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Research article

Locating a Sealed Cave in Kentucky Using Electrical Resistivity Surveys

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Abstract: Clifton Cave in Woodford County, Kentucky, was known as the habitat for two unique cave-dwelling species only found living in the cave and associated nearby habitats. The cave was surveyed in 1964, but the only cave entrance was destroyed and sealed by road improvements in 1970. To determine whether these species are still present in the cave and to plan future conservation efforts, researchers need to regain access to the cave. A vertical access hole into the cave passage was proposed because the 1964 cave survey provided the general location of the cave passages. In order to determine potential drilling sites to locate cave passages, we conducted two electrical resistivity surveys. Orientation, length, electrode spacing, and location of the surveys were designed to detect three estimated cave passage targets. The survey results showed excellent correspondence between the high resistivity anomalies and all the estimated targets. Although survey results have not been confirmed by drilling, the excellent correspondence suggested the electrical resistivity method is a promising reconnaissance tool for locating caves at relatively shallow depths.

Keywords: karst; cave; geophysical methods; electrical resistivity; high resistivity anomaly

1. Introduction

In investigating geologic and hydrologic features near the earth's surface, geophysical methods are often employed to collect preliminary information because of their low costs and non-invasive nature. In principle, geophysical methods are aimed at locating features of interest based on differential responses of earth materials to external excitations, such as seismic waves or electromagnetic signals. The electrical resistivity method is a widely applied geophysical technique that detects variations in electrical resistivity of earth materials by sending electric currents to the subsurface and measuring electric potentials at the surface and below ground. Because earth materials differ in electrical resistivity values, detected variations in electrical resistivity can provide clues as to what geological or hydrologic features exist in the subsurface.

In karst terrains, caves not only are fascinating to visit but also provide unique underground habitats for rare species. Caves big enough for humans to explore can be measured and mapped directly. On the other hand, locating inaccessible caves and voids must often rely on geophysical methods. Because air has infinite electrical resistivity, air-filled caves tend to have higher electrical resistivity values than surrounding rocks and thus provide a major detection target for electrical resistivity surveys [1,2]. Gambertta et al. [3] applied surface electrical resistivity surveys to the location of a known shallow cave and found the high resistivity values correlate well with the cave passages. However, surrounding materials can complicate the correlation between resistivity survey results and the presence of subsurface voids. Putiska et al. [4] suggested that a cave may show no resistivity contrast or even low resistivity values when a thin layer surrounding the cave has resistivity lower than the background environment, which may shield the current from reaching the cave. Loke [5] discussed advantages and disadvantages of different 2D arrays in detail.

In this study, we applied electrical resistivity surveys to a special case; the goal being to locate a cave in Kentucky which was previously accessible but whose entrance was later obliterated and permanently sealed during road construction activities. The purpose of the surveys was to provide possible targets for drilling boreholes to regain access to the cave passages.

2. Geologic setting

Clifton Cave is a biologically significant cave whose only entrance has been sealed for nearly half a century, a casualty of road construction in 1970. The cave is located in Woodford County among the highlands along the Palisades section of the Kentucky River, a deeply entrenched gorge that extends more than a hundred miles from Frankfort to Boonesborough. This section is included within the Inner Bluegrass Karst Region (IBGK), a terrane of Middle Ordovician carbonate rock centered on Lexington that covers an area of about 5,600 km^2 (Figure 1) [6].

The IBGK is a broad, gently rolling upland plain of nearly uniform elevation (275–300 m or 900-980 feet) which is dissected by the deep gorges of the Kentucky River and its tributaries. Geologic structure is dominated by the Cincinnati Arch, the axis of which is oriented north-south and extends through much of the eastern mid-continent from Alabama to Michigan. Strata dip gently at about 7.5 m/km (40 feet/mile) in all directions away from a local structural high located on the Arch known as the Jessamine Dome, except to the southeast where the strata have been downfaulted. The region is bounded by the contact where the limestone dips beneath overlying shales on the limbs of the Arch [7]. The lowest elevations occur in the gorge of the Kentucky River in the south and west of the region, ranging from 140–170 meters (460–560 feet) [8].

