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Quasi 3-Dimensional Electrical Resistivity Mapping of Air-filled Karst Conduits and Policy Implications

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Quasi 3-Dimensional Electrical Resistivity Mapping of Air-filled Karst Conduits and Policy Implications

by

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A thesis submitted in partial fulfillment of the requirements for the degree of: Master of Science
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College of Arts and Sciences
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Dedication

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Abstract

This study assesses the capability and practical applications of quasi 3-Dimensional (3D) electrical resistivity surveying (ER) for mapping air-filled karst conduits. Vadose zone caves within the Brooksville Ridge of West Central Florida are relatively similar in architecture, with N-S elongation, and do not consist of an interconnected network of conduits. A high resolution quasi-3D ER survey was performed over two mapped cave systems on the Brooksville Ridge. The resultant survey verified the general effectiveness of quasi-3D ER in locating the two known near-surface cave features. Several other locations in the survey show similar or stronger resistivity anomalies trending in a N-S direction; these are interpreted to represent previously unknown voids. The quality of inversion results were tested by comparing results against the known void locations and by computing cross-over errors from surveys conducted at the same point with different orientations. Our results show that 3D inversions of multiple adjacent parallel profiles produces higher quality results (lower cross-over errors, better fit to cave locations) than 2D inversions. The data indicate that no single value of resistivity can be used as a reliable indicator of the presence of a void, presumably due to variable void size and the complexity in resistivities in the host rock. With sinkholes continuing to be of concern to residential and urban development in West Central Florida, the results of this research show the
necessity of applying geophysical techniques in order to reduce the potential hazards posed by karst terrain.
Chapter 1:

Introduction

Living on karst terrain brings with it a host of geologic, hydrologic, and environmental hazards. These hazards are commonly brought to our attention by media coverage of a collapsed roadway, the formation of a surface depression, or by the appearance of settlement cracks in a nearby structure(s). Nevertheless, development on karst landscapes continues with little or no knowledge about the hazards below the surface. Previous studies have shown that not adequately considering the geologic and hydrologic nature of karst terrain increases the long-term economic cost and environmental hazards for future residents (Newton, 1987; White, 1988; Brinkmann et al., 2008).

A compelling reminder of this issue occurred in April of 2004, when a section of the Lee Roy Selmon Expressway in Tampa, Florida, collapsed during construction. The collapse was caused by a sinkhole which formed beneath a support column, which added an estimated $99 million dollars to the overall cost of the project (TBT, 2004). Additional concerns were raised regarding inadequate testing, suggesting that a more detailed investigation of the subsurface may have identified the karst hazard prior to construction. This underscores the need to accurately map and
characterize karst terrain, particularly in areas prone to sinkhole activity. Karst sensitive areas have become increasingly developed and in many cases urban land now exist which has significantly altered and re-contoured the natural land surface. This alteration of the land surface can have dire consequences and increases the potential for future karst hazards (Newton, 1987; Sowers, 1996, Zhou and Beck, 2011).

Karst terrain can be very complex and change abruptly over a relatively short distance. The heterogeneity of karst terrain makes the use of high resolution geophysical surveys most appropriate for detailed subsurface imaging. The purpose of this research is to use quasi 3D Electrical Resistivity to map air-filled karst conduits, assess the strengths and limitations of this method, and assess the policy implications of using geophysical studies as a karst management tool.
Chapter 2:
Previous Studies

A wide range of geophysical methods can be applied for cavity detection; however, the most appropriate method should be determined based on the target depth, soil conditions, and site characteristics (e.g., topography and urban effects). Prior studies show that joint interpretation of two or more methods may help to solve resolve ambiguities not easily determined with a one method approach (Doll et al., 1998; Sumanovac and Weisser, 2001; El-Qady et al., 2005; Kruse et al., 2006; Xia and Miller, 2007; Cardarelli et al., 2010;). Electrical Resistivity (ER), MicroGravity (MG), and Seismic Refraction Tomography (SRT) have shown the most significant promise in accurately detecting subsurface cavities; however, Ground Penetrating Radar, Electromagnetics, and Magnetics may also be an appropriate method in the right geologic setting (Kirk, 1981).

Micro-Gravity has been well documented as a highly effective method for detecting subsurface voids and cavities (Kirk, 1981; Dahm et al., 2010; Orfanos and Apostolopoulos, 2011), however this method is less frequently used. This is most likely due to the cost of the equipment and because Micro-Gravity is affected by instrumental drift, tidal effects and ocean loading, topography, latitude, altitude, seismic noise, and slopes. Meaningful Micro-Gravity data for karst terrain is largely dependent on closely spaced data measurements with
elevation data sufficiently accurate that Bouguer corrections are smaller than the void gravity signal. This elevation accuracy may be expensive to obtain where the subsurface geology is not homogeneous and the density contrast is relatively small. As previous studies suggest, inaccurate data correction from tidal effects, topography, and nearby building structures most significantly impact the accuracy and interpretation of Micro-Gravity investigations (Debeglia and Dupont, 2002; USDOT, 2010).

Seismic methods (i.e., seismic refraction, seismic reflection, and multi-analysis shear wave) are most often used for top of rock studies and provide a wide range of surveying strategies with the deepest effective depth of investigation for near-surface geophysical surveying. Seismic surveys tend to be the most time consuming and the most costly of the geophysical methods to deploy. However, refraction studies have shown to be an effective method for determining lateral variations in the shear-wave field and to a lesser extent the compressional-wave field (Castagna et al., 1985; Dobecki and Upchurch, 2010). Variations in the shear-wave velocity are indicative of soil and rock density/strength. The variation in the velocity of materials is a useful tool for identifying suspected ravel zones within the near-surface soils and for detecting possible weak zones at the bedrock surface. Although, seismic refraction tomography (SRT), using both P-waves and S-waves, has been used to detect sinkholes (Castagna et al., 1985; Dobecki and Upchurch, 2010; Carrozzo et al., 2008) SRT studies for void detection have had mixed results (Sheehan et al., 2005a; Sheehan et al., 2005b). Alternatively, potential successes have been
noted using MASW for sinkhole (Park and Taylor, 2010) and for void detection (Xu and Butt, 2006).

Electrical Resistivity (ER) is one of the oldest geophysical methods and its success for mapping sinkholes and voids in karst terrain has been well documented (Doll et al., 1998; Schoor, 2002; Gibson et al., 2004; and Gambetta et al., 2011). ER surveys in the vadose zone are capable of measuring the resistivity contrast between the host bedrock material and the “infinitely resistive” void space within. More recently, Electrical Resistivity Tomography (ERT) using multi-electrode array systems has significantly decreased the survey time and increased the amount of data points that can be collected. This approach has led to the more frequent use of two-dimensional (2D) and now three-dimensional (3D) ERT studies. True 3D ERT surveys are impractical for deep geologic characterization as the number of measurements needed are costly in time to acquire and process. Consequently, most 3D resistivity surveys are quasi 3D surveys with orthogonal line sets (Papadopoulos et al., 2006; Rucker et al., 2009; Neyamadpour et al., 2010).

Electrical Resistivity involves applying an electrical (DC) current into the ground and measuring the potential difference in volts that arises from the current flow in the ground. The movement of charged particles over a given unit of time is the current \( i \), which is measured in amperes, and is proportional to the voltage \( v \). Ohm’s Law states that current is proportional to voltage \( v \) and inversely proportional to resistance \( r \).

\[ v = i \times r \]
Resistance (\(r\)) to current flow is based on the material and the dimensions through which the current is being passed. In geophysics one is interested in the material property resistivity (\(\rho\)), which can be related to the total resistance to current flow by the expression:

\[ \rho = r \frac{a}{l} \]

where \(a\) is the cross-sectional area of current flow, and \(l\) is the length of the current flow path. Resistivity has units of (ohm-m (\(\Omega\)m)). Because the current flows through a finite area of ground, the measured voltage reflects an “apparent” resistivity value (\(\rho\)) which is a “weighted average” of the bulk volume of material being measured.

Factors which affect the resistivity values of a material include: soil type, water content, pore space, and the pore fluids of the subsurface material. Van Nostrand and Cook (1966) noted that for homogeneous ground approximately 70 percent of the current flow is above the horizontal plane equal to the electrode spacing. Thus to drive significant current to greater depths requires that a larger electrode separation be used.

