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In-Cave and Surface Geophysics to Detect a "Lost River" in the Upper Levels of the Mammoth Cave System, Kentucky

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Abstract
In early 1960, explorers accessed a significant underground river through a crawlspace beneath a ledge in Swinnerton Avenue southeast of the Duck-Under. However, later expeditions failed to find this crawlspace. Instead, the level of sediment in the passage is now generally at or above the rock ledge, leaving no openings to lower level passages other than the Duck-Under itself. Apparently recent organic material (leaves, twigs, etc.) observed in passages just below the Duck-Under may be related to open channel flow from storm events which could theoretically provide local sediment transport. Therefore we have used in-cave spontaneous potential (SP), ground penetrating radar (GPR), and acoustic profiling, as well as surface mise-a-la-masse resistivity profiling, in an attempt to locate the river itself rather than the missing crawlway. In-cave dye studies and additional geophysical profiling are needed to work out the detailed 3-D hydraulics of this region of the cave system.

Background and Purpose
At least two cave explorers recall accessing a significant underground river through a crawlway beneath a ledge in Swinnerton Avenue on the upper level of the Mammoth Cave system just southwest of the Duck-Under on January 2 and March 19, 1960 (see Figure 1). Recent expeditions to Swinnerton Avenue (in the 1980s and 2000s) failed to find this crawlway. Instead, the rock ledge in the area where the explorers recall the crawlway is at or only slightly above the level of sediment in the passage. Previous expeditions in 2007 and 2010 failed to find the crawlway, but did identify sediment transport features (ripple marks with gypsum fluff in the troughs, and gravelly rills; see Figure 2). However for sedimentation to have concealed the crawlway, it must have occurred between the 1960s and 1980s, and cosmogenic dating of sediments at the level of Swinnerton indicates that they have been underground for about 2.5 million years (Granger et al, 2001). In addition, according to records of the USGS gauging station BRKN2 just south of Mammoth Cave at Brownsville, KY, the largest flood since 1905 occurred on January 24, 1937 and raised the Green River 44.94 feet above normal pool (NOAA, 2013). This is far less than the 200 or more foot rise (Palmer 1981) necessary to backflood Swinnerton Avenue. However, the authors have observed recent organic material in passages just below Swinnerton in 2003, 2007, and 2010, as well as flowing water in a narrow (impassable) channel obliquely crossing Swinnerton north of the Duck-Under, suggesting open channel flow of infiltrating surface water. Such flow, particularly if it is intense during and/or after storm events could have moved sediments within the cave. Alternatively localized aeolian sediment transport within the upper levels of Mammoth may be indicated by a famous set of "dunes"

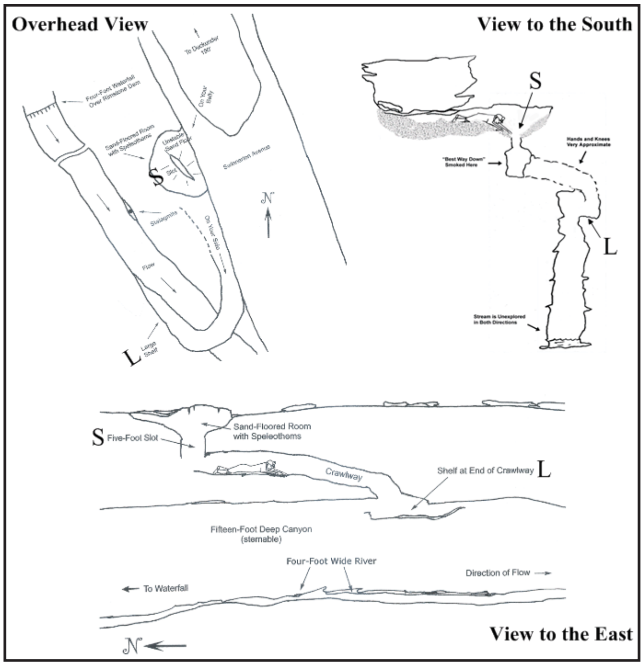

Figure 1: Eyewitness sketches of the crawlway to the "Lost River". For orientation, the slot is labeled S in each view, and the shelf or ledge is labeled L.

in Turner Avenue, and by the preferential occurrence of gypsum fluff in the troughs of ripple marks as observed in Swinnerton itself (Figure 2).

