GEOPHYSICAL RECONNAISSANCE OF KARST FEATURES ASSOCIATED WITH SINKHOLES ON THE ANTIOCH UNIVERSITY CAMPUS IN YELLOW SPRINGS, OHIO: WESTERN AREA

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science

By

BRENT MATTHEW ZERKEL
B.S., Wright State University, 2003

2007

Wright State University
I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Brent M. Zerkel ENTITLED GEOPHYSICAL RECONNAISSANCE OF KARST FEATURES ASSOCIATED WITH SINKHOLES ON THE ANTIOCH UNIVERSITY CAMPUS IN YELLOW SPRINGS, OHIO: WESTERN AREA BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science.

________________________
Ernest Hauser, Ph.D.
Thesis Director

________________________
G. Allen Burton, Ph.D.
Department Chair

Committee on Final Examination:

________________________
Ernest Hauser, Ph. D.

________________________
Doyle R. Watts, Ph. D.

________________________
Cindy K. Carney, Ph. D.

________________________
Joseph F. Thomas, Jr., Ph. D.
Dean, School of Graduate Studies
Abstract

Zerkel, Brent M.S., Department of Earth and Environmental Sciences, Wright State University, 2007. Geophysical Reconnaissance of Karst Features Associated With Sinkholes on the Antioch University Campus in Yellow Springs, Ohio: Western Area

Antioch University is located in Yellow Springs, OH. This study was conducted on the Antioch University Campus in the commons area and is concentrated on the area west of the easternmost sinkhole. The primary purpose of this study is to locate and identify buried anomalous karst features, such as joints and collapses that may be hazardous to nearby buildings on the Antioch University Campus. The secondary purposes of this study are to identify remaining features in the geophysical data that may be related to manmade structures, and to identify areas for future studies.

It is known that an 8-inch steel sewer pipe runs east-west, and a 1-inch water line runs southeast-northwest, through the survey area. This steel sewer pipe and the water line may be the cause of two of the anomalous features discovered. There is, however, a feature in the ground penetrating radar data that seems to be related to the sinkholes in the study area. This feature is most likely a joint or collapse that is related to the karst topography in the study area.

At least one sinkhole has been visible since 1975 when an Antioch University chemistry professor noticed the geological feature. Since that time the sinkholes have been filled in with rocks, dirt and similar materials.
Preliminary electrical resistivity studies by Wright State University geophysics students in 2004 indicated a low resistivity anomalous feature in the subsurface. Five geophysical methods were used in this study to locate the extent of known anomalous features in the area. These five methods are: electrical resistivity, magnetic surveying, ground penetrating radar, electromagnetic surveying, and seismic refraction.

Anomalous features were discovered with each method employed. Electrical resistivity produced low resistivity anomalous features in each line. These features vary in shape and size. Low resistivity features are found near the sinkholes. These features are most likely the result of a steel water line. The magnetic surveying method produced mixed results. Some magnetic anomalous features were discovered that correlate with other methods in this study, and some features did not correlate as well with the other methods. High amplitude responses in the ground penetrating radar data correlate very well with low resistivity anomalous features. Electromagnetic data correlates well with the known extent of the 8-inch steel sewer pipe, and the 1-inch steel water pipe.

Seismic surveying produced excellent results in relation to the known sinkholes. Seismic energy was greatly attenuated at the middle sinkhole exactly where it was expected. This high attenuation is most likely the result of a joint in the bedrock, and not likely the result of the buried steel pipe. A steel pipe would create some impedance but not as much as displayed in the seismogram. The seismic attenuation found near the middle sinkhole is found in the same location as a probable collapse feature in the GPR data, a low resistivity anomalous feature in the resistivity data, an anomalous feature in the magnetic data, and an anomalous feature in the electromagnetic data.
Table of Contents

Chapter | Title |
--- | --- |
Chapter 1: | Introduction |
| Chapter 2: | History and Theory of Geophysical Methods |
| Chapter 3: | Methodology |
| Chapter 4: | Electrical Resistivity |
| Chapter 5: | Ground Penetrating Radar |

Chapter 1: Introduction

- Site Description
- Dimensions of Study Area
- Previous Research
- Geologic History of the Area

Chapter 2: History and Theory of Geophysical Methods

- Electrical Resistivity
- Ground Penetrating Radar
- Magnetic Surveying
- Electromagnetic Surveying
- Seismic Refraction

Chapter 3: Methodology

- General Methodology
- Electrical Resistivity
- Ground Penetrating Radar
- Magnetic Surveying
- Electromagnetic Surveying
- Seismic Refraction

Chapter 4: Electrical Resistivity

- Data Acquisition
- Data Processing
- Results and Discussion
- Interpretation of Results

Chapter 5: Ground Penetrating Radar

- Data Acquisition
- Data Processing
- Results and Discussion
- Interpretation of Results
Chapter 6: Magnetics.................................................................66
  Data Acquisition...............................................................66
  Data Processing...............................................................69
  Results and Discussion.....................................................70
  Interpretation of Results....................................................72

Chapter 7: Electromagnetic Surveying ....................................74
  Data Acquisition...............................................................74
  Data Processing...............................................................75
  Results and Discussion.....................................................75
  Interpretation of Results....................................................78

Chapter 8: Seismic Refraction................................................80
  Data Acquisition...............................................................80
  Data Processing...............................................................80
  Results and Discussion.....................................................82
  Interpretation of Results....................................................84

Chapter 9: Conclusions.......................................................85
  Suggestions for Future Studies.............................................86

References.............................................................................87

Appendix A: Composite Figures (Magnetic Profiles, Ground Penetrating Radar
  Profiles, and Resistivity Profiles)............................................89

Appendix B: Electromagnetic Data..........................................107

Appendix C: Seismic Data......................................................110

Appendix D: Study Site Map..................................................112
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Study site location.................................2</td>
</tr>
<tr>
<td>1.2</td>
<td>The sinkholes in the study area..........................4</td>
</tr>
<tr>
<td>1.3</td>
<td>The sinkholes outside the study area....................5</td>
</tr>
<tr>
<td>1.4</td>
<td>Yellow Springs regional map of known sinkholes........6</td>
</tr>
<tr>
<td>1.5</td>
<td>Base map of the study area with relative topography...9</td>
</tr>
<tr>
<td>1.6</td>
<td>Gamma ray log north of study area......................10</td>
</tr>
<tr>
<td>1.7</td>
<td>How surface depressions are formed......................16</td>
</tr>
<tr>
<td>1.8</td>
<td>Map of Ohio karst areas....................................17</td>
</tr>
<tr>
<td>1.9</td>
<td>Photos of joints in Glen Helen Gorge...................18</td>
</tr>
<tr>
<td>2.1</td>
<td>Simplified diagram of an electrical circuit..............20</td>
</tr>
<tr>
<td>2.2</td>
<td>GPR diagram..................................................23</td>
</tr>
<tr>
<td>2.3</td>
<td>Magnetometer diagram.......................................27</td>
</tr>
<tr>
<td>2.4</td>
<td>EM diagram..................................................29</td>
</tr>
<tr>
<td>2.5</td>
<td>Geophone diagram............................................33</td>
</tr>
<tr>
<td>3.1</td>
<td>Base map of complete survey boundary..................34</td>
</tr>
<tr>
<td>4.1</td>
<td>Base map including long and short resistivity lines...39</td>
</tr>
<tr>
<td>4.2</td>
<td>Photos of Sting/Swift system..............................40</td>
</tr>
<tr>
<td>4.3</td>
<td>Exterminate bad datum points window....................42</td>
</tr>
<tr>
<td>4.4</td>
<td>Diagram of the model blocks and apparent resistivity datum points........43</td>
</tr>
<tr>
<td>4.5</td>
<td>RES2DMOD section with resistivity line 080.............48</td>
</tr>
<tr>
<td>4.6</td>
<td>Base map of utilities.......................................50</td>
</tr>
<tr>
<td>4.7</td>
<td>Resistivity line 080........................................51</td>
</tr>
<tr>
<td>4.8</td>
<td>Resistivity line 085........................................51</td>
</tr>
<tr>
<td>4.9</td>
<td>Resistivity line 090........................................52</td>
</tr>
<tr>
<td>4.10</td>
<td>Resistivity line 095........................................52</td>
</tr>
<tr>
<td>4.11</td>
<td>Resistivity line 100.........................................53</td>
</tr>
<tr>
<td>4.12</td>
<td>Line 125 composite figure..................................54</td>
</tr>
<tr>
<td>5.1</td>
<td>Base map of long and short GPR lines...................56</td>
</tr>
<tr>
<td>5.2</td>
<td>GPR lines 085 and 090.....................................59</td>
</tr>
<tr>
<td>5.3</td>
<td>Line 050 composite figure..................................61</td>
</tr>
<tr>
<td>5.4</td>
<td>Line 075 composite figure..................................62</td>
</tr>
<tr>
<td>5.5</td>
<td>Line 090 composite figure..................................63</td>
</tr>
<tr>
<td>5.6</td>
<td>Radargram from Ghor Al Haditha study..................64</td>
</tr>
<tr>
<td>5.7</td>
<td>Line 095 composite figure..................................65</td>
</tr>
<tr>
<td>6.1</td>
<td>Base map and gray scale shaded relief of magnetic anomalies......68</td>
</tr>
<tr>
<td>6.2</td>
<td>Line 080 composite figure..................................71</td>
</tr>
<tr>
<td>6.3</td>
<td>3D wireframe map of magnetic diurnal correction data...73</td>
</tr>
<tr>
<td>7.1</td>
<td>A GEM-2 electromagnetic surveying unit in use...........74</td>
</tr>
<tr>
<td>7.2a</td>
<td>EM data base map key.......................................76</td>
</tr>
<tr>
<td>7.2b</td>
<td>Base map of 1170 Hz EM data..............................76</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------------------------------------------------</td>
</tr>
<tr>
<td>7.2c</td>
<td>Base map of 3930 Hz EM data</td>
</tr>
<tr>
<td>7.2d</td>
<td>Base map of 13590 Hz EM data</td>
</tr>
<tr>
<td>7.2e</td>
<td>Base map of 42150 Hz EM data</td>
</tr>
<tr>
<td>8.1</td>
<td>Base map of seismic survey line and shot points</td>
</tr>
<tr>
<td>8.2a</td>
<td>Seismograph of north shot point</td>
</tr>
<tr>
<td>8.2b</td>
<td>Seismograph of south shot point</td>
</tr>
<tr>
<td>A.1</td>
<td>Line 000 composite figure</td>
</tr>
<tr>
<td>A.2</td>
<td>Line 025 composite figure</td>
</tr>
<tr>
<td>A.3</td>
<td>Line 035 composite figure</td>
</tr>
<tr>
<td>A.4</td>
<td>Line 040 composite figure</td>
</tr>
<tr>
<td>A.5</td>
<td>Line 045 composite figure</td>
</tr>
<tr>
<td>A.6</td>
<td>Line 050 composite figure</td>
</tr>
<tr>
<td>A.7</td>
<td>Line 055 composite figure</td>
</tr>
<tr>
<td>A.8</td>
<td>Line 060 composite figure</td>
</tr>
<tr>
<td>A.9</td>
<td>Line 065 composite figure</td>
</tr>
<tr>
<td>A.10</td>
<td>Line 070 composite figure</td>
</tr>
<tr>
<td>A.11</td>
<td>Line 075 composite figure</td>
</tr>
<tr>
<td>A.12</td>
<td>Line 080 composite figure</td>
</tr>
<tr>
<td>A.13</td>
<td>Line 085 composite figure</td>
</tr>
<tr>
<td>A.14</td>
<td>Line 090 composite figure</td>
</tr>
<tr>
<td>A.15</td>
<td>Line 095 composite figure</td>
</tr>
<tr>
<td>A.16</td>
<td>Line 100 composite figure</td>
</tr>
<tr>
<td>A.17</td>
<td>Line 125 composite figure</td>
</tr>
<tr>
<td>B.1</td>
<td>Base map of 1170 Hz EM data</td>
</tr>
<tr>
<td>B.2</td>
<td>Base map of 3930 Hz EM data</td>
</tr>
<tr>
<td>B.3</td>
<td>Base map of 1359 Hz EM data</td>
</tr>
<tr>
<td>B.4</td>
<td>Base map of 42150 Hz EM data</td>
</tr>
<tr>
<td>C.1</td>
<td>Seismograph of north shot point</td>
</tr>
<tr>
<td>C.2</td>
<td>Seismograph of south shot point</td>
</tr>
<tr>
<td>D.1</td>
<td>Study site map</td>
</tr>
</tbody>
</table>
List of Equations