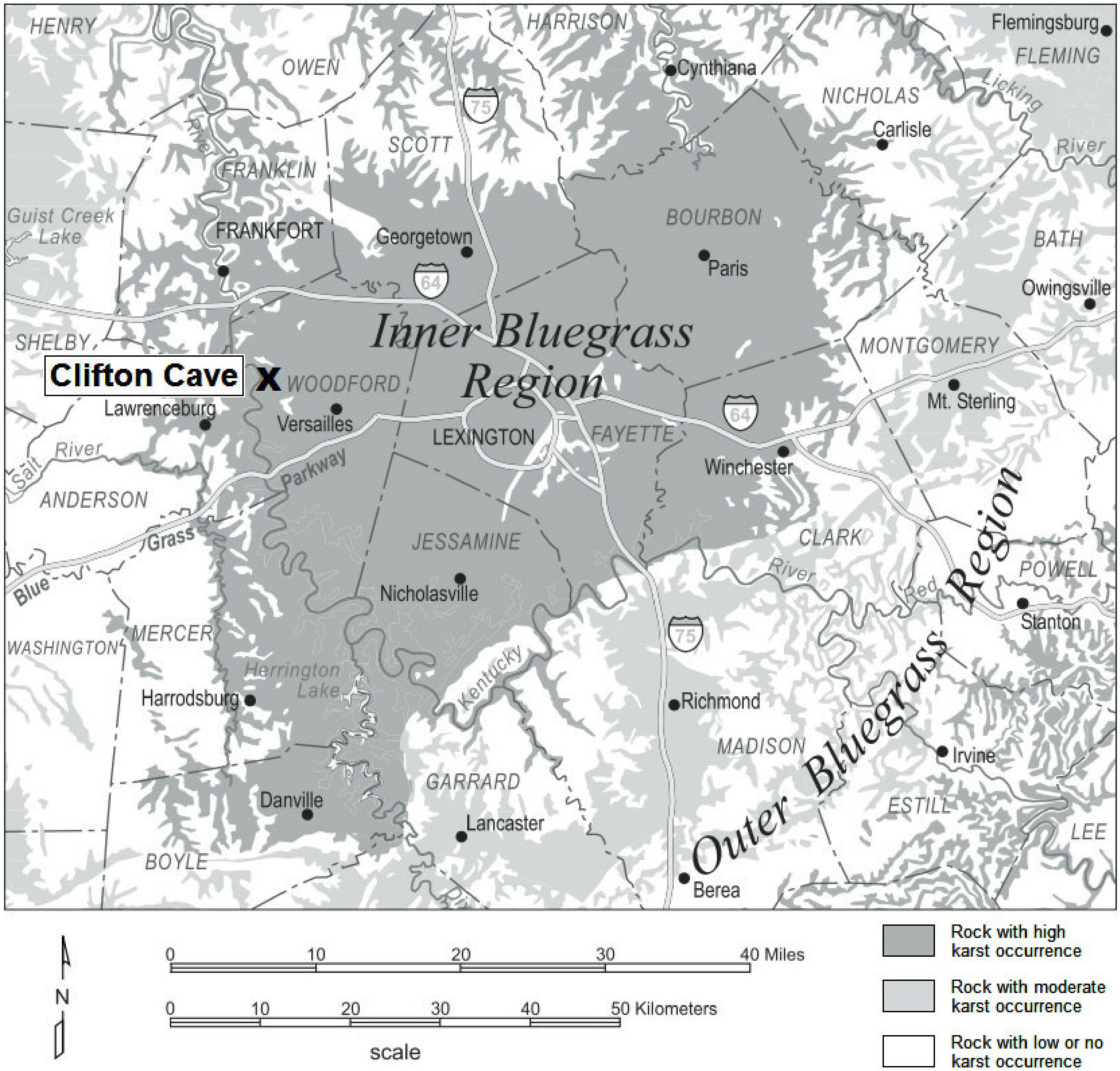

Figure 1. The Inner Bluegrass Karst Region (Modified from Currens and Paylor [7] and Barton et al. [10]). The "X" symbol shows the location of the field site.

Stratigraphy consists of relatively pure lower Ordovician carbonates overlain by thinly interbedded upper Ordovician limestones and shales. The lowermost of the underlying carbonates, the Camp Nelson Limestone and the Oregon and Tyrone Formations, constitute the thickly bedded members of the High Bridge Group. Collectively ranging in thickness up to 75 m (250 feet), these represent the oldest exposed rocks in the state and may be seen only in the Kentucky River gorge. The Tyrone Formation is overlain by the thinly bedded Lexington Limestone, which forms the Lexington Karst Plain and ranges in thickness from 60–90 m (195–295 feet); the lower third of the Lexington Limestone, like the members of the High Bridge Group, is exposed only in the gorge of the Kentucky River. The highest unit in the region, the Clays Ferry Formation, consists of limestone and shale and overlies the Lexington Limestone except where the latter is exposed by erosion [6,7,9]. Table 1 shows a generalized stratigraphy of the Lexington Limestone in the IBGK.