The purpose of this investigation was to determine whether there is evidence in Swinnerton of recent sediment transport that could explain the apparent disappearance of the entrance to the "Lost River". In addition, while preparing for this study, the authors became aware of the "Three Springs Conundrum" formulated by Meiman et al (2001) based on dye tracing that showed that the disappearing stream fed by Three Springs has not been found underground, and that shallow and deep flow pathways may go in different directions. The volume and direction of flow in the "Lost River" as recalled by early explorers even before formulation of the Conudrum is consistent with a likely explanation for the Conundrum – that is, the Lost River is in the right place and flowing the right direction to represent the swallowed Three Springs water. Thus, a second complementary purpose became collection of data that might indicate the path taken by water that emerges at Three Springs, and is quickly lost again into the Mammoth plumbing system.

2010 Spontaneous Potential Survey

In order to check for evidence of relatively recent water flow in Swinnerton Avenue, an expedition was undertaken in August 2010 to perform spontaneous potential (SP) measurements in Swinnerton Avenue southwestward from the Duck-Under. The SP method involves measuring the

Figure 2: Photos of aeolian phenomena from 2010; a) one of the apparent "dunes" in Turner Avenue, and b) gypsum fluff in the troughs of ripple marks in Swinnerton Avenue.

electrical potential field caused by naturally occurring DC electrical currents in the earth. Natural electrical currents occur nearly everywhere in the earth, and may be due to myriad phenomena, but in karst areas are generally dominated by the movement of subsurface water or the electrokinetic effect. This is a well-known (but little understood) phenomenon that arises wherever a pressure gradient causes fluid to flow through the capillaries of a permeable medium and evokes a charge separation in the bulk material. As a result, one can observe a decrease in the electrical potential in the direction of fluid flow, with the magnitude of the anomalous potential linearly related to the fluid flow velocity (Bechtel et al, 2007).

On the 2010 expedition, the crew used an Advanced Geosciences, Inc. Sting R-1 as a high impedance voltmeter (in SP-GRAD mode), and a pair of ceramic, non-polarizing electrodes to measure the SP gradient at ten-foot intervals along a roughly 1200 foot profile. The profile indicated a smooth gradient downwards towards a zone of negative values approximately 200 feet southwest of the Duck-Under – near the historical crawlway, with values rising smoothly beyond this to become positive again. The smooth gradient is consistent with water movement through the Swinnerton sediments towards the negative anomaly, and downward infiltration in the anomaly. However, the SP data do not reveal the age and timing (i.e. intermittent versus continuous) of this flow. On this expedition, it was observed that the May 5, 2010 Green River flood had enlarged the opening of a lengthy belly crawl in Pohl Avenue on the lowest level of the cave to allow mobilization to Swinnerton of bulkier equipment.

2011 Resistivity, GPR, and Acoustic Survey

In June of 2011 a second geophysical expedition was undertaken perform several measurements: (a) surface electrical resistivity profiling using the mise-à-la-masse technique in an attempt to determine the subsurface pathway of the water swallowed from the stream below Three Springs – that is the intention was to use electrons as a groundwater tracer that can be tracked from the ground surface; (b) in-cave ground penetrating radar (GPR) in an attempt to detect the Lost River crawlway beneath the rock ledge at the edge of Swinnerton, and (c) acoustic profiling in an attempt to listen for the flow of the Lost River where it reportedly crosses obliquely beneath Swinnerton.