For this study, the Dipole-Dipole and Inverse Schlumberger arrays were used to measure the resistivity of the subsurface materials at the site. Both array configurations have been successfully used in previous investigations to map subsurface cavities and have their own distinct advantages. Previous studies have specifically noted the benefits of the Dipole-Dipole array (for horizontal profiling) and Schlumberger array (for deeper vertical sounding) (Ward, 1995; Chambers et al., 2006; Neyamadpour et al., 2010).
The Dipole-Dipole array (Figure 1) geometry allows for greater lateral resolution of horizontal contacts (Ward, 1995). In the Dipole-Dipole array, a pair of closely spaced current electrodes are placed one scaling factor \((n)\) apart from a pair of closely spaced potential electrodes as measurements are made. This method sacrifices depth for increased resolution of horizontal layers as more densely spaced measurements are made in the near-surface.

(Figure 1) Dipole-Dipole Array Diagram

The Inverse Schlumberger array (Figure 2) is a sounding method that is less susceptible to telluric (natural) or cultural (unnatural) interference (Ward, 1995). This method provides for a relatively shorter cable length for a slightly deeper depth of investigation with less distinct lateral resolution in the near-surface. The result is a method more sensitive to depth, less sensitive to horizontally layered structures, with a high signal to noise ratio. In the Inverse Schlumberger array, the current electrodes are moved in laterally one scaling factor from the potential electrodes as measurements are made.
(Figure 2) Inverse Schlumberger Array Diagram
Chapter 3:

Study Rationale

In 2002, the importance of karst land use regulation became the topic of much debate in Hernando County, Florida. A dispute arose regarding the environmental impact that a proposed residential development, which included 1680 residential homes and a golf course, would have on a recently discovered cave system located directly beneath the development site. The cave was named the Brooksville Ridge Cave and is to date, the largest, most pristine cave in the state of Florida with very unique cave formations (Fleury, 2009). Caves of this type are rare and most prone to environmental impacts from groundwater withdrawal, surface pollutants, and vandalism. Ultimately, the dispute contributed to the halt of the development project.

Hernando County’s Ordinance 94-8 governs land use by protecting and maintaining groundwater quality. This is implemented by “providing criteria for land uses and the citing of facilities which use, handle, produce, store or dispose of Regulated Substances; and by providing protection to vulnerable features which discharge directly to the Floridan aquifer” (Hernando County Ordinance 94-8). Wellhead Protection Areas (WHPA’s) and Special Protected Areas (SPA’s) are used to define and protect the borders of karst landforms such as sinkholes and caves that may discharge directly into the aquifer. WHPA’s and
SPA’s in sensitive locations restrict or prohibit dumping, certain agricultural activities, and criteria for residential and golf course development. Under such ordinances, the county can require landowners to submit to an inspection and examination of their property (Fleury, 2009).

In the case of the Brooksville Ridge Cave, the county ruled in 2005 for development to proceed, a hydrologic evaluation at and around the proposed project site was required. The new requirements included buffer zones, cave maps, and data from test borings in order to describe and identify all subsurface features and their hydrologic significance to the Brooksville Ridge Cave (Fleury, 2009). To date, development over the Brooksville Ridge Cave system has not occurred; however, questions about karst land use regulations and the need for enforcement continue. Fleury (2009) stated that accurate scientific data was needed to aid in necessary in understanding Florida’s karst and to evaluate the protection of sensitive karst areas such as the Brooksville Ridge Cave.

This study seeks to address the issue of producing accurate scientific data to enable the identification of karst conduits in the vadose zone by applying high resolution quasi-3D ERT mapping. The hypothesis of this project is that quasi-3D ERT can be used to accurately identify the location of air-filled cave systems. The results this research should help assess the effectiveness of this type of geophysical analysis as a karst management tool.
Chapter 4:

Study Area

The study area is located on the Brooksville Ridge of West Central Florida. The ridge is an upland area of West Central Florida which is comprised of several air-filled caves (Florea, 2006, Harley, 2007, Pace-Graczyk, 2007, and Polk, 2009). The larger southern portion of the Brooksville Ridge, where the study area is located, is approximately 110 miles in length and varies from 10 to 60 miles in width. The ridge trends in a NW to SE direction and is parallel to the western edge of Florida’s coastline. The elevation of the Brooksville Ridge ranges from 20 to 60 meters with irregular areas of limestone outcrops (White, 1970). The study area’s elevation is approximately 25 meters above sea level (Figure 3).
(Figure 3) Regional view of the study area located on the Brooksville Ridge of West Central Florida at an elevation of approximately 25 meters above sea level.
The site contains two well-documented phreatic cave features, Legend Cave (Figure 4) and Bottlecap Cave (Figure 5), which are located within the Withlacoochee State Forest of Citrus County Florida. The cave entrances are approximately 100 meters apart and are separated by a limestone quarry located at the southeast corner of the study area. The limestone quarry shows signs of previous activity as scarification marks from heavy machinery are present on the exposed limestone surface. The abandoned limestone quarry is a topographic low approximately 20 meters in diameter with a vertical relief ranging from approximately 3 to 7 meters around the perimeter of the quarry (Figure 6). The limestone quarry has a water table that is perched for most of the year which is underlain by organic material situated on siliceous Suwannee Limestone. The surficial groundwater table for this area is below a depth of 16 meters.

**Legend Cave**

The entrance to Legend Cave is located at the southeast corner of the quarry and extends northward along the eastern boundary of the quarry pit. Legend Cave was first identified on historical maps, but until recently; its orientation and cave length was still uncertain. Recent mapping of the cave identified a cave depth ranging from approximately 3 to 9 meters below grade, extending approximately 41 meters in length in a north-south direction. Legend Cave is marked by considerable breakdown from roof collapse and infilling of sediments on the cave floor. Large volumes of sediments and boulders from debris flows are readily visible throughout the cave. Three large rooms are located within Legend Cave which are separated by smaller passages which
open up into each of the rooms. In the far northernmost room, Legend Cave ends abruptly by breakdown from ceiling collapse.

(Figure 4) A map of Legend Cave located on the eastern edge of the limestone quarry.
Bottlecap Cave

Bottlecap Cave is located NNW of Legend Cave and is oriented in a NE-SW direction. Bottlecap Cave is characterized by a very tight system of flattened passages which trends to the southwest at a depth of approximately 5.5 to 8.5 meters below grade. An isolated vertical cavity extending to a depth of approximately 16 meters is located in the central portion of the cave. Bottlecap Cave has a total linear cave length of approximately 43 meters and has a very complex cave structure.

(Figure 5) A map of Bottlecap Cave which dips from the northeast to southwest.
(Figure 6) Aerial view of the study area and cave locations.
Soil Survey

The *Soil Survey of Citrus County, Florida*, (1988), prepared by the U.S. Department of Agriculture, Soil Conservation Service, was used to determine the shallow soil types present at the study area. The soils for the study area are classified as Broward fine sand, which is part of the Arrendondo-Kendrick Sparr association.

The Arrendondo-Kendrick-Sparr association is described as nearly level to moderately sloping, well drained and poorly drained soils that are underlain by loamy material. The landscape consists of rolling hillsides and narrow ridges on the upland area of Lecanto, Florida. The slope ranges from 0 to 12 percent with sandy soils from a depth of .5 to more than 1 meter below grade. Sinkholes are described as common and provide most of the drainage outlets for the soils in this map unit.

The Broward fine sand is described as sandy marine deposits located over lithic bedrock. These soils can be found on broad flatwoods and rises on marine terraces. The typical soil profile consists of fine sand in the upper 1 meter of soil overlying unweathered limestone bedrock. In some areas, scattered boulders and rocks are at or near the surface with rock outcrops.

Regional Geology

The central portion of the Brooksville Ridge where the study area is located is covered by Miocene aged (5 to 23 Ma) siliclastic material which overlies exposed sections of Suwannee and Ocala Limestone. The siliclastic sediments consist of sands and clays of the Hawthorn Group. The Hawthorn
Group forms the upper confining unit to the Floridian aquifer system (Scott, 1989). Changes in sea level have resulted in the formation of several air-filled caves along the Brooksville Ridge. The paleokarst features located on the Brooksville Ridge reveals a time of intense karstification during the late Oligocene exposure (Florea, 2006).