Table 1. Generalized stratigraphy of the Lexington Limestone (Modified from Barton [10])

	Clays Ferry Formation	
Upper Ordovician	Lexington Limestone	Upper Tongue of the Tanglewood Member
		Millersburg Member
		Sulphur Well Member
		Brannon Member
		Perryville Member
		Grier Member
		Logana Member
		Curdsville Member
	Trenton-Maquoketa Unconformity	
	High Bridge Group	Tyrone Formation
		Oregon Formation
		Camp Nelson Limestone

3. Hydrogeologic setting

The Kentucky River meanders through the southern and western edges of the IBGK through the gorge known as the Palisades, which represents incision of the river of about 100 m (330 feet) below the adjacent land surface. Topography associated with members of the High Bridge group tends to consist of cliffs and steep slopes developed along the gorge of the Kentucky River and its tributaries. Numerous grikes (sub-vertical to vertical joints enhanced by dissolution) occur within the walls of the gorge. The upper few meters of the Tyrone and the lower members of the Lexington Limestone (Curdsville, Logana, and Grier) form more gentle slopes extending into the uplands [10].

The IBGK is among the most intensively studied karst areas in the world. Initial efforts during the 1960s by members of a newly established Lexington chapter of the National Speleological Society known as the Blue Grass Grotto (BGG) involved inventory of regional karst features and relatively crude surveys of most of the major caves; co-author O'Dell was among the many who participated in this effort. At this time, biologists associated with the short-lived Institute of Speleology at the University of Kentucky carried out a number of biological inventories of IBGK caves. The majority of the karst basins in the central part of the region was delineated through qualitative dye tracing during the 1970s and 1980s [6], and since that time, more sophisticated approaches, including various geophysical methods, have also been undertaken.

Conduit development in the IBGK generally takes place along bedding planes, displays a dendritic pattern, and is limited to depths of less than 23 meters (75 feet) except in the vicinity of the Kentucky River gorge. Although some caves in the region exhibit abandoned flow routes, the majority of caves and karst features are active elements of the contemporary hydrologic system [9], despite the lowering of regional base level due to the incision of the Kentucky River. This appears to be related to the generally low relief of the upland surface in which development of karst systems is tied to local base levels of the major surface streams more distant from the river gorge, and to the perching effect of bentonite beds located in the upper Tyrone and lower Curdsville Formations. Many of the groundwater basins in the region appear to be strongly influenced by structural controls, with flow paralleling linear faults and fractures oriented northwest-southeast. Other conduit systems have no apparent relationship to fracture patterns or to topography [7]. Sinkholes and sinking streams commonly occur through the region, along with blind valleys, pocket valleys and karst windows.

Most of the groundwater basins in the vicinity of the Kentucky River Palisades are relatively small, generally less than 4 km^2 (1.5 mi^2). Conduit development in this section is more vertical than in the Lexington Karst Plain because of the greater relief and steep hydrologic gradient along the gorge [7]. Stress-release fracturing associated with incision of the gorge has provided breaches of the bentonite beds in the upper part of the High Bridge, so that sinkholes and shafts are numerous in the uplands along the river corridor. Some of the shafts and active levels of several cave systems penetrate as far as the base level of the river, usually ending in sumps.

The former entrance to Clifton Cave was located high on the valley slope of Rowe's Run, a minor tributary of the Kentucky River, at a distance of about 1 km from the river and at an elevation of about 221 m (725 feet). The valley drops steeply about 35 m (115 feet) from the cave entrance to the valley bottom. The cave is developed in the Grier member of the Lexington Limestone, a relatively pure, thinly bedded, coarse grained, and fossiliferous limestone that is overlain by 28–43 cm (11–17 inches) of a well-drained clayey soil, known as the Fairmont-Rock complex, typically associated with the margins of the Kentucky River gorge [11,12]. The Logana member, consisting of interbedded limestone and shale, lies approximately 20 m (65 feet) below the Grier limestone in the vicinity of the cave entrance. The entrance was through a shaft, developed along a minor vertical joint that dropped about 3.7 meters (12 feet) to a mound of rubble on the floor of the underlying passage.