For the resistivity survey, an attempt was made to make the Lost River behave as an electrical line charge (a variation on the mise-à-la-masse method; Telford et al, 1990). One current electrode was placed in the Three Springs stream, while the other was driven into the ground in the woods nearly a mile to the northeast. The R-1 was used in Resistance mode to drive a 400 Volt, 100 milliAmp current between these two, while measuring the voltage between two potential electrodes at a fixed separation of twenty feet. Each measurement was repeated in reversing polarity cycles until the cumulative error was less than three percent. Sequential measurements along three NW-SE profiles (roughly perpendicular to the presumed Lost River) covered distances of 800 to 1300 feet. The predicted electrical anomaly for this type of gradient measurement across a line charge is shown in Figure 3a. Note that the anomaly width is related to the depth of the line charge. Figure 3b shows the field data for the three profiles convolved with model anomaly profiles for line charge depths of 10, 20, 40, 80, 160, and 320 feet. The greatest correlation values are for a depth of 20 feet, followed by 10 and 40 feet, with low and decreasing values for 80, 160, and 320 feet. This indicates that the impressed current is probably flowing at a depth of about 20 feet – well above Swinnerton Avenue, and in fact probably within the epikarstic Haney

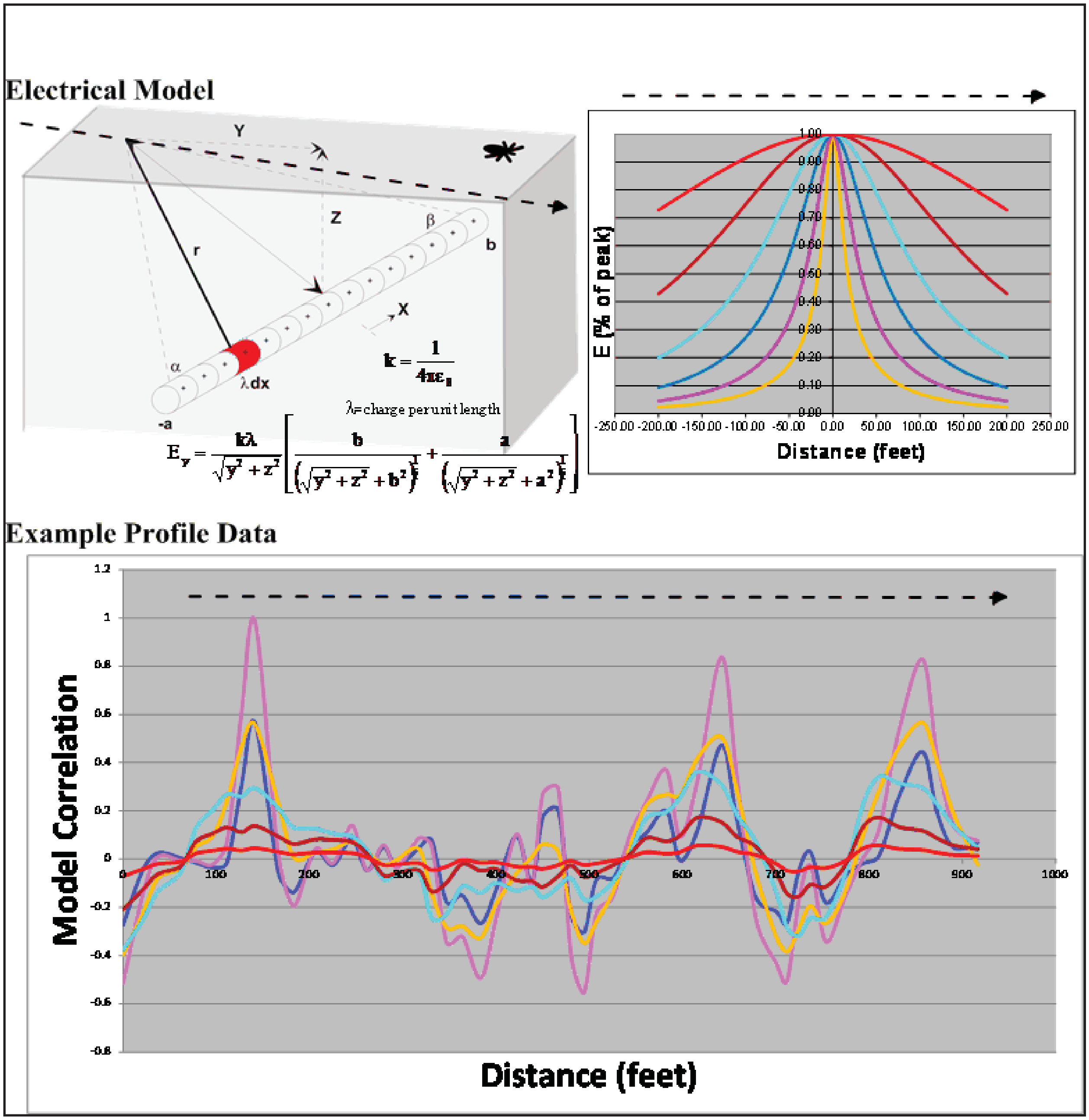

Figure 3: Mise-a-la-masse electrical surveying to detect subsurface flow related to Three Springs. Top; sketch and model data for different depth line charges (fluid flow conduits). Note how the anomaly width changes with flow depth. Bottom; data from one of the recorded profiles. The single profile of field data has been correlated with a sliding shape-matching filter to estimate the depth of current flow. Depths are gold-10, magenta-20, blue-40, cyan-80, brown-160, and red-320 (feet). Peak correlations for the magenta profile indicate dominant electrical flow at approximately 20 feet below ground. Dashed black arrows show the orientation of the profile relative to presumed line charges.

Limestone above the Big Clifty Sandstone that forms the caprock for the Mammoth Cave System. Thus, the electrical survey appears to be primarily tracking the water flowing towards Three Springs. There may be some signal from electrons flowing in the swallowed water downstream of the springs (which was the intended target), but the signal from the much shallower flow in the epikarst dominates. This highlights an important difference between using chemical or microsphere tracers (Benischke et al, 2007) versus electrons as groundwater tracers; electrons can flow upstream!