\[ I = q/t \] [equation 1] .................................................................................................................. 20
\[ I = V/R \] [equation 2] .................................................................................................................. 20
\[ J = I/A \] [equation 3] .................................................................................................................. 21
\[ D = \frac{1}{2} (V \cdot t) \] [equation 4] .................................................................................................. 57
Acknowledgements

There are many people that helped make this thesis possible. First I would like to thank Dr. Hauser for assisting in collection of the geophysical data, for access to his knowledge about the geophysical equipment used in the study, and for his assistance in data processing. I would also like to thank Kevin Parkman for his assistance with data collection. Thank you to my thesis committee members, Dr. Hauser, Dr. Carney, and Dr. Watts for their guidance, support, and suggestions.

I would like to thank the Ohio University Geological Sciences department for the extended use of their 28 smart electrodes for Wright State’s Sting/Swift system. The extra electrodes certainly made the electrical resistivity survey proceed much more rapidly.

I would also like to thank Dr. Michael Zaleha from Wittenberg University in Springfield, Ohio for the use of the Geological Sciences department’s Supersting equipment. The Supersting equipment saved time and performed particularly well when Wright State’s Sting/Swift equipment was malfunctioning.

I would also like to thank Darrel Cook and the rest of the Antioch University Grounds Department for their consideration and for gladly working with us. Thank you for mowing around our grid of garden stakes for the duration of the summer of 2004.

Last, but certainly not least, I would like to thank my family and friends for their love and support especially during this process.
Chapter 1: Introduction

Five geophysical methods were used in this study to determine the location and extent of known low electrical resistivity anomalous features. These features are believed to be associated with three sinkholes on the Antioch University Campus Commons area. The five methods employed in this study are: electrical resistivity, magnetic surveying, ground penetrating radar, electromagnetic surveying, and seismic refraction. These geophysical methods are used in environmental and geological applications throughout the world every day (Burger, 1992). These techniques are used to determine the locations and geometry of buried wells, buried ordinance, landfills, contamination plumes, pipes, trenches, joints, lithologic interfaces, voids, and aquifers (Burger, 1992).

Site Description

The village of Yellow Springs is located in Greene County, Ohio. It is situated approximately 16.5 miles northeast of Dayton, Ohio. Ohio State Route 68 passes through Yellow Springs in a northeast-southwest direction. Antioch Commons is part of Antioch University and is situated between Corry Street and State Route 68 in Yellow Springs, Ohio (Figure 1.1). In August 2005, the Antioch Commons became the site of a disc golf course.
Figure 1.1. Study site location. The study site is located in Yellow Springs, Ohio on the Antioch University Campus. The inset detail displays the study site which is highlighted in yellow (modified from Garmin, 1999-2002).
Sinkholes have been visible on the Antioch University Campus since the mid-seventies. According to Peter Townsend, Professor of Environmental Science and Geology, the first known collapse was discovered on the Yellow Springs campus in 1975 by an Antioch University chemistry professor. When discovered, dirt and rocks were deposited into the sinkholes. Every three years since the discovery, dirt and rocks have been deposited into the sinkholes (Goertzen, 2003).

At the beginning of data acquisition in June 2004, there were three visible sinkholes located on the campus of Antioch University. Two of the sinkholes are in close proximity to each other, approximately 7.8 meters apart. The third and easternmost sinkhole is approximately 41.4 meters east of the middle sinkhole and is located approximately 355 meters (0.22 miles) from Yellow Springs Creek. The three sinkholes vary in width and depth. As of March 31, 2005, the westernmost sinkhole was 1.9 meters in the north-south direction and 3.0 meters in the east-west direction. The bedrock, the Cedarville Dolomite, was visible at this location. The middle sinkhole was 1.0 meter in the north-south direction and 1.25 meters in the east-west direction. The easternmost sinkhole was 3.0 meters in the north-south direction and 3.5 meters in the east-west direction (Figure 1.2).
Figure 1.2. The sinkholes in the study area. Clockwise from the top left: The western most sinkhole (1.0 meter by 3.0 meters, joint trending N45W), the middle sinkhole (1 meter by 1.25 meters), the eastern most sinkhole (3.0 meters by 3.5 meters), and the backfilling of the sinkholes in June 2005.
There are two more known sinkholes in the surrounding area that are located outside of the study area (Figure 1.3). One is near the study site and located just south of the Antioch School. It is approximately 1.7 meters in the north-south direction and 2.4 meters in the east-west direction. The final sinkhole is located in John Bryan State Park, near the rim of the gorge (Figure 1.4). It was 3.5 meters in the northwest-southeast direction and 4.0 meters in the northeast-southwest direction as of March 31st, 2005. It was observed that the three sinkholes within the study area on the Antioch University Campus grew wider over the course of one year’s time, but records were not kept to determine how much the sinkholes expanded.
Figure 1.4. Yellow Springs regional map of known sinkholes. The five known sinkholes are circled in red, and a joint in Glen Helen Nature Preserve is circled in green. Sinkholes 1, 2, and 3 are found in the study area. Sinkhole 4 is just south of the Antioch School, and sinkhole 5 is found in John Bryan State Park. The borehole location is found outside of the map area, to the north-west of sinkhole 1 (the western most sinkhole). Notice all the sinkholes are found in upland regions, above the Yellow Springs Creek and the Little Miami River. See appendix for GPS coordinates of these features (modified from Garmin, 1999-2002).

Dimensions of Study Area

The dimensions of the grid used in this survey are approximately 250 meters in the east-west direction and 166 meters in the north-south direction. The grid was divided into two sections. The eastern half of the grid contains line 150 through line 250. This section of the study area was processed by Kevin Parkman and is beyond the scope of
this thesis, although some of his data will be referenced. The western half of the grid contains line 000 through line 125. The long lines are parallel to each other and are spaced 25 meters apart in the east-west direction. The shorter lines are 110 meters in length and spaced 5 meters apart in the east-west direction. The shorter lines are labeled 035, 040, 045, 055, 080, 085, 090, and 095 and are located at the respective distance in meters along the grid in the east-west direction. The line labeled 000 is the westernmost line in the survey (Figure 1.5).

The north-south locations of the short lines vary because these lines were placed according to locations of known anomalies. Resistivity data was collected at each long line, and at various short line locations. Magnetic and GPR data was collected along each long and short line. EM data was collected at 5 meter intervals, starting at line 000 and Seismic data was exclusively collected in close proximity to the sinkholes along line 100.