4. History and Significance of Clifton Cave

Clifton Cave has been well known to the residents of northwestern Woodford County for more than two centuries, ever since the settlement of the region in the late eighteenth century. The shaft entrance was easily negotiable without special equipment, and was prominently situated on the inner margin of the road (KY 1964) from the city of Versailles that wound down through Rowe's Run to the village of Clifton, a small river port during the steamboat era [13]. The cave is of minor historical note as the likely inspiration for the writer Robert F. Schulkers, the early twentieth century author of the popular "Seckatary Hawkins" adventure stories for children who often featured caves as settings and key plot devices for his literary creations. The highlands overlooking Rowe's Run to the north were the home of his wife's family and a place that, beginning in 1915, he often visited [14,15].

In 1964, members of the recently established BGG made a survey of the accessible passages within Clifton Cave, which mapped out to a total length of about 550 m (1,800 feet). The cave assumes the shape of a broadly curving "S" and consists of horizontal passageways 1-5 m wide (3–16 feet) and 3-6 m (10–20 feet) high, with very little vertical relief (Figure 2). Biological inventories conducted at about this time identified a troglobitic beetle and a stygobitic isopod that are known only from this cave and associated nearby habitats (Figure 3). Clifton Cave is the type locality for a carnivorous, subterranean-obligate beetle, *Pseudanophthalmus caecus* Krekeler (Clifton Cave beetle); the holotype, allotype and 22 paratypes were collected from the cave by J.R. Holsinger on June 24, 1963 [16]. Initially recognized as a subspecies, *P. horni caecus*, by Krekeler, the taxon was elevated to full species status by Barr [16, 17]. Clifton Cave is also the type locality for an aquatic crustacean, *Caecidotea barri* Steeves, which is restricted to the groundwater aquifer associated with the cave and the springs in the immediate area. The holotype, allotype, and two male paratypes of this species were also collected by Holsinger [18]. *P. caecus* is listed as threatened by the Kentucky State Nature Preserves Commission (KSNPC), and considered a Candidate for Listing by the U.S. Fish and Wildlife Service (USFWS). *C. barri* is listed as endangered by KSNPC [19,20]. Both species are ranked as G1 (critically imperiled) species by NatureServe [21].