The in-cave GPR scanning was performed along the west ledge of Swinnerton using a GSSI SIR-2000 controller and a 400 MHz transducer. A prove-out scan across the Duck-Under produced a distinct reflection pattern (Figure 4). Since the Duck-Under is an air-filled passage, and the Lost River Crawlway may be partially sediment filled, a reflection set as remarkable as that in Figure 4a was not expected. Along the 1200 feet of GPR profile, numerous other reflections were detected (Figure 4b and 4c), but all of them were associated with recognizable (not hidden) features, and were too small to represent the lost crawlway.

Acoustic monitoring of the floor of Swinnerton was performed at five foot intervals using a Flow Metrix DLD detector. Relative noise levels were uniformly low along the survey area extending southwestward from the Duck-Under, but rose steadily eastward from the Duck-Under towards the visible stream that obliquely crosses Swinnerton. No flow sounds from beneath the floor of Swinnerton in the area of the suspected Lost River were detected.

While the in-cave geophysical surveys did not produce data to reveal the location and fate of the lost crawlway, the action of collecting the data forced a very thorough and careful inspection of the west ledge of Swinnerton. This inspection revealed four tin cans with flaking paper labels hidden in a crevice at floor level (Figure 5). The labels were sufficiently intact to recognize the cans as Banquet canned chicken and Diet Delight fruit cocktail. Contact with vintage advertising and food label collectors revealed that the Banquet cans date from no later than c. 1964, and the particular Diet Delight logo was used from c. 1951 to 1962. Since the labels are still partially intact, and light and fragile label flakes still lie in the bottom of the crevice (Figure 5), this garbological dating (Rathje and Murphy, 2001) indicates that there cannot have been significant sediment movement in this area of Swinnerton since c. 1964. Thus, any large scale sediment transport to conceal the entrance would need to have taken place between March 19, 1960 and sometime around 1964. Note that the persistence of the label flakes in the protected crevice does not preclude the aeolian (?) movement of light gypsum fluff, but transport of large enough volumes of sediment to bury a crawlway is not likely after c. 1964.