**Previous Research**

Wright State University geophysics students collected resistivity and seismic data at the study site. Several resistivity lines were employed at various locations on the study site. Anomalies were discovered by the preliminary resistivity testing and their locations were confirmed by the geophysical methods used in this study. The results of former data sets were incomplete; therefore previous data was used only for correlation and comparison.
Geologic History of the Area

The Silurian Period ranges from 417 to 443 million years before present. Exposed outcrops of Silurian age are visible in John Bryan State Park, just 3 miles southeast of the Village of Yellow Springs (Ausich, 1987). The outcrops are highwall exposures of the Little Miami River Gorge (Ausich, 1987). These mid-Silurian age rocks are part of the Niagaran Group (Hansen, 1998). The Niagaran Group deposition occurred when Ohio was near the equator during the Paleozoic Era. At this time Ohio’s climate was tropical. Ohio was covered by relatively calm, shallow, and warm seas (Hansen, 1998).

Overburden was measured on the edge of the gorge with a tape measure. The overburden was measured in two locations just east of the study area (west of Yellow Springs Creek). The soil and glacial overburden was measured to be 0.50 meters in the first location and 0.30 meters in the second location. Overburden thickness is approximately 1.50 meters thick at the westernmost sinkhole. Overburden was measured at this location with a tape measure to the base of the sinkhole where the exposed bedrock is visible. The estimated overburden thickness in the gamma ray log (Figure 1.6) was approximately 3.66 meters (12 feet) in 1983 (Gitelson, 1985).
Figure 1.5. Base map of the study area with relative topography. Lines 000 through 125 are in the found in the study area. Notice the sinkhole south of the study area, this is located approximately 100 meters south of the Antioch School.
Figure 1.6  Gamma ray log north of the study area. The log was interpreted by L.A. Weidman and drafted by B.L. Hockensmith (From Gitelson, 1985). The location of this bore hole, relative to the study site is found on the base map (Figure 1.5).
Starting with the lowermost exposed formation and ascending to the uppermost exposed formation the units are as follows: Brassfield Formation, Dayton Formation, Osgood Shale, Laurel Limestone, Massie Shale, Euphemia Dolomite, Springfield Dolomite, and the Cedarville Dolomite (Ausich, 1987). These units are described below.

**Brassfield Formation**

The Brassfield Formation is approximately 8 meters thick in its entirety (Ausich, 1987). The uppermost 7.4 meters of the Brassfield Formation is exposed on the southern gorge wall at John Bryan State Park. Lenticular bedding is present and approximately 10 centimeters thick on average. The Brassfield Formation varies in color from white to grayish-orange to pink. Crinoids (broken), bryozoans, brachiopods, corals, trilobites, and stromatoporoids are common fossils found in this formation (Ausich, 1987).

**Dayton Formation**

The Dayton Formation is approximately 3.8 meters thick (Ausich, 1987). Bedding is thick and even. This unit is white to grayish-orange in color. Broken echinoderm particles are present in thin section, although fossils are not common at John Bryan State Park. (Ausich, 1987).
Osgood Shale

The Osgood Shale ranges from 6.2 to 8.1 meters in thickness at John Bryan State Park (Ausich, 1987). It is interbedded, mottled, dark gray to green-gray with blue-gray silty shale and recrystallized micrite in the lower three quarters of the formation. In this interbedded zone, shale predominates over limestone, and the beds are approximately 10 centimeters thick (Ausich, 1987). At approximately 2 meters above the base of the formation, two limestone beds are predominate. The two limestone beds average 15 centimeters in thickness. Mottling is considerable, and fossil occurrence is fairly low, but crinoids, bryozoans, brachiopods, gastropods, trilobites, and corals have been collected from this formation (Ausich, 1987).

Laurel Limestone

The Laurel limestone is approximately 0.9 meters in thickness at John Bryan State Park (Ausich, 1987). The average thickness of bedding is 10 centimeters, with irregular contacts between beds of uniform thickness. The color of the Laurel Limestone is dark gray. Fossils include crinoids, brachiopods and corals (Ausich, 1987).
**Massie Shale**

The Massie Shale is approximately 1.7 meters in thickness (Ausich, 1987). This formation is dark blue-gray in color. Fossils are rare and include crinoids, bryozoans, brachiopods, trilobites and gastropods (Ausich, 1987).

**Euphemia Dolomite**

The Euphemia Dolomite varies in thickness from 5.2 to 8.5 meters (Ausich, 1987). There are four, 10 centimeter thick beds present at it’s base, the remainder of the formation is massively bedded and vuggy. The Euphemia Dolomite is light-gray in color. It contains normal marine fossils as well as discontinuous beds of *Pentamerus* brachiopods near the contact of the Euphemia Dolomite and the Springfield Dolomite (Ausich, 1987).

**Springfield Dolomite**

The Springfield Dolomite varies in thickness from 6.2 to 7.2 meters (Ausich, 1987). This formation is evenly bedded with an average bed thickness of 10 centimeters. The color is grayish-orange. Ostracods and *Pentamerus* brachiopods are present (Ausich, 1987).
**Cedarville Dolomite**

Only the lower 5.4 meters of this formation are exposed (Ausich, 1987). Cedarville Dolomite in this region is estimated to have been up to 30 meters thick. The Cedarville Dolomite is massively bedded and vuggy. This formation color is light gray to grayish-orange. Fossils include a discontinuous zone of *Pentamerus* brachiopods near the contact of the Springfield and Cedarville Dolomites. Molds of cystoids, crinoids, brachiopods and possibly corrals are also present (Ausich, 1987).

The sinkholes in this study occur in the Cedarville Formation. The Cedarville Dolomite is well known for its massive bedding. Note the blocky, massive bedding of the Cedarville Dolomite and the thinner bedding and less resistive nature of the underlying Springfield Dolomite shown in Figure 1.6.

Viewing a hand sample with a hand lens, the high porosity and coarsely crystalline texture is clearly visible. This coarsely crystalline dolomite was most likely an echinoderm grainstone before dolomatization took place (Ausich, 1987). Lithologically, this formation is very similar to the Euphemia Dolomite (Ausich, 1987). Average size of the replacement crystals, in the Cedarville Dolomite are 0.8 mm. These crystals are slightly larger than the Euphemia Dolomite, with an average crystal size of 0.7 mm, and much larger than the Springfield Dolomite with an average crystal size of 0.06 mm (Roche, 1999). Since dissolution rates are partly determined by surface area, it is not difficult to understand why the Springfield Dolomite is less resistant than the Cedarville Dolomite (Roche, 1999).
Clifton Gorge is located approximately 3 miles east of the study area. Fractures are believed to be instrumental in the formation of the Clifton Gorge (Roche, 1999). There are two hypotheses for the processes that created the fractures. The first is that tectonics were responsible, the second is that Pleistocene glaciers were responsible. The bedrock formations in southwestern Ohio and the study area are part of the Cincinnati Arch (Roche, 1999). This is a large anticlinal structure that causes the bedrock of Ohio to gently slope; it is less than 2 degrees within Clifton Gorge (Roche, 1999). For this reason, tectonics are probably not the reason for the fractures and joints in Clifton Gorge. It is likely that an initial glacial event caused stress and joints in the bedrock, and then later glacial movement caused fractures along the preexisting joints (Roche, 1999).

Karst is a region where underlying water-soluble carbonate rocks, such as limestone, dolomite, salt or gypsum deposits, dissolve and form voids in the subsurface (Schumacher and Hull, 2006). These voids continue to dissolve and expand, and then eventually collapse. Karst regions are characterized by subsurface waterways, cavern systems, and sinkholes. The process of bedrock dissolution is called karstification (Figure 1.7). When a natural collapse appears at the surface, it is commonly known as a sinkhole (Schumacher and Hull, 2006).

A chemical reaction occurs when dissolved carbon dioxide reacts with water. This reaction creates carbonic acid (Roche, 1999). This weak acid reacts with the calcium carbonate (limestone or calcite) and forms bicarbonate ions. Factors, such as temperature, air pressure, and available carbon dioxide, affect the rate of this reaction. Dolomite reacts with carbonic acid, but the dissolution rate is slower than that of limestone (Roche, 1999).
A karst map of Ohio displays, in red, the probable karst regions in Ohio (Figure 1.8). Here these regions are generally limited to upland areas with soluble bedrock that is overlain with less than 20 feet of relatively impermeable bedrock or unconsolidated materials such as glacial till and soil (Schumacher and Hull, 2006). Eastern Ohio contains few sinkholes because the youngest regional bedrock, which is generally sandstone, is greater than 20 feet in thickness and overlies any soluble bedrock.
Two joints were measured in Glen Helen Nature Preserve northeast of the study area. The angles of the joints were measured with a sighting compass. Both of these joints are trending at N45W. The joint in the Cedarville Dolomite, discovered in the western most sinkhole, is also trending N45W. GPS data points were gathered at the
Figure 1.9. Photos of joints in Glen Helen Nature Preserve. Clockwise from top left: A joint in Glen Helen Nature Preserve that trends N45W, and is approximately 1.25 meters wide (with GPS coordinates). The second joint also trends N45W and is approximately 1.70 meters in width. The massive bedded, more resistive Cedarville Dolomite overlies the thinner bedded, less resistive Springfield Dolomite. From the top of the Cedarville Dolomite to the trail is a height of 5.10 meters.

location of the first joint (coordinates could not be gathered for the second location, due to a weak signal). The GPS coordinates for the location of the first joint are: North 39 degrees, 48.009 minutes and West 83 degrees, 53.055 minutes.
Chapter 2: History and Theory of Geophysical Methods

Electrical Resistivity

Electrical prospecting dates back to the 1830’s (Burger, 1992). Robert W. Fox experimented with sulfide ore deposits and their natural currents at Cornwall, England. In the early 1900s Conrad Schlumberger (France) and Frank Werner (United States) applied electrical current into the ground. They then measured the potential difference of the electrical current, and so created the direct-current resistivity method (Burger, 1992). Finally by 1930, almost a century later, all electrical methods except the magnetoelluric method had been investigated in some form. Since 1930 developments of theoretical basis, instrument refinement, and computing technology have improved interpretation of all electrical methods (Burger, 1992).