**Suwannee Limestone**

The Suwannee Limestone can be fossiliferous, is of marine origin and is typically white to cream in color. The Suwannee Limestone formed during the Lower Oligocene (30 to 35 mya) time period and overlies the Ocala Platform forming part of the intermediate confining unit of the Florida aquifer system (FGS, 2006). Portions of the Suwannee Limestone consists of dolostone to dolomitic limestone and is described as highly weathered and fractured. Highly silicified limestone is common in Suwannee Limestone, where the calcium carbonate has precipitated out of the limestone to form chert. The Suwannee Limestone consists of vuggy to moldic limestone which contains fossilized mollusks, foraminifers, corals and echinoids. Due to a change in sea level, the Suwannee Limestone is exposed in the central portions of the Brooksville Ridge where eroded siliclastic sediments are thin to missing (Scott, 1997; Brinkmann and Reeder, 1994). Areas where the Suwannee Limestone has been eroded away the Ocala Limestone can be found exposed at the surface.

**Ocala Limestone**

Limestone exposures at or near the surface on the Brooksville Ridge are generally characterized as Ocala Limestone. The Ocala Limestone is a soft and
highly porous limestone that can be hard due to the cementation of particles by crystalline calcite (FGS, 2006). The Ocala Limestone formed during the Upper Eocene (35 to 40 mya) time period and underlies most of Florida. The limestone is generally white to cream in color and is composed almost entirely of calcium carbonate. Fossils consisting of foraminifers, echinoids, bryozoans and mollusks are abundant within the Ocala limestone as well as silicified limestone (chert). The Ocala Limestone is exposed in only a few places, most of which are in west-central Florida on the Brooksville Ridge. Numerous disappearing streams and springs have been identified within the same region as Ocala limestone. The Ocala limestone is characterized as highly permeable limestone, which has undergone extensive karstification, and can exhibit several feet of topographic change.

**Phreatic Caves**

Most of the cave features along the Brooksville Ridge are phreatic formed cavities which developed during times of higher sea level. Many of these phreatic cave features are characterized by a distinctive “keyhole” or diamond shape appearance which formed as a result of high and low gradient groundwater flow (Photo 1). Present day sea level is now approximately 30 to 45 meters lower than the Upper Eocene time period (Lane, 1994), in which case; several phreatic formed caves are now located within the vadose zone of the Brooksville Ridge and can serve as direct conduits to the Floridian Aquifier below. Consequently, this geomorphic setting makes the region’s groundwater
particularly susceptible to surface pollutants discharging directly into the aquifer (Florea, 2006; Fleury, 2009).

A strong correlation between Florida cave levels and marine terraces have been reported suggesting a tiered system of subaerial caves on the Brooksville Ridge (Florea et al., 2007). The direction of the cave passages within the ridge are generally along a NE to SW and NW to SE system of fractures. Changes in sea level have significantly influenced the topography and the formation of caves in the state of Florida as indicated by the Marine Terraces and Shoreline of Florida Map (Healy, 1975). The two caves imaged in this study are located between the Wicomico and Penholoway terrace. The contact between the
Wicomico and Penholoway terrace is at an elevation of approximately 21 meters which corresponds with the elevation of the study area (Figure 8). Many of the cave passages on the Brooksville have been reported as similar in architecture and characterized by laterally extensive air-filled cavities with bedrock pillars, dissolution features, and cavities which often terminate in blind pockets (Florea, 2006).
(Figure 7) A map recreated from the Marine Terraces and Shorelines of Florida (Healy, 1975).
Chapter 5: 
Methods

The quasi-3D ERT method is a practical ER approach for high resolution 3D subsurface imaging. This survey was performed by integrating a series of closely spaced parallel 2D ERT transects across the survey area. Each parallel transect was kept in close proximity in order to limit the amount of interpolation performed during the modeling process. For this survey, each parallel transect was separated by a distance equal to 2 times the electrode or “a spacing”. A close series of parallel transects may not always be attainable given time, costs and site conditions, however; closely aligned parallel transects should be the goal for any high resolution quasi 3D ERT survey.

Field Survey

Total Station measurements were recorded at the study area to identify the exact boundary of the survey area and mark the location of the ERT transects with respect to existing land features. This was performed by establishing a base station at the highest point of our survey area where the entire site could be observed. Existing land features such as the fence line, perimeter of the limestone quarry pit, and cave entrances were then recorded. The existing fence line was used as our base line from which all of the ERT transects were established and the survey boundaries recorded with the Total
The Total Station measurements helped control the accuracy of the ERT transects and survey maps from which this study was based. Each of the ERT transects were then laid out using a fiberglass tape measure which connected each of the established end points. Additional GPS data points were collected at the boundary of the site for increased ground control and to identify the location from which aerial photos and Lidar data were extracted. The Total Station data was collected using the Nikon DTM 350 survey meter with an accuracy of ± 5 millimeters.

**Topographic Survey**

A topographic map was created from Lidar data collected over Citrus County, Florida, by the Southwest Florida Water Management District (SWFWMD, 2006). Topographic data were extracted over the study area, and a digital elevation model was created in order to map the variability in elevation and perform terrain correction for the ER survey (Figure 8). The topography of the site was characterized by approximately 9 meters of elevation change across the study area (USGS, 1988). The Citrus County Lidar data has a resolution of approximately 0.3 meters (SWFWMD, 2006).
Accurate maps are an important aspect of a cave survey. In order to determine the accuracy of cave maps, a grading system for speleological mapping is typically used. The UIS Information Commission has in place a grading system to describe the method and expected accuracy of a cave map (Häuselmann, 2010).

Each of the caves imaged in this study were mapped at a Grade 5 level survey. Grade 5 level maps include the use of a tape measure, compass and clinometer readings. Each of the survey stations were measured in both directions, the loop closed and adjusted in the field. The precision length is
expected to be within 0.05 meters, and the compass and clinometer readings are expected to be within 1 degree of accuracy. Based on the UIS mapping grades, the cave maps for both Legend and Bottlecap Cave are of “UISv1 5-4-B” survey grade with an expected overall accuracy of 2 percent (Häuselmann, 2010).

**Quasi 3-Dimensional Electrical Resistivity Survey**

**Data Acquisition**

The ER equipment used for this study consisted of a DC power source, a SuperSting R8 Memory Earth Resistivity Meter, stainless steel metal stakes, a passive cable, and a switch box with 56 electrode capability. The equipment used for this project was manufactured by Advanced Geosciences, Inc. (AGI), of Austin, Texas, and was designed for shallow environmental, geo-technical, and engineering applications.

A 2D forward model was also performed in order to simulate the suspected ER results and determine the optimum transect line layout prior to surveying (Figure 9). Based on the suspected cave depths and the forward model results, a linear array of 56 electrodes were selected, with an electrode spacing of 2 meters. The ER transects were collected using the Dipole-Dipole and Inverse Schlumberger array. Each parallel 2D transect was collected in succession and spaced 4 meters apart (2 times the a-spacing) (Photo 2). This was performed across the survey area which consisted of a total of twenty-nine (29) ER transects. Twenty-two (22) parallel transects were performed from west to east which trended from the south of Legend Cave to the north of Bottlecap Cave. Seven (7) additional transects were performed in a south to north...
direction over the long axis to both Bottlecap and Legend Cave (Figure 10). The south to north transects were performed to better resolve ambiguities not readily determined by the west to east transect lines. The direction and path of the transect lines were selected to optimize coverage over the two known cave systems and limit the effects of topography and existing land features (e.g. fence, road, and the limestone quarry).

(Figure 9) A 2D ER forward model of a suspected void feature to determine the optimal transect layout.

The quasi 3D ERT survey consisted of twenty-nine (29) 2D ER transects performed across the study area. The ER transects ranged from 88 to 110 meters in line length and surveyed an area of approximately 84 meters from south to north. Based on a site reconnaissance and existing cave maps, it was estimated that the two cave entrances were located approximately 100 meters
apart and generally extend horizontally at a depth of approximately 2 to 9 meters below land surface (Harley, 2007; Polk, 2010).

(Photo 2) A view of the parallel 2D ERT transects trending from west to east and conducted in succession from the south to the north portion of the survey area.