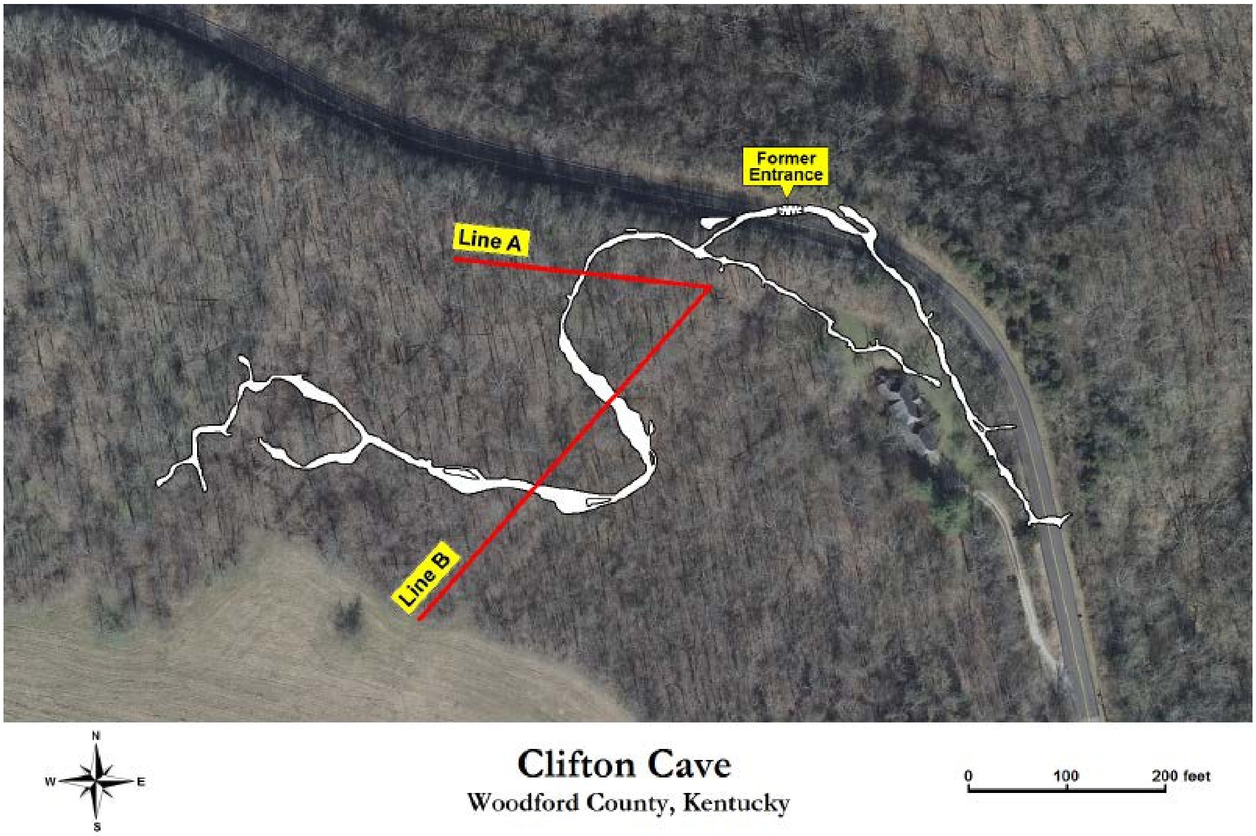

Figure 2. Overlay of Clifton Cave map showing electrical resistivity survey lines in red. Base imagery from Kentucky Geonet, Kentucky Aerial Photography & Elevation Data (KYAPED), 2012–2014 mosiac,1-foot (0.305m) resolution.