Modern electrical resistivity (ER or resistivity) methods direct low-frequency alternating current into the earth’s surface, and the potential difference is measured between two points or potential electrodes (Burger, 1992). Resistivity instruments of today are capable of measuring minute levels of electrical resistance (Kearey et al., 2002). The result of the potential difference, or the resistivity, indicates the type of earth material (or lack of material) the current is flowing through (Burger, 1992.) Subsurface materials are usually not homogeneous over the distance of the survey, for this reason current flow can be irregular and complex (Houston, 2002). Positive charges must move from the low potential at the negative terminal of the battery to the high potential at the
positive terminal of the battery. The movement of electrons created by the battery of the instrument is similar to that of a pump. This movement of electrons is the called electromotive force, or emf. The Volt (V) is the unit of emf. The movement of charges through the conducting wire is the current (I) (Burger, 1992). Current is described by the following equation:

\[ I = \frac{q}{t} \text{ [equation 1]} \]

Where \( I \) is the current in amperes, \( q \) is the charge in coulombs, and \( t \) is time in seconds.

Resistance can be quantified as follows: one ohm of resistance allows a current of one ampere to flow when one V of emf is applied.

Ohm’s law is the fundamental principle behind electrical resistivity, it is stated as follows:

\[ I = \frac{V}{R} \text{ [equation 2]} \]

Where \( I \) is current in amperes, \( V \) is voltage in Volts, and \( R \) is resistance in Ohms. (Burger, 1992). The current is directly proportional to the voltage and inversely proportional to the resistance. Resistivity survey instruments measure the ratio of \( V \) to \( I \) (Kearey et al., 2002).

Figure 2.1. Simplified diagram of an electrical circuit. These are the basic components of the Sting/Swift apparatus where the Earth’s shallow subsurface is the resistor. (From Burger, 1992)
Alternating currents are used in electrical resistivity instruments. In other words, the cations and anions switch positions periodically. Two effects would occur if alternating currents were not used. One effect is electrolytic polarization, this process forbids further arrivals of ions at an electrode once permeation occurs. The alternating currents prevent anions and cations from building up in the electrodes themselves, and in the earth materials surrounding the electrodes (Kearey et al., 2002).

The second effect of using direct current is the production of telluric currents. These natural electric currents flow parallel to the Earth’s surface and cause regional potential gradients (Kearey et al., 2002). Telluric currents are the result of the flow of charged particles in the ionosphere. These charged particles are the result of solar discharges. Telluric currents are altered by the varying conductive properties of different rocks. The use of alternating currents eliminates the effect of telluric currents because the telluric current alternately increases or decreases the measured potential difference by the same value. Therefore, the true potential difference is found by summing the measured potential differences over several cycles (Kearey et al., 2002).

Current density is defined as:

\[ J = \frac{I}{A} \] [equation 3]

Where I is the current, and A is the cross-sectional area (Burger, 1992). A complication of the resistivity method is that not only is the resistance of a material dependent on the material the current is flowing through, but also the dimensions of the material (Burger, 1992). If two resistors consist of the same material, are of the same length, and have equal measures of electric current flowing through them, current will most easily flow
through the resistor with the greatest width. If two resistors of the same material and of the same cross sectional area, but different lengths have equal measures of electric current flowing through them, the resistor with the shortest length will have the least resistance to current flow (Burger, 1992).

**Ground Penetrating Radar**

Ground penetrating Radar (GPR) originated from the use of electromagnetic signals to locate buried objects (Reynolds, 1997). Continuous wave transmission techniques were first used by Hulsmeyer and patented in Germany in 1904. In 1926, Hulenbeck developed the first use of pulsed radar for subsurface investigation. Pulsed methods were developed further over the next fifty years (Reynolds, 1997). Early civilian development in the 1960's originated from radio echosounding of polar ice sheets. Impulse radar was first employed for galciological purposes in the 1970's. Ground penetrating radar became widely popular in the mid 1980's, even though it has been used in geological science applications since the 1960's (Reynolds, 1997).

Although GPR peak frequencies vary greatly (from 20 Mhz to 2 Ghz) for geological applications, when depth penetration is more important than resolution, frequencies of 500 MHz or less are desired. (Reynolds, 1997). Greater frequencies produce higher vertical resolution and less depth penetration, therefore the inverse is also true.

GPR is used in a wide variety of geological, environmental, galciological, engineering, construction, archeology and forensic science applications (Reynolds, 1997). This geophysical method is used to determine location of underground storage tanks.
(USTs), contaminate plums, joints, voids, pipes, and wells and other man-made structures. GPR is invaluable in forensic science applications and is used to locate recently buried bodies and remains. It is effective in archaeological studies to determine the location of ancient graves and other buried artifacts. GPR has even been used to determine the location of buried bullion in London, England after a robbery in the late 1980’s (Reynolds, 1997).

A GPR system consists of a signal generator, a transmitting antenna, a receiving antenna, and a receiver (Reynolds, 1997). The final output of the GPR survey is a radargram, which is synonymous to a seismogram. Some more advanced systems have an onboard computer with a real time display of the color radargram on the computer screen (Figure 2.2).

![Figure 2.2. GPR diagram. (A) Components of a radar system, (B) interpreted section, and (C) the radargram display (From Reynolds, 1997).](image-url)
The GPR transmitter generates pulses of electromagnetic energy. This energy is in the form of a radio wave. These radio waves are generally repeated 50,000 times per second. The receiving antenna is usually adjusted to scan the returning signal at a fixed rate, up to 32 times per second. Each scan lasts as long as the two-way travel time range (Reynolds, 1997).

As the radio waves are transmitted into the subsurface attenuation occurs. Attenuation is a complex function of dielectric and electrical properties of the media (in this case the shallow subsurface) in which the radar waves are traveling (Reynolds, 1997). Both composition and water content of subsurface materials affect electromagnetic wave propagation in terms of speed and attenuation (Reynolds, 1997). Reduction of radio wave energy is caused by several factors. Weakening of radio wave energy occurs in the subsurface due to reflection/transmission, (this will occur at each boundary and lithology change) absorption of energy by materials, geometrical spreading, Mie scattering (objects with the same order and wavelength of the signal that cause scattering) and attenuation (Reynolds, 1997).

The GPR dielectrics are either employed in bistatic or monostatic mode depending on the apparatus. Bistatic mode is where two independent antennae are used, one serves as the transmitter and one serves as the receiver. Monostatic mode is where one antenna serves as both the transmitter and the receiver (Reynolds, 1997).

A dielectric is a non conductor of direct electric current. Contrast in the relative dielectric constant between layers in the subsurface causes the reflection of incident electromagnetic radiation. The greater the contrast in the dielectric constant, the greater the volume of radio wave energy that is returned to the GPR receiver (Reynolds, 1997).
Magnetic Surveying

The history of man measuring the magnetic field of the Earth dates back to the second century BC (Reynolds, 1997). The Chinese are believed to be the first to use loadstone (a magnetite-rich rock) in the second century BC as a crude directional technique. In the twelfth century references were made to magnetite compasses used for navigation in Europe. A scientific analysis of the Earth’s magnetic field was first published by an English physicist named William Gilbert. His book, *De Magnete*, was published in 1600. Measurements of the magnetic field were made in Sweden to locate iron ore deposits by 1640 (Reynolds, 1997). By 1870, Thalen and Tiberg developed instruments to measure the magnetic field of the Earth for procedural prospecting. Adolf Schmidt made a balance magnetometer in 1915. This allowed more widespread magnetic surveys to be utilized. During World War II, advances in technology permitted geophysical methods to progress. Optical absorption magnetometers were produced to take highly sensitive and rapid measurements during air reconnaissance surveys. Since the 1970's, magnetic gradiometers have been used to measure the magnetic gradient between sensors and the total magnetic field of the Earth (Reynolds, 1997).

Compasses, such as the crude magnetite instruments used by Europeans in the twelfth century, only measure the orientation of the Earth's magnetic field by rotating into parallelism with it. However, the intensity of the earth's magnetic field is measured by a magnetometer (Burger, 1992). A vector quantity can define the earth's magnetic field at any single point on the earth's surface. Many different factors may affect the local magnetic field such as: voids in the subsurface, objects that produce their own magnetic fields, electrical lines, metal objects, solar flares or storms, the location of celestial bodies, time of day, remnant magnetism, and thunderstorms (Burger, 1992).
A flux-gate magnetometer is an instrument that measures the horizontal and vertical components of the Earth’s total magnetic field (Burger, 1992). A proton-precession (or nuclear-precession) magnetometer simply measures the absolute intensity of the earth's total magnetic field without regard to horizontal and vertical components. Two proton-precession magnetometers, specifically the Geometrics G-856, were used in the Antioch University campus survey. This type of magnetometer's sensor is a cylindrical container filled with a hydrogen atom rich liquid such as water, kerosene, or decane (Geometrics, 2002). Decane is used in both of Wright State University's Geometrics G856 magnetometers. These magnetometers have a resolution of .1 nT and an accuracy of .5 nT and have the ability to store 999 data points (Geometrics, 2002). The magnetometer's sensor, mounted onto an aluminum staff, is connected to the power supply and electronics housing by a cable.