The total survey time took approximately 9 field days to perform. Given the line length and electrode spacing, a one man crew was capable of completing 3 to 4 lines per day and a two man crew was capable of completing 4 to 5 lines per day. The largest obstruction to this type of survey method is open access. Surface features such as roads, building structures, and underground utilities are the largest impediment to this type of survey.
A view of the survey area with twenty-two (22) ER transects performed in a west to east direction which trended from the south of Legend Cave to the north of Bottlecap Cave. Additionally, seven (7) orthogonal ER transects were performed over the approximate centerline of Bottlecap and Legend Cave.

**Data Processing**

Measurements for each of the 2D ERT transect lines were collected using the Dipole-Dipole and Inverse Schlumberger arrays. The data collected from both arrays were combined, modeled, and terrain corrected, using *EarthImager* software 2D version 2.4.0 and *EarthImager* 3D version 1.5.4 (32-bit).

The 2D raw data processing involved inverting the measured apparent resistivity values for a best-fitting resistivity structure. Before the inversion, data points which fell outside the expected range of resistivity values were removed. This was performed by reviewing the convergence curve and selecting the
proper number of iterations not to exceed a root mean square (RMS) error of 10 percent. The data misfit histogram was then reviewed, and the data points which were poorly fit were selected for removal. The resistivity cross-plot was then assessed, and the process continued until the measured versus predicted data points fell along the expected range of apparent resistivity values determined by the software. In the inversion process, various fit criteria can be specified. Fits can optimize for a combination of smoothness in the model and minimization of errors (misfit between data and models). In this study the inversion sought the solution that best fit the observations in a least squares sense. In EarthImager, a Smoothness constrained algorithm was chosen. Various studies have showed mixed result regarding the Robust versus Smoothness inversion method for cavity detection (Gharibi, 2005; Papadopoulos et al., 2006; Neyamadpour et al., 2009; and Neyamadpour et al., 2010). Such results suggest that the most effective inversion model may be site specific, in either case; both inversion methods have shown success in modeling subsurface cavities. The inversions were also constrained so that resistivity values could not exceed 10,000 Ohm-m in the model.

The 2D data modeling was performed by processing each of the Dipole-Dipole and Inverse Schlumberger arrays separately. The 2D results were then merged into a 3D dataset existing of X, Y, and Z coordinates to create a 3D block model. In the 2D modeling process, no data from neighboring lines is incorporated into the inversion process, and the model assumes that structures are 2 dimensional perpendicular to the strike of the survey.
For more accurate results, 3D data inversion is desirable. However, due to computer memory limitations, only the combined results of six (6) 2D transects could be processed together at one time. This approach was carried out by modeling the data in subsections with 2 overlapping transect lines for each 3D block models (Figure 11). Each of the 3D models were processed and the number of iterations determined based on the conversion curve (root mean square error versus the iteration number).

![Diagram showing the 7 models](image)

**Figure 11** A diagram showing the 7 models which were individually processed, terrain corrected, and imported into a larger 3D data set.

The 3D modeling consisted of seven 3D block models which were then terrain corrected using the Lidar topographic data. The 3D ER results were then contoured and saved in an XYZ data format. Data from each of the 3D models
were then combined into a master 3D data set and terrain corrected using Matlab. The terrain corrected 3D data file was then imported into Voxler 3D to provide a 3D visual site model of the subsurface.

**Data Validation**

Results from the resistivity survey were compared with information obtained from the Soil Survey, our knowledge of the geologic conditions at the site, and from the existing cave maps (Polk, 2010 and Polk, 2012). Additionally, cross-over points from the intersecting ERT transects were compared for further analysis of the ERT data. A flow chart of the research methodology is provided below (Figure 12).
(Figure 12) Flow chart outlining the research methodology.
Chapter 6:

Results

Comparison of the Dipole-Dipole and Inverse Schlumberger Array

An initial assessment of the resistivity data was performed to determine the most effective array type and modeling strategy. Both the Dipole-Dipole and Inverse Schlumberger array were modeled and analyzed using the 2D inversion method. The 2D inversions were performed on transect line T-28 which was located along the long axis of Legend cave. The findings from this comparative analysis were used to determine the most effective array to use in the 3D model.

An assessment of the resistivity response indicated a wide range of resistivity values across the study area. This was most likely related to the natural variability within the limestone bedrock and the orientation of the ER transects over the cave features. After several modeling attempts and a review of the ER response overlying the known cave features, a contour interval ranging from 20 to 2,500 $\Omega$m was determined to be the most effective resistivity range for assessing the ERT data. An assessment of the 2D Dipole-Dipole versus the Inverse Schlumberger array was performed to determine the most effective data collection method and 3D modeling strategy.
2D Inversions of the Dipole-Dipole and Inverse Schlumberger Array

Dipole-Dipole Array (Transect 28 Facing West)

(Figure 13) A profile view of Legend Cave using the Dipole-Dipole array, note the discontinuity at 44 meters in the large north room where Legend Cave is truncated by roof collapse.

Inverse-Schlumberger Array (Transect 28 Facing West)

(Figure 14) A profile view of Legend Cave using the Inverse-Schlumberger array, note the elongated void feature with no apparent cave entrance.
A review of the Dipole-Dipole and Inverse Schlumberger array types indicated a distinct advantage of the Dipole-Dipole over the Inverse Schlumberger array. One likely reason is that the Dipole-Dipole array most accurately defines horizontal layers with an increased amount of data points in the near-surface. Additionally, the cave features themselves are relatively horizontal features within the bedrock. Although both array types were capable of identifying Legend Cave, the true geometry and structure of Legend Cave was least defined by the Inverse Schlumberger array (Figure 14).

This was most evident by the lack of response near the cave’s entrance and the elongated ER response indicated by the Inverse Schlumberger array. This was most likely related to the Inverse Schlumberger array’s vertical
sounding approach which sacrifices data points in the near-surface for data
points at depth. In which case, the Inverse Schlumberger array had a decreased
number of measurements diminishing the array’s ability to accurately define the
cave system.

A review of the model statistics indicated a higher RMS error and L2-norm
in the Dipole-Dipole array than the Inverse Schlumberger array (Table 1). This is
a characteristic benefit of the Inverse Schlumberger array which typically has a
higher signal to noise ratio of other arrays, but this method performed more
poorly in determining the size and shape of the cave feature. This shows that a
low RMS error and a good L2-norm fit of poor quality data is not always indicative
of the best model.

The merged Dipole-Dipole and Inverse Schlumberger modeling method
indicated a moderate to low RMS error and good L2-norm fit. The advantage
was obviously in the increased number of data points being modeled by
combining both data sets. This helped to take advantage of the benefits from
each array and help to constrain the higher data values and worse fit data from
the Dipole-Dipole array. However, a review of the merged Dipole-Dipole and
Inverse Schlumberger array did not indicate a significant improvement in the
modeled results (compare Figure 13 with Figure 15). The improvements appear
to be more in the model statistics than what was actually observed (Table 1).
Preliminary 3D inversion models of the Dipole-Dipole and Inverse Schlumberger array were also performed which indicated similar results and modeling statistics to the 2D inversion models. Additionally, it was noted that during the 3D modeling process, the increased number of data points from the combined approach led to an increased range in resistivity for the known voids and therefore a larger exaggerated size, shape, and dimension of the suspected cave features. In which case, it was determined that 3D modeling using the single Dipole-Dipole array was more advantageous in delineating the true size and shape of the cave features at this site. Determining the best array type for delineating void features is most likely site specific and should be determined on a case by case basis. Other studies have reported similar success when mapping cave features using the Dipole-Dipole array (Gharibi, 2005, Pánek et al., 2010 and Neyamadpour et al., 2010).