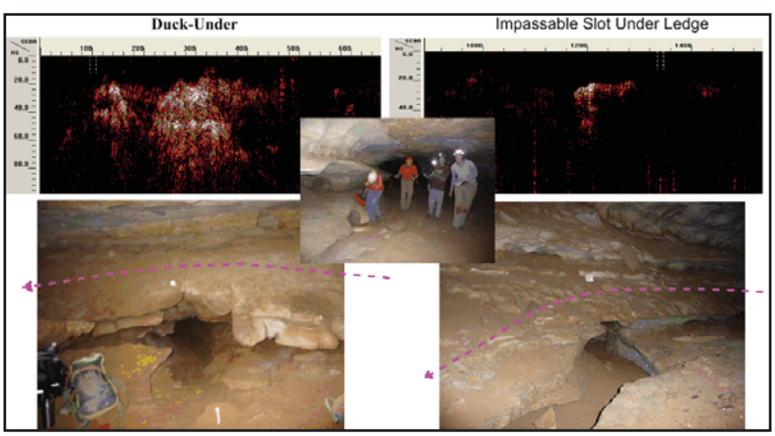

Figure 4: Example GPR profiles and their locations (dashed lines). Inset shows scanning of the ledge in progress.

Conclusions

The results of this study indicate the following:

- Swinnerton Avenue lies at a level far above the highest historic backflooding levels.
- However, there is recent evidence of open channel flow of infiltrating water at the level of Swinnerton.
- The occurrence of gypsum fluff in the troughs of ripple marks in Swinnerton suggests aeolian movement of these light particles.
- Measured spontaneous potentials indicate that there has been movement of water within the sediments of Swinnerton Avenue, but the age of this flow cannot be determined.
- Electrical illumination of the water draining Three Springs (by the mise-à -la-masse resistivity method) revealed the flow paths of water draining towards the springs above the Big Clifty sandstone caprock. Swallowed water flowing in the Mammoth plumbing system (perhaps the Lost River?) was almost certainly illuminated as well, but the epikarstic flow close to the ground surface measurement locations dominates the recorded signal.
- GPR scanning of the west ledge in Swinnerton easily detected the known Duck-Under, and numerous smaller (impassable) side openings, but nothing large enough to represent a hidden crawlway.
- Acoustic monitoring led to a visible stream crossing Swinnerton northeast of the Duck-Under, but did not detect any distinct flow sounds from beneath the floor west of the Duck-Under.
- Discovery of food tins, dateable by their distinctive labels to the 1950s or early 1960s, and the persistence of label flakes on the floor of Swinnerton precludes large scale sediment transport after c. 1964.

Figure 5: Cans left by early explorers found in a crevice along Swinnerton Avenue. The date ranges of the flaking but recognizable labels indicate that they are undisturbed since c. 1964.

Eyewitness accounts of the Lost River are now over fifty years old, but were transcribed at the time in sufficient detail to strongly suggest its existence. In addition, the documented hydrogeology of the Three Springs-Swinnerton (three-dimensional) region nearly requires its existence. Further work to find the presumed river and explain the Three Springs Conundrum could include:

- Dye injection at Three Springs with monitoring at in-cave locations. This would identify connections to known flows, but not detection of the lost river.
- Another Mise-à-la-masse illumination of the Three Spring plumbing, but with potential measurements carried out in the cave – presumably closer to the plumbing system flow from the springs than to the epikarstic flow feeding the springs. This would

require independent decoupled current transmitter and voltage receiver since one will be at the surface and the other in the cave.

- In-cave gravity profiling using a compact meter (e.g. LaCoste & Romberg Model D Aliod) to detect potential passages beneath Swinnerton. Although gravity readings are omnidirectional (i.e. not discriminating between mass anomalies above or below the meter), since Swinnerton lies on the uppermost level of the Mammoth System, apparent gravity lows should be more likely to represent cavities beneath the floor than mass excesses overhead (and mass excesses are not expected geologically in this setting).

Finally, the evidence of aeolian sediment transport suggests that long-term monitoring of air movement in the cave (to detect possible short duration-high intensity events) using battery-powered, data logging anemometers might yield interesting data.

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