There is a coil in the liquid decane that is magnetically charged when power is applied. This artificially generated magnetic field is parallel to the coil axis and 50 -100 times greater than the natural geomagnetic field (Kearey et al., 2002). The new artificial magnetic field is now aligned at right angles to the Earth’s magnetic field, or the natural geomagnetic field (Reynolds, 1997). The hydrogen nuclei then line up, in a different direction, with this new magnetic field. When the power is cut to the sensor, the hydrogen nuclei precess (spiral) around the earth's total geomagnetic field (Burger, 1992). The precession induces a small alternating current to flow in the coil at the precession frequency (Figure 2.3).
The frequency of precession is proportional to the strength of the total magnetic field. Because of the previous fact, and that the constant of proportionality is a well-known gyromagnetic ratio of the proton, the total magnetic field strength is measured very accurately (Reynolds, 1997).

**Electromagnetic Surveying**

Most probably, the very first electromagnetic method (EM) to be used for mineral ore exploration was developed by Karl Sundberg (Reynolds, 1997). Sundberg developed this method in Sweden during the two decades after World War I. His EM method in
now termed the Sundberg method, and was developed in 1925. As well as mineral ore exploration, his method was also used in hydrocarbon exploration and structural mapping. Innovative work in the 1930's was completed by the Russian geophysicist V.R. Bursian. Separate EM methods have only been commercially available since World War II, and more so since the mid-1960's (Reynolds, 1997).

EM surveying methods may be classified into two systems, time-domain (TEM) or frequency-domain, or FEM (Reynolds, 1997). FEM equipment employ either one or more frequencies, while TEM equipment records data as a function of time. EM methods are either active or passive. Active EM equipment employs an artificial transmitter while a passive system utilizes natural ground signals. In this study a GEM-2 device was employed in the FEM mode. The GEM-2 equipment utilizes an artificial transmitter, therefore it is an active EM method (Reynolds, 1997).

EM surveys are especially useful for surveying large areas in a relatively short period of time (Geophex, 2006). Since EM methods do not require direct contact with the ground, the user may wear the unit over their shoulder and walk at a normal pace while collecting data. The EM method is most useful for shallow reconnaissance surveys, and provides substantial advantages to other geophysical methods for shallow subsurface environmental modeling (Geophex, 2006). The survey can be performed by a single operator, it is unintrusive, uncomplicated logistically, and does not involve labor intensive field work. Buried pipes, geologic joints, trenches and other subsurface anomalous features are easily located and mapped with the EM method (Geophex, 2006).
Electromagnetic surveying equipment utilizes applied currents to locate and distinguish geometry of conducting bodies in the subsurface (Burger, 1992). The induction of current flow results from the magnetic component of the electromagnetic field. A primary electromagnetic field is produced by passing alternating current (AC) through a conductive coil of wire (Figure 2.4).

Figure 2.4. EM diagram. A schematic diagram of the circuitry of an EM (GEM-2) unit (From Geophex, 2006).

If the subsurface material is homogeneous, there is only a slight reduction in amplitude of the electromagnetic waves when compared with the electromagnetic waves traveling through the air (Kearey et al., 2002). If a conducting body is present (not a homogeneous subsurface), the magnetic component of the electromagnetic field penetrating the ground induces alternating currents. These alternating currents are also
known as eddy currents. These eddy currents generate their own flow. The EM receiver then acquires primary currents and secondary currents. The differences between the transmitted and received electromagnetic fields provide information about the electrical properties and geometry of the conductor (Kearey et al., 2002). The depth of penetration of the electromagnetic field depends on the medium it is traveling through. It also depends on the frequency and electrical conductivity. Electromagnetic fields attenuate as they travel through the ground. The amplitude of the signal exponentially decreases with depth. As with GPR, the lower the frequency of the electromagnetic signal the deeper the depth penetration. The maximum depth penetration of the EM method is approximately 500 meters (Kearey et al., 2002).

Seismic Refraction

Exploration seismic methods originated from earthquake studies. These innovative earthquake studies occurred in the mid-to-late nineteenth century. An Irish physicist, Robert Mallet, was the first person to use an artificial energy source in a seismic experiment. He was also the first to coin the term “seismology”. A drop weight was first employed in seismic studies by John Milne in 1885. In 1888, August Schmidt developed travel time-distance graphs to ascertain seismic velocities. In 1899 G. K. Knott explained the generation, reflection and refraction of energy waves at discontinuity boundaries (Reynolds, 1997). Andrija Mohorovicic identified separate phases of S and P waves on travel-time charts calculated from earthquake data. Mohorovicic attributed these separate energy waves to refractions that were traveling along a boundary. This boundary separates a lower velocity material above a higher velocity material. The
interface is the boundary between the crust and the mantle and is now termed the “Moho” (Reynolds, 1997). Significant developments in the refraction method were developed during WWI, to determine the location of heavy artillery. The first seismic reflection survey was performed by K.C. Karcher from 1919 to 1921 in Oklahoma, and by 1927 the reflection method was used routinely for exploration for hydrocarbons. Since the age of computers, major advancements in seismic studies have evolved because of revolutions in computer technology (Reynolds, 1997).

The essential principle of exploration seismology is to study energy waves that travel through the subsurface and are refracted and reflected back to the surface where the signals are recorded (Reynolds, 1997). There are two main types of waves, P-waves and S-waves. P-waves are compression waves and produce elastic deformations and ground particle motions. S-waves are surface waves that are caused purely by shear strain. The velocity of these returning energy waves may then be used to determine the subsurface material and even the rock type that the waves traveled through. The waveforms are recorded and then processed to derive information about the subsurface materials. Subsurface images may then be developed from this information (Reynolds, 1997).

Seismic surveys would not be possible without the sensors that detect the movement of the earth. The detectors are known as geophones. Geophones are employed to convert seismic energy into electrical voltage. An excellerometer is a type of geophone that measures acceleration, and a hydrophone is used in water based seismic surveys (Reynolds, 1997).
A typical geophone consists of a cylindrical coil suspended by springs (Reynolds, 1997). A magnetic field is produced by a small permanent magnet that is fastened to the geophone casing (Figure 2.5). The coil is suspended from a spring, thus creating an oscillating system. A resonant frequency creates the oscillating system that is dependent on the mass of the spring and the rigidity of the suspension. The geophone is implanted into the Earth’s surface via a spike protruding from the base of the casing. The spike ensures good ground coupling. Shear-wave geophones may have two spikes mounted side by side (Reynolds, 1997).
Near surface seismic refraction is invaluable in engineering and environmental applications (Reynolds, 1997). The major advantage to seismic refraction is that it can be used to determine the lateral changes in depth to the top of a refractor (interface). From this, the seismic velocity may be calculated. Seismic surveys are useful in determining how easily the rock can be ripped up by an excavator, the rock strength, and the fluid content in a formation or formations (Reynolds, 1997).
Figure 3.1. Base map of the complete survey boundary. Note: Lines 150, 175, 200, 250 (with red lines and numbers), and several shorter lines (dashed white lines) were collected and processed by Parkman (the red lines and the aerial photo are modified from Parkman, 2006). Lines 000 through 125 were collected and processed by the author of this thesis. Notice the sinkhole south of the survey area, it is located approximately 100 meters south of the Antioch School building.
Chapter 3: Methodology

General Methodology

As previously stated, the survey grid dimensions are 250 meters by 166 meters. The original grid was 250 meters by 150 meters (and 275 meters in width at the south end of the eastern-most line). The grid pattern trends approximately N12E. After the first electrical resistivity line was employed, the line length was increased by 16 meters to accommodate the resistivity line length after two rolls. Every long line was then increased to this length. It was determined that the survey grid would be spaced at 25 meters in the east-west direction. Wooden garden stakes were placed in the ground every 50 meters in the north-south direction, and every 25 meters in the east-west direction. The grid pattern, size, and position was selected to center over the known electrical resistivity anomaly and the sinkholes. The known electrical resistivity anomaly was discovered near line 000 during the spring of 2004. The positioning of the grid was to optimize the likelihood of capturing anomalous features in the survey. It was arbitrarily determined that I would process lines 000 through 125, and the remaining lines would be processed by Kevin Parkman.

After the grid pattern was established and the garden stakes were in place, data collection began. First, electrical resistivity data was collected. Data collection started at line 000 and continued through line 125, working from west to east (Figure 3.1).
Originally there was a line parallel to Corry Street, but it was eventually removed. Lines 200, 225, and 250 were extended in the northern direction by Kevin Parkman after data collection commenced. Line 200 was moved three meters east by Parkman, because of an obstruction, to create line 203.

**Electrical Resistivity**

Electrical resistivity data was collected along each long line, from west to east, with an electrode spacing of 2 meters. The long lines were all 166 meters long in the north-south direction and are spaced 25 meters apart in the east-west direction. Next, two different lengths of short resistivity lines were collected. The shortest lines were 080, 085, 090, and 095 at 54 meters in length. These lines were collected using Wittenburg University’s Supersting equipment. There were 28 smart electrodes available for use. With a spacing of 2 meters, each line length was 54 meters with electrode one starting at 0 meters. The longest of the short lines were 110 meters in length. Wright State University’s Sting/Swift equipment was employed for these lines. The fifty-six smart electrodes were spaced at 2 meters to equal 110 meters total.

**Ground Penetrating Radar**

The lowest frequency antenna available was an 80 MHz, GSSI (Geophysical Survey Systems, Inc.) monostatic GPR antenna. This antenna was used because for the deepest penetration. Resolution is not as fine as a higher Mhz antenna such as a 300 Mhz or 500 Mhz antenna, but depth penetration was of greater concern than resolution in this study. GPR data was collected along each long line and each short line with the 80 MHz antenna.
Magnetic Surveying

Magnetic data was collected from west to east. Data collection started from the north end and worked south for each long and short line. A base station magnetometer was set up and a second rover magnetometer collected data every meter along each line. The base station magnetometer collected data once every minute. Data was collected manually with the rover at varying time intervals.