### 3-Dimensional Block Models

#### Quasi 3-Dimensional Modeling using the Dipole-Dipole Array

Results from each of the quasi 3D ERT models using the Dipole-Dipole array are described below. The models consisted of resistivity measurements

<table>
<thead>
<tr>
<th>Array Type</th>
<th># of Data</th>
<th>Measured Apparent (Ωm)</th>
<th># of Iterations</th>
<th>RMS Error %</th>
<th>L2-Norm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole-Dipole (Figure 13)</td>
<td>497</td>
<td>-1,259</td>
<td>3</td>
<td>10.21</td>
<td>6.91</td>
</tr>
<tr>
<td>Inverse Schlumberger (Figure 14)</td>
<td>322</td>
<td>24 - 1,492</td>
<td>4</td>
<td>8.24</td>
<td>2.98</td>
</tr>
<tr>
<td>Merged Dipole-Dipole and Inverse Schlumberger (Figure 15)</td>
<td>819</td>
<td>14 - 1,659</td>
<td>3</td>
<td>8.87</td>
<td>4.84</td>
</tr>
</tbody>
</table>
that ranged from approximately 8 to 10,000 Ohm-meters (Ωm) across study area. The RMS error ranged from approximately 8.47 to 13.23 percent and L2-norm ranged from approximately 2.8 to 6.9. Overall, the RMS error and the L2-norm for each of the seven (7) 3D block models were moderately low indicating a good fit of the measured versus calculated apparent resistivity values. The RMS error is an average data misfit of all the data points. The L2-norm is another measure of data misfit which is the sum of the squared weighted data errors. Table 2 summarizes the model statistics for each of the 3D models performed.

Table 2. Model Statistics of the seven 3D Models using the Dipole-Dipole array.

<table>
<thead>
<tr>
<th>3D Model</th>
<th>Survey Section</th>
<th># of Data</th>
<th>Measured Apparent (Ωm)</th>
<th># of Iterations</th>
<th>RMS Error %</th>
<th>L2-Norm</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Figure 16A and 16B) Model 1</td>
<td>1 - 20 meters W to E</td>
<td>3,133</td>
<td>9 - 6,944</td>
<td>4</td>
<td>13.23%</td>
<td>6.9</td>
</tr>
<tr>
<td>(Figure 17A and 17B) Model 2</td>
<td>16 - 36 meters W to E</td>
<td>2,563</td>
<td>3 - 10,000</td>
<td>5</td>
<td>10.32%</td>
<td>3.6</td>
</tr>
<tr>
<td>(Figure 19A and 19B) Model 3</td>
<td>32 - 52 meters W to E</td>
<td>3,827</td>
<td>8 - 10,000</td>
<td>4</td>
<td>10.35%</td>
<td>4.2</td>
</tr>
<tr>
<td>(Figure 20A and 20B) Model 4</td>
<td>48 - 68 meters W to E</td>
<td>4,350</td>
<td>11 - 10,000</td>
<td>3</td>
<td>10.63%</td>
<td>3.2</td>
</tr>
<tr>
<td>(Figure 21A and 21B) Model 5</td>
<td>64 - 84 meters W to E</td>
<td>4,257</td>
<td>19 - 4,462</td>
<td>3</td>
<td>8.63%</td>
<td>3.1</td>
</tr>
<tr>
<td>(Figure 22A and 22B) Model 6</td>
<td>1-12 meters S to N</td>
<td>2,867</td>
<td>16 - 10,000</td>
<td>4</td>
<td>9.69%</td>
<td>3.6</td>
</tr>
<tr>
<td>(Figure 23A and 23B) Model 7</td>
<td>96 - 104 meters S to N</td>
<td>1,520</td>
<td>17 - 6,303</td>
<td>4</td>
<td>8.47%</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Shown below are the quasi 3D Dipole-Dipole cave models (i.e., Model 1 thru Model 7) which were performed in succession across the survey area (Figure 11). The images are shown in both directions and have been terrain corrected (Figures 16 thru 22).
Quasi 3-Dimensional Dipole-Dipole Model 1
Model 1 (Transects 1-20m Facing North)

(Figure 16A) A view of Model 1 facing North. The southern portion of Legend Cave can be observed to the east.

Model 1 (Transects 1-20m Facing South)

(Figure 16B) A view of Model 1 facing South. Note the elongated shape of a suspected cave feature to the west, typical structure of a phreatic cave feature.
Quasi 3-Dimensional Dipole-Dipole Model 2
Model 2 (Transects 16-36m Facing North)

(Figure 17A) A view of Model 2 facing North. Note the elongated area of increased resistivity to the west and the cylindrical feature to the east, both areas where voids are suspected.

Model 2 (Transects 16-36m Facing South)

(Figure 17B) A view of Model 2 facing South. To the east and west, two isolated areas of increased resistivity where the suspected void features continue further north.
Quasi 3-Dimensional Dipole-Dipole Model 3

Model 3 (Transects 32-52m Facing North)

(Figure 18A) A view of Model 3 facing North. Note the subsurface depression along the northern edge of the limestone quarry. To the west, the suspected void feature has diminished significantly.

Model 3 (Transects 32-52m Facing South)

(Figure 18B) A view Model 3 facing South. Note multiple suspected void features to the east and a view of a portion of Bottlecap Cave to the west.
Quasi 3-Dimensional Dipole-Dipole Model 4

Model 4 (Transects 48-68m Facing North)

(Figure 19A) A view of Model 4 facing North. Note the area of increased resistivity to the east and a portion of Bottlecap Cave to the west.

Model 4 (Transects 48-68m Facing South)

(Figure 19B) A view of Model facing South. Note the multiple suspected cave features to the east and a portion of Bottlecap Cave to the west. Note the similarity in shape, size, and depth of the suspected cave features when compared to Bottlecap Cave.
Quasi 3-Dimensional Dipole-Dipole Model 5

Model 5 (Transects 64-84m Facing North)

(Figure 20A) A view of Model 5 facing North. Note the multiple cave features extending further to the north at the northeast portion of the study area and Bottlecap Cave to the west.

Model 5 (Transects 64-84m Facing South)

(Figure 20B) A view of Model 5 facing South. Note the entrance to Bottlecap Cave and multiple parallel cave features at the northeast portion of the study. Note the elongated shape of the cave features, which are characteristic of phreatic formed caves.
Quasi 3-Dimensional Dipole-Dipole Model 6

Model 6 (Transects 0-12m Facing West)

(Figure 21A) A view of Model 6 facing West. Note the cave entrance and northern portion of the Bottlecap Cave.

Model 6 (Transects 0-12m Facing East)

(Figure 21B) A view Model 6 facing East. Note how many of the suspected void features are discontinuous and do not appear to be interconnected.
Quasi 3-Dimensional Dipole-Dipole Model 7
Model 7 (Transects 96-104m Facing West)

(Figure 22A) A view Model 7 facing West. Note the entrance to Legend Cave and the large room at the north end of Legend Cave. An obvious breach is noted toward the central portion of the model where Legend Cave is truncated by roof collapse.

Model 7 (Transects 96-104m Facing East)

(Figure 22B) A view of Model 7 facing East. Note the cross-sectional view of Legend Cave which conforms with the known cave length. To the north, a large void feature is suspected.
A review of the 7 quasi 3D Dipole-Dipole Models shows generally good correlation between areas of increased resistivity and the areas of the two known cave systems. Areas of increased resistivity exhibited a geologic structure similar to the known caves with respect to the length, depth, and to a lesser extent the shape. With respect to Bottlecap Cave, the depth of the cave is approximately 8.5 meters below land surface and dips to the southwest. This corresponds with the depth and path of the cave system as observed in the 3D models (Figures 18 thru 21). With respect to Legend Cave, the depth of the cave ranges from approximately 3 to 9 meters below grade with a cave length of approximately 41 meters. This conforms with the general depth and cave length observed in the 3D models, however the known structure of Legend Cave is not as well defined (Figures 22A and 22B). Several other suspected cave features are also observed which are similar in structure to the two known cave features. The known and suspected cave features exhibited a geologic structure which is consistent with phreatic formed caves in vadose zone of West Central Florida.

Additional horizontal slices of inverted resistivity were extracted from the 3D models for further comparison of the ER results.

**Horizontal Slices**

Further analysis of the 3D models were performed by conducting Z slices from each of the 3D inversions performed over Bottlecap and Legend Cave. Model 6 and Model 7 were performed over a large portion of the two known caves and were used to analyze the 3D model’s interpreted path and depth of the cave system. The horizontal slices were corrected for variations in
topography and show a topographic high of approximately 5 meters for the two
cave models (Figures 23 and 24). The horizontal slices for each of the cave
systems are shown as well as a horizontal Z slice extracted at the approximate
depth of the cave’s largest horizontal plane. The outline of the cave system was
then overlaid onto the Z slice to assess the accuracy of the 3D model.
Quasi 3-Dimensional Dipole-Dipole Model 6
Model 6 (Horizontal Z Slices over Bottlecap Cave Facing West)

(Figure 23A) A view of the horizontal Z slices conducted over Bottlecap Cave facing West.

