has taken place only down dip from the source of the present cave stream. Finally, surface seeps occur only on the down-dip side of the ridge.

The first stage in the development of the cave was the opening of a channel along the main joint at the top of the first shale unit. One possible origin of the channel is that water from the surface travelled vertically down the joint until it encountered the impermeable shale layer. Another possibility is that a surface stream in the hollow in which the entrance is located was captured by developing subsurface channels. These channels would have been nearly parallel to the strike and near the top of the first shale. When they intersected the main joint, the water was diverted and began moving down dip along the joint. Surface stream capture, in light of the present route of the cave stream, seems a likely origin for the water that enlarged the main joint.

After erosion and corrosion had operated along the contact of the first limestone and the first shale for a short time, a local base level was reached, as indicated by the cave fill. The higher base level present at this time may have been due to stream aggradation during the latest glacial period, or it may have been due to a water table perched on the first shale. The impounded water that resulted from the deposition of the cave fill may have been responsible for the phreatic-type enlargement of the ceiling in the upper end of Penny Passage (Fig. 6). Later, when base level was lowered and the stream was rejuvenated, most of this fill was removed.

Fig. 6. A portion of Penny Passage along the main joint. The ceiling channel has been developed up into the first limestone.

The cave fill indicates that an outlet through the Helictite Bend passage existed when rejuvenation of the drainage began. Why the water followed this sinuous route is not well understood. Perhaps a pre-existing depression in the shale captured the flow from the joint. Also at this time, the retreat of a series of waterfalls similar to those present today began. These had their start either from vertical shafts that penetrated several shale layers, or from a now-covered resurgence similar to but much higher than the one present today. However, there is no evidence that such a waterfall existed at the end of the Helictite Bend passage.

As rejuvenation progressed, the stream in the Helictite Bend passage developed openings down joints leading to the second and third shales. Passages began developing at limestone-shale contacts along these joints and pirated the flow from the Helictite Bend level, forming an intermediate level. Several paths were used by the water flowing in the Helictite Bend passage in reaching a canyon forming along the main joint. Eventually, the stream abandoned the Helictite Bend passage when the retreating waterfall forming the canyon captured its source at the entrance to the Helictite Bend passage. This event marked the beginning of the development of the large vadose canyon in the main passage.

Canyon development advanced along a channel previously cut into the shale by the stream below the main joint. As the waterfall retreated headward, blocks of limestone from the walls became unsupported and fell and the remaining shale slumped into the passage, plugging the narrow points.

Water from Annex Pit joins the main stream at Big Pit. When the retreating waterfall reached this point, water from Annex Pit formed another waterfall that began cutting a passage. The large diameter of Big Pit is due to the combined action of these two waterfalls at the same point.

Waterfall retreat followed by limestone breakdown and shale slumping continued from this point until the canyon began developing beneath the hollow that now contains the entrance. When the waterfall removed the support for the walls and ceiling, the passage collapsed, forming the entrance sink. This collapse blocked the passage, forcing the stream to find a new route to the main passage. When this was accomplished, the recessional waterfall began its work again at the edge of the canyon. Since that time, the waterfall has receded approximately 150 ft to its present position.

Conclusions

Three major geologic factors have contributed to the morphology of Up and Down Cave: 1) layers of relatively insoluble and impermeable (but easily erodable) shale alternating with soluble limestones, 2) the occurrence of one or more major joints, 3) parallelism of the major joints with the dip of the strata. The main passage of the cave was formed by a recessional waterfall following a channel cut into the shale below the major joint. The details of the development of the Helictite Bend area are more obscure than are those of the remainder of the cave. However, the multiple recessional waterfall theory seems to be a plausible answer here, also. The chemical data indicate that the process is actively continuing today.

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Sub-Minimum Diameter Stalagmites

Herbert W. Franke [*]

The theoretical framework for the regular forms of stalagmites, initially set forth by myself (Franke, 1961 ff) and recently elaborated by Curl (1973), is now essentially complete. A particular value of this theory is that it provides a basis for understanding certain irregular forms as deviations from regular forms. In this note, I would like to point out an exceptional case which leads to *sub*-minimum diameter stalagmites.

According to Curl, a minimum diameter for stalagmites occurs because, at low flow rates upon the stalagmites, the solute arrives in "quanta" determined by the size and concentration of individual drops. If, however, a situation should arise in which such dropwise quantization does not occur at low flows, the "large diameter" theory (assuming a continuous supply of solvent to the stalagmite) should apply and predict *sub*-minimum diameters. Such a situation occurs when a stalagmite grows to join and engulf a soda-straw, which supplies it with water. Water transfer then becomes continuous and uninterrupted from stalactite to stalagmite. Moreover, the water is protected from loss of CO_2 (and, hence, prevented from depositing calcite) while within the soda-straw. Examples are shown in figs. 1 and 2.

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This special case does not often appear in nature. If, however, one wishes to interpret stalagmite diameters in terms of climatological or physical-chemical variables, one must be aware of this exception to "minimum" diameters.

The existence of a soda-straw or a thin stalactite joined with a stalagmite may indicate that the condition permitting the development of a *sub*-minimum diameter is present. However, soda-straws and thin stalactites are very fragile formations and may have been destroyed at some time during the growth of the speleothem. The resulting *sub*-minimum diameter stalagmite in their absence may then appear to present an anomalous condition of growth, if interpreted only in terms of Curl's minimum-diameter theory.

Because of the observation of *sub*-minimum diameter stalagmites (those having diameters below about 3 cm) primarily in association with soda-straws (as shown in the figures) and their general absence otherwise, I see this *exception* to minimum-diameter theory to confirm both that theory and the explanation offered here for *sub*-minimum diameters.

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