Electromagnetic Surveying

Electromagnetic (EM) data was collected at 5 meter intervals starting at line 000 and working east through the entire study area. Four different EM frequencies were collected at the same time. A global positioning system unit simultaneously collected coordinates for correlation of the EM data points. The known data points were then used to correlate position with a base map.

Seismic Refraction

Seismic refraction data was collected using a 48 station geophone array, with a spacing of 1 meter. The array is located along line 100. Six different shot point locations were established for the array. The geophones were aligned so that geophone 24, which was the center of the array, was directly adjacent to the middle sinkhole in the study area. Each shot point was separated by a length of 12 meters. The purpose of this seismic refraction survey was simply to locate the zone of attenuation caused by the suspected bedrock collapse and joint that created the sinkholes.
Chapter 4: Electrical Resistivity

Data Acquisition

Resistivity data acquisition began on June 18\textsuperscript{th}, 2004. The dipole-dipole array started at the westernmost long line, designated line 000, and then worked in an easterly direction. (Figure 4.1). Fifty-six smart electrodes were used in conjunction with Wright State University’s Sting/Swift system. Twenty-eight electrodes are the property of Ohio University and 28 electrodes are the property of Wright State University. A smart electrode was placed every two meters along each north-south trending line. This spacing was implemented to give the maximum coverage possible while still maintaining excellent resolution (Figure 4.2).

The fifty-six smart electrodes spanned a distance of 110 meters with the two-meter spacing (starting with electrode 1 at 0 meters). The electrodes are coupled to the ground with electrically conductive stainless-steel stakes. After electrodes 1 through 14 were finished collecting data, the connection between the 14\textsuperscript{th} and 15\textsuperscript{th} electrode was disconnected and then added to the south end of the line. More simply, electrode one was connected to electrode 56.
Figure 4.1. Base map including long and short resistivity lines. Inferred locations of resistivity anomalies are extended east of line 125 by 50 meters.
This process is called rolling. In theory, there is no limit to the number of times rolling may be performed; the only limiting parameter is physical space. With one roll complete, the total length of the resistivity line was 138 meters (adding the 14 electrodes to the south end spaced at 2 meters). The process was repeated again. This time it was repeated with electrodes 15 through 28, until the resistivity line is a total of 166 meters in length (again 14 electrodes spaced at 2 meters).

After the 6 long lines were collected and the anomalies were located using the RES2DINV software, it was determined that several shorter lines should be deployed in between the long lines. The shorter lines were 110 meters in length, and spaced 5 meters apart in the east-west direction, except for the line 080, 085, 090 and 095. These lines were only 54 meters in length because Wittenberg University’s Supersting equipment was utilized for these surveys. This particular Supersting system is equipped with 28
smart electrodes instead of 56 smart electrodes. The short lines are labeled 035, 040, 045, 055, 080, 085, 090, and 095 and are located at the respective distance in meters along the grid (with line 000 as the westernmost line). Anomalies correlating with the major lines were discovered in each shorter line. Resistivity line 060 was collected but technical problems with Sting/Swift system produced incomplete and erroneous data, therefore this data was not included in the final data set.

**Data Processing**

Two computer software programs were utilized to process the electrical resistivity data; RES2DINV software for Windows 95 and Windows NT (version 3.4 by Geotomo software Malaysia, distributed by Advanced Geosciences), and RES2DMOD modeling software (version 3.01 copyright 1995-2002 by M.H. Loke). Several situations were modeled with the latter software program that produced anomalies similar to those found in the processed resistivity profiles.

Once the data was collected in the field and stored in the Sting apparatus, it was downloaded to a computer using the cable provided. A hardware device called a dongle was connected to the printer port on a computer to download the resistivity data. Next RES2DINV was opened from the start menu. Under the “file” menu the "Import Data in AGI Format" option was selected. The data was imported and converted from ASCII format to AGI format by selecting the "read data file" option. Then the data was saved as a *.DAT file extension. Next, this file with the *.DAT file extension was opened. Under the edit menu, the "Exterminate Bad Datum Points" option was utilized. All data points are graphically represented in this window (Figure 4.3). The outlying and erroneous data
points (highlighted in red) were selected and exterminated, and the file was then saved with a new file name to indicate the original data was edited.

![Figure 4.3](image)

Figure 4.3. Exterminate bad datum points window. The “exterminate bad datum points” window found in the “edit” menu of the software program RES2DINV. Extraneous data points may be removed in this window before the data is inverted (from AGI, 1997).

The model refinement option was used in the processing of each resistivity profile. This setting produces a more refined final resistivity profile by interpolating twice as many finite difference data points. To use this feature, the “model refinement” option was selected under the “inversion” option in the main toolbar (Figure 4.4). When model refinement was chosen, “use model cells with widths of half unit spacing” was then selected.
Next the inversion was performed. The first option under the file menu in the main menu, “read data file” was selected (this time selecting the edited file if appropriate). A prompt appears reading, “The data points have been sorted. Do you want to save a copy of the sorted data?” Option “No” was selected. Next under the Inversion menu, the “least squares” option was selected. A window appears to prompt the user to create a file name for the inversion results. The inversion began and the file was saved as an *.INV file extension. The RMS, or root mean square, is the difference between the measured apparent resistivity model and the calculated pseudosection. The RMS errors are normally small, usually less than 5%. If the RMS error is greater than 5% a window will prompt the user to continue with iteration, or a “zero” is entered to terminate the process.

Figure 4.4. Diagram of the model blocks and apparent resistivity datum points. When model refinement is selected during processing, data points are interpolated and model blocks are refined (from AGI, 1997).
The contour intervals were modified from the initial defaults of the program to make each profile consistent in resistivity range. The advantage to creating one consistent profile range is to control the contour definition. The smaller the minimum contour interval, the greater the definition between the modeled resistivity contours becomes. Since the anomalies are of a lower resistivity than the surrounding bedrock, and the minimum apparent resistivities are higher than 25 Ohm-m, the minimum contour was set 25 Ohm-m for each resistivity profile.

The option for changing contour intervals is found in the main menu of RES2DINV. The “change settings” option was selected and “option for contour intervals” was selected next. The option “user defined logarithmic contour intervals” was selected, next the option “1.19, doubles every 4 contours” was chosen. Finally the minimum contour was selected (as noted previously, 25 Ohm-m).

Relative topography was also added to each profile. Relative topography for each line was acquired using Wright State University’s theodolite. Elevation data was taken every four meters along each line, starting at 4 meters. The elevations included for each line were taken from: 4, 28, 56, 80, 108, 136, and 164 meters. For the short lines of 110 meters, elevations were chosen at 4, 22, 44, 66, 88, and 110 meters. For the short lines that required Wittenberg University’s Supersting that were 54 meters in length, elevations at 0, 9, 18, 27, 36, 45, and 54 meters were used.

The secondary and complimentary software program (to RES2DINV) utilized was RES2DMOD. By reading and viewing examples in the help menu, a text file was created to simulate a geologic situation. In this case a low resistivity anomaly was simulated. Once the text file was created, the “file” tab was selected from the main
menu. Next “read file with forward model” was selected. The formerly created text file was then selected from the file directory. Then “model computation” was selected from the main menu and then “calculate apparent resistivity values” was selected. A window appears that states “calculations completed time was 0.00 seconds.” OK was selected and the window closed. Next the “edit” tab was selected from the main menu, and then “display model” was selected. A window appears with several options for contour intervals, the “logarithmic contour intervals” option was selected. Now the file may be saved as a *.DAT, or *.INV file. The file was saved as a *.DAT, was read back into RES2DINV, and the inversion process proceeded as described above. The final resistivity profile was then saved as a *.BMP file extension. The depth to base of each row in the text file (*.TXT file extension) was copied and pasted from the FAULT.MOD file found in the RES2DMOD manual.

Results and Discussion

The resistivity data was very useful in determining the location and depth of the low resistivity anomalies discovered in this study. This geophysical method was also the most labor intensive and time consuming. Difficulties and malfunctions with Wright State University’s Sting/Swift system increased manual labor and consumed valuable field time. However, this method did prove critical to the discovery of the location and size of the anomalies in the survey area. It also gave a vital clue as to the materials that form the anomalous features.

Some false anomalies were discovered in the resistivity data profiles. The false anomalies that are found at the bottom and sides of the profile are known as edge-effects.
Edge-effects occur because of variations in topography and/or variances in resistivity values. What appear to be pronounced lower resistivity edge effects are found in lines 035, 040 in the bottom left corner of each profile (See Appendix A). The possibility will not be dismissed that these low resistivity features are the edges of low resistivity anomalies in some cases. In fact similar low resistivity anomalous features that may correspond with the edge effect features in lines 085 and 090 are found at the bottom of profiles 100 and 125 (Figures 4.8, 4.9, 4.11, and 4.12 respectively).

Depth penetration of the resistivity profiles varied. The longest lines (166 and 110 meters) penetrated deeper into the subsurface than the shortest lines (54 meters). The longest and medium length lines penetrated approximately 17 meters (56 feet) into the subsurface while the shortest lines of 54 meters in length penetrated approximately 11 meters (36 feet). Depth of penetration is due not only to electrode spacing, (2 meters for profiles in this study) but also survey length and subsurface materials. The greater the length of the survey, the deeper the electric current will penetrate into the subsurface.

Low resistivity anomalies surrounded by higher resistivity bedrock are found in each resistivity profile. These low resistivity anomalies from line 000 through line 045 appear to have a similar, thin and slender geometry that extends all the way to the bottom of the profile. The majority of lines from 050 to 125 (except for line 100) have a thicker base and broader spread (See Appendix A). The anomaly found in line 100 centered at 69, and in line 125 at 73.5 meters is only slightly higher in resistivity than the overburden (Figure 4.11, and 4.12, arrow labeled “C”).