Model 6 (Horizontal Z Slices over Bottlecap Cave Facing East)

(Figure 23B) A view of the horizontal Z slices conducted over Bottlecap Cave facing East.
Quasi 3-Dimensional Dipole-Dipole Model 7

Model 7 (Horizontal Z Slices over Legend Cave Facing West)

(Figure 24A) A view of the horizontal Z slices conducted over Legend Cave facing West.

Model 7 (Horizontal Z Slices over Legend Cave Facing East)

(Figure 24B) A view of the Horizontal Z slices conducted over Legend Cave facing East.
A review of the horizontal Z slices performed over Bottlecap and Legend Cave indicated variations in the path and depth of the two cave systems. Model 6 performed over Bottlecap Cave indicated that a large portion of the cave system is at a depth of approximately 8.5 meters below land surface (Figures 23A and 23B). Increases in resistivity were observed at depths above and below Bottlecap Cave indicating vertical variations in the 3D void space being measured. Model 7 performed over Legend Cave indicated increases in resistivity at a depth of approximately 5 meters below land surface (Figures 24A and 24B). Vertical increases in resistivity were observed varying from approximately 3 meters to 9 meters below land surface within Legend Cave. This range in depth corresponds with the existing map of Legend Cave.

**Horizontal Plane**

In order to assess the location and depth of the two cave systems from the 3D models a horizontal plane was extracted. For Legend Cave a horizontal plane was extracted from Model 7 at a depth of 5 meters below land surface where a large portion of the cave system was observed (Figure 25). This also conformed with the depth indicated from the Legend Cave map. For Bottlecap Cave, five ERT lines were selected over the cave system and incorporated into a larger 3D block model. Due to processing limitations in *EarthImager 3D*, ERT lines were skipped in order to encompass the entire cave system. A horizontal plane was then extracted over Bottlecap Cave at a depth of approximately 8.5 meters below land surface to access the accuracy of the model’s cave path.
The depth of 8.5 meters also conformed well with the known depth of Bottlecap Cave.

(Figure 25) A plan view of Legend Cave at a depth of 5 meters below land surface.

(Figure 26) A plan view of Bottlecap Cave at a depth of 8.5 meters below land surface.
A review of the horizontal plane extracted from the 3D block models shows some correlation with the general structure of the two known caves, however inconsistencies are observed. With respect to Legend Cave, the Z slice extracted at a depth of 5 meters is in agreement with the presence of the large room to the south and north of the cave but the central room, which is smaller, is not as well defined (Figure 25). Additionally, the Z slice extracted at a depth of 8.5 meters over Bottlecap Cave shows good correlation with the area of increased resistivity to the southwest. Other high resistivity areas are also identified which are not interconnected with Bottlecap Cave. It is important to note that at the entrance to Bottlecap cave a very tight cavity was noted which was too tight to explore. This may be part of a larger cavity as a large area of increased resistivity was observed at the northeast portion of the study area (Figure 26).

Correlation in the horizontal plane was observed, however complex 3D cavities are not well delineated in the horizontal plane. As observed with both Legend and Bottlecap Cave, undulating cave features make a horizontal plane extraction difficult to assess a cave’s path. This underscores the importance of 3D imaging of complex void features in karst terrain.

2-Dimensional vs. 3-Dimensional Inversion Slices

A comparison of the 2D and 3D inversion slices were performed along four ERT transect lines across the study area. The four slices were selected in areas directly in-line with and perpendicular to the two known cave systems. A 2D inversion of each transect line was performed and terrain corrected, and the
same 2D inversion was exported into the 3D block model. A 2-dimensional Y-
slice was then extracted from the 3D block model for comparison with the initial
2D inversion model (Figures 27 thru 30). Multiple 1D resistivity logs were then
extracted from both the 2D and 3D inversion results at the cross-over points of
the South to North and West to East transect lines. In some cases, resistivity
logs extracted at the edges of the model may only have data to a depth of
approximately 6 meters, in which case; only the upper 6 meters of data were
analyzed for comparison. The resistivity logs from the 2D and 3D inversion
models are shown below.
2D Inversion along Transect T-2

(Figure 27A) A view of the 2D inversion along transect T-2 extending West to East with resistivity logs extracted at 8 and 100 meters along the ERT line. Note the entrance to Legend Cave.

2D Slice extracted from the 3D Inversion along Transect T-2

(Figure 27B) A view of the 3D inversion along transect T-2 extending West to East with resistivity logs extracted at 8 and 100 meters along the ERT line. Note the entrance to Legend Cave and the absence of the increase in resistivity at the 24 meters.
2D Inversion along Transect T-28

(Figure 28A) A view of the 2D inversion along transect T-28 extending South to North with resistivity logs extracted at 4, 40, and 64 meters along the ERT line. Note the location of Legend Cave.

2D Slice extracted from the 3D Inversion along Transect T-28

(Figure 28B) A view of the 3D inversion along transect T-28 extending South to North with resistivity logs extracted at 4, 40, and 64 meters along the ERT line. Note the location of Legend Cave.
2D Inversion along Transect T-11

(Figure 29A) A view of the 2D inversion along transect T-11 extending West to East with resistivity logs extracted at 22, 28, and 100 meters along the ERT line.

2D Slice extracted from the 3D Inversion along Transect T-11

(Figure 29B) A view of the 3D inversion along transect T-11 extending West to East with resistivity logs extracted at 22, 28, and 100 meters along the ERT line. Note the enlarged area of increased resistivity at the West (left) side of the transect when compared to the 2D inversion.
2D Inversion along Transect T-25

(Figure 30A) A view of the 2D inversion along transect T-25 extending South to North with resistivity logs extracted at 4, 40, 60, and 72 meters along the ERT line. Note the entrance to Bottlecap Cave.

2D Slice extracted from the 3D Inversion along Transect T-25

(Figure 30B) A view of the 3D inversion along transect T-25 extending South to North with resistivity logs extracted at 4, 40, 60, and 72 meters along the ERT line. Note the entrance to Bottlecap Cave.
A comparison of the 2D and 3D inversion slices show considerable differences between the two inversion models. In most cases, the 3D inversion slices show larger areas of high resistivity than the 2D inversion models (Figures 27B thru 30B). This is as expected, as they 2D models assume any resistivity anomaly extends infinitely away from the plane of the profile. However, we do note that in some cases areas of increased resistivity observed in the 2D inversion model were not present (compare Figures 27A and 27B) or considerably smaller in the 3D inversion slice (compare Figures 28A and 28B). These results suggest that the features observed in a given 2D line were not comparably observed in neighboring lines in the 3D inversion. Additionally, the 3D inversion slice appeared to more clearly distinguish the breakdown at far north end of Legend Cave than the 2D inversion (compare Figures 28A and 28B), although uncertainty in resolution of the feature in both 2D and 3D analysis is limited by its proximity to the ends of the profiles.

Theoretically the 3D inversion produces a more accurate model of the subsurface than the 2D inversion model. This is because the 3D inversion incorporates the resistivity response of the adjacent ERT transects, and does not require that structures extend to infinity perpendicular to the profile. This is most important when resistivity features are not elongated perpendicular to the profile. Several resistivity logs were extracted from the 2D and 3D models at the cross-over points of the ERT transects. In theory, cross-over errors should be smaller on profiles derived from 3D inversions than on those from 2D inversions.
The size of cross-over errors is an additional way to estimate errors associated with the inversions.

**Cross-over Points**

Several cross-over points were extracted and analyzed from crossing ERT transects. At each of the cross-over points, cave maps were also used to estimate depths (if present) of air-filled voids. Thus comparison of the resistivity logs in both directions allowed closer assessment of the resistivity data and helped assess interpretation the ERT results at known “air-filled” cavities.

A total of twenty-three 1-dimensional resistivity logs were extracted from the 2D and 3D-derived ERT profiles. The points were selected in areas of known voids, directly overlying Bottlecap and Legend cave, and in areas outside the cave system where no voids were expected or observed (Figure 31). The resistivity inversion results at these points for the W to E and the S to N transects were then plotted versus depth, and the zone of the “air-filled” voids were then denoted on the resistivity logs for comparison (Figures 32 thru 45).
(Figure 31) A map showing the location of the cross-over points extracted from the ERT profiles.
Resistivity Log from the 2D Inversion at (8,4)

(Figure 32A) Resistivity Log at cross-over point (8,4) with no known void features. Interpreted to a depth of 4 meters.