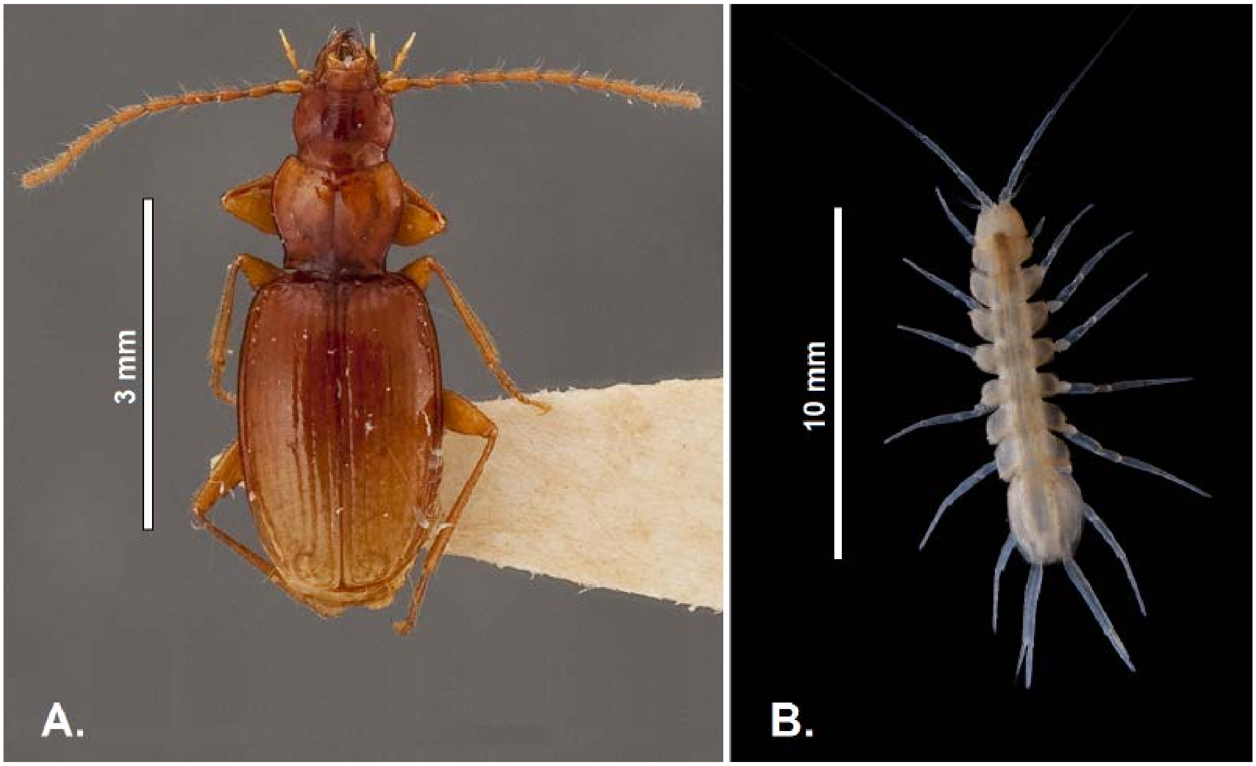

Figure 3. Unique species discovered in the cave in 1963. A: *Pseudanophthalmus caecus* (Krekeler [16]). Specimen located at the Field Museum in Chicago. B: *Caecidotea sp.* similar to *Caecidotea barri* (Steeves [18]). Specimen from Eblen Cave, Roane County, TN, photographed by Michael E. Slay, The Nature Conservancy. By permission.

In 1968, as a new member of the BGG, co-author O'Dell visited Clifton Cave in company with other members of the organization. On a solo return visit to the area two years later, O'Dell was astonished to discover road work in progress, widening and deepening the cut of Clifton Road through Rowe's Run. The road construction blueprint shows the location of the cave entrance and indicates that the cut extended to a point 4.6 m (15 feet) below the surface of the old highway and thus at or below the floor level of the passageway at the cave entrance; the excavation also extended laterally about 10 m (33 feet) into the hillside beyond its former limit [22]. This had completely destroyed the entrance area of the cave so that the remaining passages were no longer accessible.

5. Developing the Project Concept

Despite the apparently permanent closure of Clifton Cave, interest in the unique subterranean-obligate life forms in the cave remained high, particularly after the passage of the federal Endangered Species Act in 1973. In 1993 the State of Kentucky, under the provisions of the recent amendments to the Endangered Species Act, received a significant grant from the USFWS to conduct studies of several threatened or endangered species within the state, including funds specifically allocated to a survey of the Clifton Cave isopod, *C. barri* [23]. The objective of the survey was "to search other caves in the area for the isopod. And, if the isopod is not found in other caves reopen Clifton Cave to check on the isopod's status." As one of the few persons familiar with the cave, co-author O'Dell was contacted in May 1994 by Thomas C. Barr, Jr., an invertebrate biologist specializing in cave fauna who volunteered to supervise the survey, to assist gaining access to the interior of the cave [24]. A quarter-century after the construction that destroyed the entrance area of Clifton Cave, an investigation by O'Dell could not locate any sign of a redeveloping entrance nor any site with excavation potential, although there were a number of small fissures visible in the roadcut.

The next step was taken by co-author Ellis Laudermilk, an invertebrate biologist with the Kentucky State Nature Preserves Commission. The Commission was established by the legislature in 1976 to protect the most significant remaining natural areas in the state, and to participate in an international network of programs that monitors biodiversity. In 1995, Ellis contacted the owner of the property containing Clifton Cave, expressing the Commission’s interest in reopening the cave to complete a biological evaluation of the cave fauna, but could not obtain permission to undertake such a project due primarily to concerns over potential liability. With this avenue blocked, the only remaining option was to see if the cave could be reopened near its original entrance along the public right-of-way of KY 1964, the Clifton Road.

In consequence, Laudermilk contacted O’Dell in early spring 2002 to provide help in another assessment of the former Clifton entrance area with the goal of locating potential sites that might be excavated for development of an entrance. The inspection was carried out on March 26, but, lacking a precise location for the former entrance, failed to reveal any viable locations for such an endeavor. On October 3, 2008, Laudermilk having secured the landowner’s and the Kentucky Transportation Cabinet's (KTC) permission to carry out excavations along the right-of-way, the KTC provided a backhoe and operator to the Commission to remove as much fill material as possible along the road cut in the vicinity of the former entrance, using the full reach of the excavator to expose the bedrock along the cut. The effort did not reveal any opening large enough to admit human entry, but uncovered a fissure containing scat from small mammals indicating use of this small opening.

During the next five years, several additional attempts were made by Ellis, O’Dell and, beginning in 2011, Bogosian, to locate a potential access site along the cut of the Clifton Road, including examination of the terrain above the cave, hoping to discover sinkholes or other features representing surface input into the system, but with disappointing results. At this point, we acknowledged the futility of further efforts of this type, concluding that the only practical way to gain access to the cave would be through determining the conduit location from the surface using geophysical methods and subsequently boring into the cave. With approval from the landowner to carry out the initial non-invasive step, we recruited Dr. Junfeng Zhu and James C. Currens of the Kentucky Geological Survey. Both Zhu and Currens had gained recent experience in applying electrical resistivity to locate conduits associated with the Royal Spring karst flow system that provides the water supply to Georgetown, Kentucky [25].