Clay has a resistivity ranging from 1-100 Ohm-meters. Soil composed of 40% clay has a mean resistivity of approximately 8 Ohm-meters (Reynolds, 1997). Therefore,
it is very possible these anomalies are soil and/or clay filled. If joints in the subsurface were air filled voids, the resistivity of the anomalies would be much greater than that of the surrounding Cedarville Dolomite. Even though the logarithmic contour intervals in the resistivity profiles do not exceed 1008.4 Ohm-meters, \((635*1.588)\) the raw data was processed several times, and no high resistivity anomalous features were discovered in any of the raw resistivity pseudo sections.

Using the RES2DMOD software, a similar situation was modeled: a low resistivity feature (geometry of a pipe) surrounded by a much higher resistivity value. A low resistivity value representing the glacial overburden and soil, in this case, was fixed at 25 Ohm-meters. The low resistivity value representing the pipe was fixed at 1 Ohm-meter.

The high resistivity value, representing the surrounding Cedarville Dolomite, was fixed at 650 Ohm-meters. The resulting resistivity anomaly is very similar to resistivity profile 080 in this study (Figure 4.5). Both the modeled and collected resistivity profiles were processed in the same manner, except for the lack of relative topography data in the modeled resistivity profile.
Interpretation of Results

The resistivity profiles modeled with simulations of a steel pipe seem to reflect the geometry of the existing high conductivity anomalies in the resistivity profiles adjacent to the sinkholes. It is believed that these resistivity anomalies, although they are in close proximity to the sinkholes, are the result of the water line passing diagonally through the study area (Figures 4.7 through 4.11). The geometries of the anomalies are similar to that of the anomalies that pass through the northern section of the profiles.
Both sets of anomalous features are symmetrical, and appear to extend all the way to the bottom of the profiles. The reason the anomalies appear to extend to the bottom of the profiles is because the high conductivity of the steel pipes. It is believed that the steel pipes, with dipoles on each side, produce an artifact in the inverted data. Therefore, the vertical extent of the anomaly in the inverted results is not considered to correlate with the vertical extent of the pipes in the subsurface.

More than likely the large anomaly visible in line 025 (Figure A.2) is the 8-inch sewer pipe that runs the length of the survey area in an east-west direction (Figure 4.6, solid green line). Similar low resistivity anomalies are present in lines 035, 040, 045, 050, 055, 075, 100, and 125 (see Appendix A) and appear to correspond to this 8-inch sewer pipe. Another similar resistivity anomaly also trends in a northwest-southeast direction toward the Antioch School building (Figure 4.6, red dashed line). This feature is believed to be a one-inch water line that was most likely miss located by Antioch Professor Peter Townsend on the utility map (Figure 4.6, blue dashed line). The low resistivity anomalies found in these resistivity profiles are symmetrical, geometrically alike, and are believed to represent the same subsurface feature (Figures 4.7 through 4.10).
Figure 4.6. Base map of utilities. This landscape drawing was prepared in 2002 by landscape architect, Roger E. Beal of Yellow Springs Design Landscape Architecture. It was designed to propose the multi-use concept plan in the Antioch Commons area. Overlapping data points were used to correlate the base map with this landscape drawing. Please notice the location of the 8-inch sewer pipe and the inferred location of the resistivity anomalies. The dashed blue line is was hand drawn in the field by the Antioch Geology professor, Peter Townsend. The northeast-southwest trending resistivity anomalies appear to extend to toward the Antioch School Building. Also, notice the sinkhole approximately 100 meters south of the Antioch School building.
Figure 4.7. Resistivity line 080. The center of a low resistivity anomaly associated with the water line is at 26.25 meters (A) and the surface expression of a filled sinkhole at 32 meters (B). The center of another slightly lower resistivity anomaly appears at approximately 35 meters (C). There is only a slight indication of a lower resistivity anomalous feature at this location, but at the bottom of the profile the contour intervals are thicker. This may indicate lower resistivity materials that are filling a void. North is on the left.

Figure 4.8. Resistivity line 085. The red arrow (A) indicates the surface expression of the adjacent sinkhole at 21 meters, and the black arrow (B) indicates the anomaly associated with the water line at 35 meters. The top of a low resistivity anomaly is visible at about 18.5 meters towards the bottom of the profile (C). This is likely the same anomaly found in lines 080, 090, 100, and 125 (Figures 4.7, 4.9, 4.10, and 4.11 respectively). North is on the left.
Figure 4.9. Resistivity line 090. The surface expression of a sinkhole occurs at 24.75 meters (A) and the center of a low resistivity anomaly associated with the water line occurs at approximately 32 meters (B). The top of a low resistivity anomaly is visible (C). North is on the left.

Figure 4.10. Resistivity line 095. The surface expression of a sinkhole is at 8.5 meters (A) and the center of a low resistivity anomaly representing the water line is at approximately 16.25 meters (B). Notice the contour intervals are thicker to the right of the anomaly (C). This could be a filled void associated with the joint system. North is on the left.
Figure 4.11. Resistivity line 100. Black arrows at 37.5 meters (A) and 90 meters (B) indicate the location of low resistivity anomalies interpreted as the sewer pipe and the water pipe respectively. What is believed to be a natural low resistivity anomaly is located at approximately 69 meters and is found at the bottom of the resistivity profile (C). The surface expression of a sinkhole is at 81.5 meters and is indicated by the red arrow (D).

Lines 100 and 125, both exhibit a third anomaly (Figures 4.11 and 4.12). This anomaly is of a higher resistivity than the overburden or the anomalies caused by the steel pipes, but it is lower than the surrounding bedrock. It is possible this anomaly is caused by a void filled with soil or clay. Also, in line 100 (Figure 4.11), directly under the surface expression of a sinkhole in at 81.5 meters a slender lower resistivity feature extends down to the bottom of the profile (D). This may be a joint filled with lower resistivity materials, such as soil and clay. There could be a void filled with these materials from approximately 81 meters to 104 meters at the bottom of resistivity profiles 100 (Figure 4.11, (C) white arrow). This is most likely the same anomalous feature found in profile 125 (Figure 4.12, (C) white arrow).
Figure 4.12. Line 125 composite figure. There is no surface expression of a sinkhole adjacent to this resistivity profile. There is a trough feature in the GPR data between approximately 75 meters and 105 meters. The center of two low resistivity anomalies occurs at approximately 27 meters and 105 meters (A) and (B) respectively. The center of a low resistivity anomaly is at 73.5 meters and is located at the base of the profile (C).
Chapter 5: Ground Penetrating Radar

Data Acquisition

Ground penetrating radar data collection started on October 1st, 2004, and was completed the same day. GPR data was collected along each long and short line (Figure 5.1). An 80 Mhz ground penetrating radar was employed for data collection in this survey. Orange marking flags were set at each end of every line. The GPR antenna was pulled as straight as possible along the survey line from the starting flag to the ending flag. An operator sat in a pick up truck bed holding onto the GPR antenna handle. The Strataview equipment was next to the operator so he could view the LCD display of the GPR data as it was being collected. A distance wheel was attached to the antenna to create “tick marks” for every meter in the profile. Additional tick marks were added at areas of importance (such as sinkholes, or metal objects) by the user by pressing a button on the GPR antenna handle. The vehicle was driven slowly enough for the operator to hold onto the GPR antenna handle while collecting data with the instrument.

The file numbers and line numbers were recorded in a field book as the data was gathered. A corresponding file number correlates with each line number. The north-south direction of data collection was also recorded to ensure the GPR profiles were represented correctly. Data was collected from north to south starting at line 000. The direction of data collection was reversed from south to north for line 025. This process continued until all the data profiles were collected. It was more time and energy efficient
Figure 5.1. Base map of the GPR lines and anomalous features. Notice the “trough” shaped anomalies appear in lines 080 through 125 only. Some features in the GPR data appear to trend at the same angle as these “trough” shaped anomalies.
to alternate the direction of data acquisition and rotate the electronic (*.BMP) GPR profiles 180 degrees about the Y-axis, as opposed to starting data collection at the same end of each line. Alternating starting points reduced the time duration of data collection significantly.

**Data Processing**

Depth penetration of the GPR data was established by estimating the velocity of the material the radio waves are traveling through. The velocities of common geological and man-made materials first must be determined. A table was used to ascertain a velocity of radio waves in dolomite (Reynolds, 1997). The velocity of radio waves in dolomite is from 106-115 mm/ns. Depth penetration is defined as:

\[ D = \frac{1}{2} (V \cdot t) \]  
(4)

Where \( D \) (mm) is the depth to the target, \( V \) (mm/ns) the velocity is given for “average soil” at 75 mm/ns, and \( t \) is two way travel time in nanoseconds (ns). Using this equation, (with the “average soil” velocity of 75 mm/ns) depth to the soil/rock interface is approximately .375 meters. Total depth penetration was calculated using the velocity of dolomite (106-115 mm/ns). Using 110.5 mm/ns as the average velocity, total depth penetration for all GPR profiles is approximately 2.76 meters.

The Geophysical Survey Systems, Inc. (GSSI) Radan for Windows Version 3.1 software was used to process all GPR data. The first step in the GPR data processing was to open the Radan software. Next the data was downloaded from the SIR-2 to a computer. At this point in the processing all data files contained *.DZT file extensions.
The file headers of each data file contain information about the file. The purpose of the file header is to describe the settings of the GPR antenna during the time of data collection. File headers include the following information: field information, filename, antenna frequency, range, transmitted pulse position, channel, samples/scan, bits/sample, scans/meter, meters/mark, dielectric constant, and approximate depth scale (Houston, 2002). The only parameter edited in this process was the dielectric constant. This dielectric constants were edited from their original values to a value of zero in each profile. The FIR filter was used to process the GPR data. To do this, FIR filter was selected and then the “high pass horizontal” option was chosen. A value between 0 and 255 was then selected to increase the contrast in each profile.