Resistivity Log from the 3D Inversion at (8,4)

(Figure 32B) Resistivity Log at cross-over point (8,4) with no known void features. Interpreted to a depth of 4 meters.
Resistivity Log from the 2D Inversion at (22,40)

(Figure 33A) Resistivity Log at cross-over point (22,40) with no known void features.

Resistivity Log from the 3D Inversion at (22,40)

(Figure 33B) Resistivity Log at cross-over point (22,40) with no known void features.
Resistivity Log from the 2D Inversion at (24,60)

(Figure 34A) Resistivity Log at cross-over point (24,60) located within a known void feature.

Resistivity Log from the 3D Inversion at (24,60)

(Figure 34B) Resistivity Log at cross-over point (24,60) located within a known void feature.
Resistivity Log from the 2D Inversion at (28,60)

(Figure 35A) Resistivity Log at cross-over point (28,60) located within a known void feature.

Resistivity Log from the 3D Inversion at (28,60)

(Figure 35B) Resistivity Log at cross-over point (28,60) located within a known void feature.
Resistivity Log from the 2D Inversion at (32,60)

(Figure 36A) Resistivity Log at cross-over point (32,60) located on the edge of a known void feature.

Resistivity Log from the 3D Inversion at (32,60)

(Figure 36B) Resistivity Log at cross-over point (32,60) located on the edge of a known void feature.
Resistivity Log from the 2D Inversion at (36,60)

(Figure 37A) Resistivity Log at cross-over point (36,60) with no known void feature.

Resistivity Log from the 3D Inversion at (36,60)

(Figure 37B) Resistivity Log at cross-over point (36,60) with no known void feature.
Resistivity Log from the 2D Inversion at (32,72)

(Figure 38A) Resistivity Log at cross-over point (32,72) within a known void feature.

Resistivity Log from the 3D Inversion at (32,72)

(Figure 38B) Resistivity Log at cross-over point (32,72) within a known void feature.
(Figure 39A) Resistivity Log at cross-over point (100,4) located at the entrance of Legend Cave.

(Figure 39B) Resistivity Log at cross-over point (100,4) located at the entrance of Legend Cave.
Resistivity Log from the 2D Inversion at (100,40)

(Figure 40A) Resistivity Log at cross-over point (100,40) located within a known void feature.

Resistivity Log from the 3D Inversion at (100,40)

(Figure 40B) Resistivity Log at cross-over point (100,40) located within a known void feature.
Resistivity Log from the 2D Inversion at (100,64)

(Figure 41A) Resistivity Log at cross-over point (100,64) located within a suspected void feature.

Resistivity Log from the 3D Inversion at (100,64)

(Figure 41B) Resistivity Log at cross-over point (100,64) located within a suspected void feature.
(Figure 42) Resistivity Log at cross-over point (28,40) with no known void features.

(Figure 43) Resistivity Log at cross-over point (38,68) with no known void features.
Resistivity Log from the 2D Inversion at (40,84)

(Figure 44) Resistivity Log at cross-over point (40,84) located at the entrance of Bottlecap Cave.
A review of the 1-D resistivity logs noted a wide range in resistivity at the cross-over points ranging from approximately 50 to 8,000 Ωm. In areas of known “air-filled” voids, we observed resistivity values ranging from approximately 100 to 8,000 Ωm and approximately 50 to 1,000 Ωm in areas where the host bedrock (i.e., limestone) was expected. In general, the 2D cross-over points located in areas of known “air-filled” voids were not very well correlated. In contrast, areas outside the known cave system where the limestone bedrock was expected generally showed good correlation in both directions (Figures 32A, 33A, 37A, 42, and 43). Correlation within a known void was observed at cross-over point (24,60) suggesting that the void feature may be isotropic (Figure 34). We also noted a general increase in resistivity in the W to E transects compared to the S to N transects. This suggests that orientation of the ERT transects is an important factor when comparing and combining resistivity data.

We also noted that the 3D inversion logs showed improved correlation at the cross-over points both inside and outside the areas of the known “air-filled” voids (Figures 35B, 36B, 38B, and 40B). This suggests that the 3D inversion models were effective in attempting to resolve a more accurate apparent resistivity value. We did however observe a decrease in correlation outside a known cave feature in the 3D inversion results at cross-over point (36,60) (Figure 37A).

Additionally, cross-over points on the edge of known cave feature (36,60) had similar results to a known void feature with decreased correlation in the 2D inversion and improved correlation with the 3D inversion (compare Figure 36A
and 36 B). At cross-over point (32,60), an increase in resistivity was observed in the W to E direction, while a decrease in resistivity was observed in the S to N direction. This was most likely the result of the W to E transect intersecting the known “air-filled” cave feature where as the S to N transect does not.

The large increase in resistivity observed in known “air-filled” voids was expected and has been previously noted (Gibson et al., 2004, Pánek et al., 2010, Gambetta et al., 2011). The increase in resistivity was most likely a result of the “infinitely” resistive air space measured in contrast to the surrounding host bedrock. The complex 3-dimensional shape of the caves most likely contribute to the poor correlation of the cross-over points within the known cave system and at the edges of the cave. In contrast, correlation was generally observed in the limestone bedrock where the subsurface material is suspected to be more homogeneous. The presence of large cross-over areas suggests either that data are locally noisy or that the host rock is locally heterogeneous, as might be expected of limestone in karst terrains.

**3D Site Modeling**

The quasi-3D ERT method shows resistivity highs that are roughly coincident with the known extent and depths of the two air-filled cave systems on the Brooksville Ridge of West Central Florida. The presence of other observed resistivity highs suggests that unknown cave features may exist in the northeast portion of the study area. The suspected cave features exhibit similar ranges in resistivity values, depth, and structure as those of Bottlecap and Legend Cave. If they are connected to the two known cave systems, the connections must be
relatively small compared to the observed cave systems. Based on the 3D Models performed in EarthImager, they are most likely several smaller phreatic formed cavities which generally trend in a north to south direction (Figures 16 thru 22).

Due to software constraints, a 3D site model of larger survey areas is not possible with EarthImager 3D alone. In which case, it was necessary to combine the quasi-3D Dipole-Dipole models together and import the data into another 3D visualization software (i.e., Voxler 3D) for an overall 3D site model (Figures 45 and 46).
3D ER Site Model

(Figure 45) A plan view of the 3D contour site model, showing the contoured ER response at a depth of approximately 5 meters below land surface.
(Figure 46) A plan view of the 3D isosurface site model, contoured at 650 Ohm-m in dark blue and 2,500 Ohm-m in light blue.
Based on the 3D site model, bulk areas of increased resistivity (i.e., suspected cavities) can be observed throughout the study area. The central portion of the study area is a topographic high and exhibited no elevated resistivity response. Legend Cave was observed trending towards the north along the eastern perimeter of the limestone quarry and is truncated to the north by massive breakdown from roof collapse. Based on the 3D block model performed over Legend Cave, the large rooms within Legend cave were detected with an interconnecting smaller passage (Figures 22A and 22B). Their peak anomalies, however, are on the order of approximately 750 Ohm-m which are lower than those observed over numerous other features. Thus the combined 3D site models that emphasize only the highest-amplitude positive anomalies (>650 Ohm-m) (Figures 45 and 46) do not indicate Legend Cave. This suggests that Legend Cave is smaller than other voids in the area, or surrounded by lower resistivity rock.

Legend Cave does not show a connection with Bottlecap Cave; however, a large void feature was observed on the north side of Legend Cave behind the massive breakdown. The 3D site model, suggests Legend Cave may have been previously connected to an area farther to the north; where, the cave is now choked from roof collapse. This breach in the cave system was detected in Model 7 suggesting the quasi-3D methods ability to detect a change in resistivity between the “air-filled” cavities and the limestone bedrock (Figures 22A and 22B).
Similarly, Bottlecap Cave is approximately 1 to 2 meters in diameter, however the 3D site model was still able to delineate its general location and depth. In some places, the model appears to have exaggerated the volume of void space within the bedrock and indicate adjacent areas of suspected “air-filled” voids which have yet to be confirmed. This was most evident in the 3D block models of 5 and 7 performed over Bottlecap and Legend Cave (Figures 20 and 22).