6. Electrical Resistivity Surveys

The electrical resistivity surveys were conducted in May 2013. Based on the 1964 cave survey and knowledge about the general location of the destroyed entrance, we conducted two surveys. The first survey, called Line A, was placed near the former entrance to minimize the amount of overburden between the surface and passages below; the second survey, called Line B, was laid out further up the hillside, where passages more remote from the entrance were anticipated to be located at greater depth (Figure 2). Both lines were orientated to be perpendicular to the bearing of the postulated cave passages. Line A was expected to overlay a single passage whereas Line B was designed to overlay cave passages twice where the cave made a meandering turn (Figure 2).

The two surveys were conducted using an eight-channel, 84-electrode SuperSting Earth Resistivity Meter manufactured by AGI Inc. USA [26]. The dipole–dipole electrode arrangement was used because it gives more subsurface details than other standard arrangements with similar electrode spacing [27,28]. The dipole–dipole arrangement also takes advantage of the eight-channel feature to expedite data collection.

Using the "rule-of-thumb" concept that the total length of the resistivity line should be no less than 5–6 times the target depth for dipole-dipole arrangement, the length of each line was based on the estimated depth of the cave passage under the line. Line A was 85 m (280 feet) long and Line B was 125 m (410 feet). Line A was laid out to have the estimated location of the passage under the mid-point of the line and Line B was placed to overlay both target locations with sufficient lead-in lengths on both ends. The 1964 cave survey indicated that, in the surveyed areas, height of the cave passages ranged from 3–6 m (10–20 feet) and the width ranged from 1–5 m (3–16 feet). We used an electrode spacing of 3.05 m (10 feet), which is considered sufficient for the intended targets since a general recommendation for electrode spacing is smaller than 2 times the dimension of the target [26]. During the data collection, measurements were obtained through a stacking process where repeated readings were taken to achieve a standard deviation less than 2%. Both surveys had a median standard deviation of 0.2%. Terrain data were not collected as the field site has relatively low relief.

The field data were interpreted by AGI's EarthImager 2D software [29]. EarthImager 2D is a least-squares-based inversion method with three options: damped, smooth, and robust. We used the smooth model, also known as Occam's inversion that seeks the smoothest possible model whose response fits the data to an a-priori Chi-square statistic [29]. The smooth model inversion assumes a Gaussian distribution of data errors and minimizes the sum of the squared weighted data errors.

7. **Results and Discussion**

Figures 4 and 5 illustrate the inverted resistivity profiles for Line A and Line B, respectively. Each profile achieved a root mean squared (RMS) error of 3% and a L2-norm close to 1, demonstrating that the inverted resistivity profiles fit well with field measurements. The L2-norm is the sum of the squared weighted data errors divided by number of measurements. The profile for Line A (profile A) shows a prominent high resistivity anomaly at 55 m (180 feet) from the start of the survey line with depth extending from 5 to 10 m (16-33 feet) below the surface. The location and the depth of the high resistivity anomaly matched quite well with our expected passage locations and we believe the anomaly represents a promising target for drilling a test borehole.

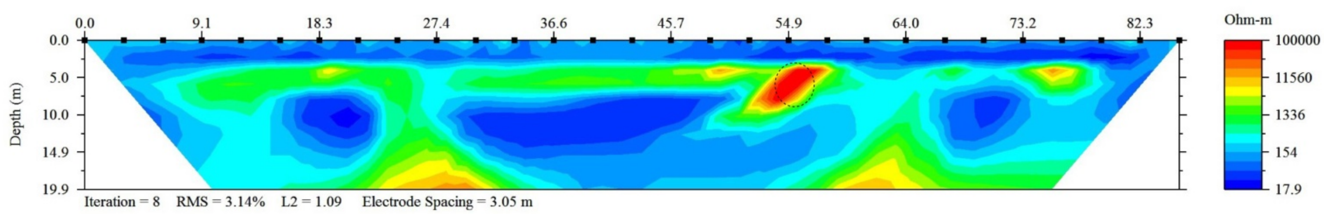

Figure 4. Inverted resistivity profile of Line A. The dashed black circle highlights the high resistivity anomaly considered to represent the cave passage.

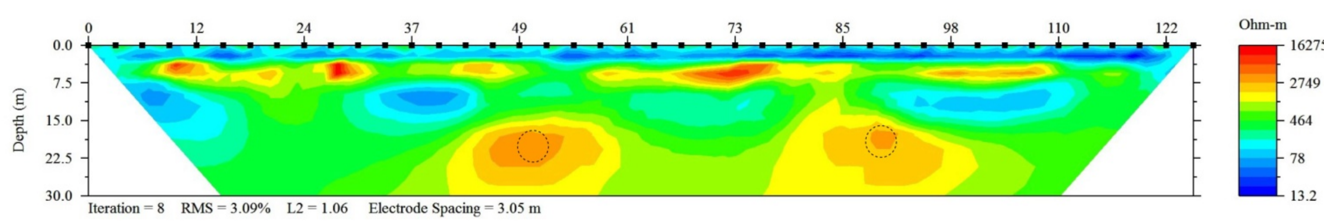

Figure 5. Inverted resistivity profile of Line B. The dashed black circles highlight the high resistivity anomalies considered to represent the cave passages.

The resistivity profile for Line B (profile B) showed two prominent high resistivity anomalies, one at 50 m (164 feet) and the other one at 87 m (285 feet) along the survey line. Both high resistivity anomalies were located approximately 20 m (66 feet) below the surface. The location and the depth of both anomalies also fit our expectations, especially the depth. Both anomalies were 15 m (49 feet) deeper than the high resistivity anomaly displayed on profile A, which was likely corresponding to both the upward slope of the land surface and the known downward trend of the cave passage. The two high resistivity anomalies in the profile B also differed from the anomaly in profile A in shape and resistivity magnitude. The anomalies in profile B appeared more circular than the anomaly in profile A. Inverted resistivity values for the anomalies in profile B were lower than the values for the anomaly in profile A. These differences likely reflect the nature of the electrical resistivity survey, where the inverted resistivity profile is a smoothed and blurred realization of the actual resistivity in the field. The blurriness also increases with depth because the sensitivity of electric signals (i.e., voltages) on the surface to resistivity in the subsurface decreases with depth. While the shape of the high resistivity anomaly in profile A may indicate the cave wall there deviates from the vertical direction, the shape of the high resistivity anomalies in profile B is less likely to reveal details about the geometry of cave passages in consequence of the blurring effect. Figure 6 shows a 1964 photo of the cave passage in the vicinity of the north part of Line B.

Both resistivity profiles revealed three visible low resistivity anomalies. All these low resistivity anomalies appeared at depth of approximately 10 m. Those anomalies may correspond to fissure/fracture zones developed under dissolution of carbonate rocks by water. Those zones tend to have low resistivity as the dissolution-enlarged zones often contain water and clay that holds water well. The similar depths of all the six low resistivity anomalies may suggest that the fracture zones have developed along a relatively flat bedding plane.

Figure 6. Area of cave passage that underlies Line B, near the northernmost crossing of this line over the cave. This photograph was taken in February 1964, prior to the sealing of the cave. Photograph courtesy of the late William M. Andrews.

From the two resistivity surveys, we identified three potential locations for drilling test boreholes. The first one was over the high resistivity anomaly in profile A and the other two were over the two high resistivity anomalies in profile B. We selected the location indicated by profile A as the more desirable site because the target was shallower than the other two targets, thus lower in cost to test drill and subsequently construct an artificial entrance allowing human access. Confirmation of survey results by drilling into the cave unfortunately could not be carried out for reasons beyond our control. However, the excellent correspondence between high resistivity anomalies and the estimated location of passages in Clifton Cave demonstrates the practicality of using electrical resistivity surveys as a reconnaissance tool for field investigations in karst areas.

8. Conclusions

In this study, we applied the electrical resistivity method to a very special case to locate a cave that was previously mapped but to which access was later lost due to sealing of the entrance. Two electrical resistivity surveys were conducted over three estimated cave passage targets. The survey results showed three high resistivity anomalies corresponding very well with the three target positions, not just in terms of location but also in depth. Although the survey results have not been confirmed by drilling, the excellent correspondence suggested the electrical resistivity method is a promising reconnaissance tool that may be used to locate shallow caves.

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