The 3D site model shows a NE-SW direction for the cave at a depth ranging from approximately 5.5 to 8.5 meters below land surface, a result that is consistent with the known map of Bottlecap Cave (Polk, 2010). Bottle Cap cave or other high resistivity areas also conforms with the depths and structure of other known caves on the Brooksville Ridge such as the Dames Caves (Brinkmann and Reeder, 1994).
Chapter 7: Discussion

Quasi-3D ERT is an effective method for identifying “air-filled” karst conduits in the vadose zone. Although the quasi 3D method exhibited good correlation with the two known cave features, exact volumetric measurements are not likely due to the physical principles of how resistivity data is collected and inverted. Based on the 2D and 3D inversions, 3D inversions showed an increase in correlation at the cross-over points indicating an improved model and a more accurate resistivity value. In this study, several suspected cave features were observed which exhibited the same geophysical characteristics as the two known caves. Test borings would be necessary to confirm the suspected cave features at site.

If the locations of these “caves” were to be confirmed at the site, this may suggest a complex system of parallel phreatic cave features generally dipping from north to south with at most small zones of interconnectivity. Such a result would therefore suggest that phreatic formed caves may be common features within the underlying bedrock on the Brooksville Ridge and are not isolated anomalous features within the limestone formation. This conforms to the local geologic structure of phreatic formed caves on the Brooksville Ridge (Florea,
2006; Florea et al., 2007) and corresponds with previous research regarding the pattern by which phreatic caves generally form (Palmer, 2003).

The collection of high quality 3D ER data for mapping karst conduits is largely dependent on the survey method and the modeling strategies. The survey method requires selecting the proper line length, electrode spacing, and array type. For this study, the Dipole-Dipole array was better suited for near-surface horizontal resolution of laterally extensive cave features than the Inverse Schlumberger array alone. The combined Dipole-Dipole and Inverse Schlumberger array approach indicated some statistical improvements of the ER data; however, no modeling improvements were visually observed. These results may be site specific and underscore the importance of a good pre-surveying strategy (i.e., Forward modeling) and post processing methods in order to select the proper geometry and most effective array type.

Difficulties with defining the precise size, shape, and volume of a cavity feature have previously been noted (Neyamadpour et al., 2009; Neyamadpour et al., 2010). This may be due to several reasons some of which are inherent to the ERT method, the survey approach, and the inversion process. In addition, similar materials can have a relatively wide range of resistivity values. Resistivity also varies with water content and pore fluids, so data collected on one day will not be identical to data collected at the same site under different saturation conditions.

The orientation of the ER transects over the suspected cavity significantly affects the size and shape of the modeled results, especially if 2D inversions are
run. The effect of direction over a suspected cavity has also been noted in previous studies (Orfanos and Apostolopoulos, 2011). Smoothing constraints performed during the modeling process may also diminish or distort the true size and shape of a suspected cavity as observed in this study. These limitations suggest that although the quasi-3D ERT method is effective for most practical applications of cavity detection, true dimensional and volumetric measurements from the quasi-3D method may not be a realistic goal.

The results from this study suggests that although large scale 3D mapping is possible, limitations of inverting large amounts of data still exist. For example in this study the inversion process had to be performed in small subsections using EarthImager 3D and then be combined into a larger 3D site model using another 3D modeling program (e.g. Voxler 3D or Oasis montaj, etc.) Limitations with current computer processing capabilities still exist, increasing the processing time for larger scale inversion of quasi 3D ER data.

Other potential limitations with this method may occur at highly developed sites where surface obstructions (e.g., buildings, roads, underground utilities, and other impervious structures) may significantly affect the accessibility and quality of a quasi 3D dataset. This has been a point of contention for using ERT in an urban setting (Dobekci, 2010) and suggests that high resolution karst imaging using the quasi-3D ER method would be most applicable prior to site development. Clearly in this study resolution of Legend Cave was limited due to inaccessibility of terrain under a portion of the limestone quarry.
Finally, the scale at which a quasi-3D ER survey method can be applied should be investigated. The limitation of resolution verses depth is a known issue with ER which may require an integrated approach of multiple geophysical techniques for deeper site characterization. It is also suspected that ERT’s ability to accurately resolve voids below the phreatic zone may diminish significantly because the resistivity contrast between a water-filled void and background may be less than that of an air-filled void and background. Furthermore, large scale surveys may require a combined 2D and 3D approach. Large scale surveying may best be performed by conducting long 2D ERT as a reconnaissance tool with closer spaced quasi-3D ERT used in areas of high interest.
Chapter 8: Policy Implications

Geophysical studies can be used to help in the management of karst landscapes. They have long been used to measure the physical properties of the subsurface materials which combined with ground truthing methods can provide an accurate model of the subsurface geology. The benefits of using geophysical methods to characterize the karst subsurface have been well documented (Erchul, 1993; Doll et al. 1998; Gibson et al., 2004; Sheehan et al., 2005b; Dobecki and Upchurch, 2010; Kruse, et al., 2006; Carrozzo et al., 2008; Gambetta et al., 2011). However, there are no current legislative requirements which mandate this type of approach.

In Florida, geotechnical investigations are typically performed as a result of county, state, and federal regulations. As noted in the Brooksville Ridge Cave case, Hernando County’s Ordinance 94-8 governs land use in order to protect and maintain groundwater quality. Similarly, Florida’s State Statute 627.707, Standards for Investigation of Sinkhole Claims by Insurers; nonrenewals—requires that upon receipt of claim for a sinkhole loss, an insurer must meet the minimum standards in investigating a sinkhole claim. To date, geophysical studies are not a legislated requirement but are only referred to in the non-
regulatory industry guidelines as a best management practice (e.g., Special Publication No. 57 and the U.S. Fish & Wildlife Service, Recommended Best Management Practices for Proposed Activities in Karst Areas-Oklahoma).

The 2004 collapse of the Lee Roy Selman Expressway in Tampa, Florida demonstrated how too little information about the karst subsurface can have a dramatic and unforeseen physical, social, and economic impact. Karst terrains tend to be more vulnerable with respect to environmental and engineering hazards increasing the risk to property which can further lead to the loss of services. Numerous studies have discussed some of the challenges of building on karst terrain and anthropogenic impact (Newton, 1987; White, 1988; Sowers, 1996; Kannan, 1999; Zhou and Beck, 2011).

Geotechnical investigations are typically performed to identify potential hazards, determine the elements of risk, and determine the probability that such a hazard may occur. This type of traditional approach is sometimes complicated by the attempt to map a 3-dimensional karst feature with a 1-dimensional testing method (e.g., SPT and CPT data). Insufficient data about the hazard can prevent an accurate risk assessment and can lead to an inaccurate prediction of the hazard occurrence. Waltham et al., (2005) discusses this further and describes the total risk at a particular place and time as:

\[
\text{Total risk} = \text{Hazard} \times \text{Elements at risk} \times \text{Vulnerability}
\]

Geophysical studies have a proven record as an effective karst management tool (Sowers, 1996; Waltham et al., 2005; Tolmachev and Leonenko, 2011) which are becoming larger in scale (Dobekci and Upchurch,
2010) with increased resolution (Kruse et al., 2006; Park and Taylor, 2010). As the capacity for 2D and now 3D geophysical studies allows larger areas to be surveyed, the application for these types of studies has increased as well. Geophysical studies as part of the larger geotechnical investigation can be highly effective for mapping complex karst terrain. Of interest would be the mandatory requirement of the geotechnical guidelines, as outlined in Special Publication No. 57, prior to the development of critical infrastructure on karst terrain (e.g., waste water treatment plants, land-fill sites, roadway design, and commercial building structures). This requirement, if mandated, could minimize unforeseen geologic and environmental hazards prior to construction and limit the potential for future remediation costs. Accurate scientific data has the ability to identify subsurface karst features which can be used to determine the proper land-use, engineering/design, and insurability of a site prior to development. The financial benefits and improved risk assessments of identifying karst activity prior to development show that a mandated approach could be effective when building on karst terrain.
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