Once the contrast for each profile was acceptable, the *.DZT file extension was converted into a *.BMP file extension. Using the Radan to Bitmap conversion utility (Rad2BMP), the *.DZT file extensions were converted to *.BMP file extensions. The original *.DZT file must first be closed before the conversion can take place. In the program window under “common options,” “24 bit color image” was selected. To the right of this option, “show markers” was selected. Under the heading “image style,” the “create single bitmap with no scale attached” option was selected. Under the heading “24 color bitmap options,” the colors “red & blue” were selected. Finally the option “show markers” was selected.

Once the files were in *.BMP format they were rotated. Here the files that were collected “backwards” were rotated on the Y-axis so that each profile had the same orientation (north on the left, south on the right). To do this, the GPR files were opened
in Windows Paint program. “Image” was then selected from the main menu, and then
“flip/rotate”. A window appeared and the option “flip horizontal” was selected, and then
“OK” was selected. Some profiles were collected in two sections. These short profiles
were combined together in Canvas 9 to make one continuous GPR profile (Figure 5.2).

Results and Discussion

Ground penetrating radar was a very time effective and valuable tool in this
survey. The speed of data acquisition made the survey process very efficient and the data
proved useful for determining the location of subsurface anomalies. Several types of
anomalies are found in the GPR data.

Figure 5.2. GPR lines 085 and 090. “Trough” shaped anomalous
features found in the GPR data are highlighted in red, white, and
blue. As is indicated, north is on the left and South is on the
right. Each file is labeled with the original *.BMP file number
and the line number for reference. Files 085 and 090 were
collected in two sections, this is the reason there are two files for
one line. See Appendix A for lines 80, 95, 100, 125, and
remaining GPR lines.
These anomalies range from small, subtle low amplitude reflections to much larger very discernable high amplitude reflections. There are also larger, trough-like reflections in the GPR data.

The geometry of this larger anomaly is repeated in more than one GPR profile. The “trough” shaped anomaly appears in the following GPR profiles: 080 between 35 and 49 meters, 085 between 10 and 34 meters, 090 between 13 and 42 meters, 095 between 5 and 25 meters, 100 between 70 and 105 meters, and 125 between 74 and 105 meters (See Appendix A for remaining lines). High amplitude reflections in the radar signal indicate high dielectric constants in subsurface materials. The inverse is also true. Several high amplitude variations are visible in the GPR survey.

**Interpretation of Results**

Some anomalies found in the GPR data are likely associated with the root system of a tree. There is an anomaly in the GPR data that is very prevalent in line 050. In the GPR profile, there is a high amplitude response at 52 meters. There are strong anomalies in the electrical resistivity data and in the magnetic survey data that correspond well with the high amplitude response in the GPR data (Figure 5.3). It appears the high amplitude GPR response may be the 8-inch sewer line running in between the tree roots. The tree roots appear between approximately 35 and 60 meters. By referring to the GPR base map (Figure 5.1) it is noted there is a tree directly adjacent to this profile at about 035 meters. There is a similar anomaly between 90 meters and 115 meters, which does not correspond with the geophysical methods. It is possible that this anomaly may be an old tree root system, or possibly glacial material buried under the soil.
Figure 5.3. Line 050 composite figure. Strong GPR responses are visible between 35 meters and 60 meters and 90 and 115 meters (encircled). A high amplitude response is enclosed in the rectangle that most likely represents the 8-inch sewer line. The dashed vertical lines are for reference.

In line 075 there are two high amplitude responses in the GPR data. These also correspond well with the magnetic data, and to a lesser extent the electrical resistivity data. There are anomalies at 48 meters and 78 meters. These anomalies are enclosed with oval lines (figure 5.4).
Figure 5.4. Line 075 composite figure. High amplitude responses in the GPR data (encircled) correspond with magnetic and resistivity data.

GPR anomalies that appear “trough” shaped are found beginning in line 080 and continue through line 125. This trough shaped anomaly found in the GPR profiles are, in most cases, offset from the resistivity anomaly by several meters. The “trough” geometry most likely represents a joint system or a karst feature such as a collapse zone. In line 090 the center of the resistivity anomaly is at about 32 meters, this corresponds well with a high amplitude anomaly in the GPR data.
In the fall of 2000, GPR surveys were conducted in the Ghor Al Haditha area, west of Jordan (Batayneh, and others, 2002). In this study a 100Mhz GPR with a two-way travel time of 300 nanoseconds, and depth penetration of approximately 15 meters was employed to survey known filled sinkhole locations. The filled sinkholes range in
size from 30 to 50 meters in diameter and 10 to 20 meters in depth and occurred adjacent to the Dead Sea shoreline (Batayneh, and others, 2002). After the field work was completed, a GPR profile was completed over a known sinkhole, and it was concluded that “…the GPR geophysical method appears to provide a rapid non-invasive means of identifying buried sinkholes…” (Batayneh and others, 2002).

A similar “trough” shaped feature that most likely represents a collapse feature appears in line 095 (Figure 5.7). This GPR line runs directly over top of a known filled sinkhole that is just west of the three sinkholes in the study (Figure 5.1).
Figure 5.7. Line 095 composite figure. Notice the “trough” shaped anomaly from approximately 5 meters to 20 meters. A surface expression of a sinkhole is adjacent to the tick mark at 8.5 meters.
Chapter 6: Magnetic Surveying

Data Acquisition

Magnetic survey data collection began on August 7\textsuperscript{th}, 2004. In this first attempt at collection, the base station was set incorrectly and did not gather data. For this reason this data set could not be used and was deleted. Actual data collection began on August 10\textsuperscript{th}, 2004.

Two Geometrics G-856 proton-procession magnetometers (property of Wright State University) were employed in the survey on the Antioch University campus. First, both the rover and the base station magnetometers were set to the correct time and Julian Day. Each magnetometer is connected to a small mobile computer unit with a cable, and is placed on top of a 6-ft aluminum pole. The computer unit rests around the user's neck with a canvas harness (for the rover only). The base station magnetometer was held upright with duct tape, and two wooden garden stakes submerged into the ground. A location for the base station was chosen near the survey area that was a great distance from any visible metallic objects (such as chain link fences, steel goal posts, and manhole covers).
Magnetics data was collected every meter along the long and short lines with the magnetometer designated as the rover. Data was collected along the long lines first. The base station magnetometer was arranged to record short-term fluctuations in the magnetic field due to external variations such as the location of the earth’s moon and other general magnetic disturbances. These fluctuations in the main-field intensities can vary by several nanoTeslas (Nt) (Burger, 1992). The base station magnetometer was set to automatic mode at the beginning of each survey, and a reading was taken every minute. The time of the data collection with the rover magnetometer was variable because the user manually collected data at every meter along the line. For this reason the time interval varied between measurements.

Data was collected starting at the north end of line 000 and proceeding to the south end of the line until every long line was collected (line 000 through line 125). Magnetic data was collected at every meter along both the long and short lines. The magnetic short lines (lines 030, 035, 040, 045, 055, 060, 065, 070, 080, 085, 090, and 095) were collected from west to east in the same manner, but were conducted separately from the long lines and on different days. There was a total of 167 data points collected for each long line (166 meters in length), and 111 data points collected for each short line (110 meters in length). The length of magnetic survey lines varied with lines 080, 085, 090, and 095 (figure 6.1).
Figure 6.1. Base map and grey scale shaded relief map of magnetic anomalies. The dark areas represent magnetic anomalies. Computer interpolation created the lineages above and below the actual survey lines, there are not magnetic anomalies. The sinkholes and resistivity anomalies are included for reference.
It should be noted that magnetic field data are not normally corrected due to variations in elevation (Burger, 1992). Change in elevation was minor in this survey so magnetic field data was not corrected.

Data Processing

Two software programs were used to process the magnetic field data used in this study. The primary software program used was Magmap2000, and the secondary program used was Surfer 8. Surfer 8 was used to create a wireframe map and a shaded relief map of the magnetic data set.

First the magnetic data was downloaded for using the Magmap2000 software. Both the base station and rover Geometrics G-856 proton precession magnetometers were connected, one at a time, to a computer via a PC interface cable. The magnetometer was then turned on. The “import” option was selected from the main menu in the Magmap 2000 program. A window appears with the prompt “select download data type” and G-856 was selected. The baud rate of data transfer is 9600.

Next the survey type was selected. There are three options to choose from, the "base station" option was selected. Once the data finished downloading, it was represented as a line graph in a window in the MagMap 2000 software program. The graph was displayed with time as the x-axis and nanoTesla as the y-axis.

Next an output file was created by the MagMap 2000 program. MagMap 2000 automatically creates a Microsoft Notepad file including the magnetic data. The output files contain X, Y, and Z columns. The X and Y data columns represent the coordinate grid values (location in meters), and the Z column was the magnetic diurnal correction in
nT. The data was then copied and pasted into a Surfer 8 file. The data points were
copied again from the Notepad file and pasted into a Microsoft Excel spreadsheet. From
here the data points were plotted as a line graph (nT vs distance in meters). In lines 000
and 100 there were outlying data points and false anomalies, caused by steel goal posts,
that were removed from the data set (see the magnetic survey wireframe map). The large
anomalies were removed to display greater detail of the plotted data. All the data was
then copied and pasted back into Surfer 8. From here wireframe and shaded relief maps
of the magnetic data were created in Surfer 8.

Results and discussion

A high magnetic response indicates a material is present with greater magnetic or
metallic content than the material surrounding it. The highest magnetic response in the
survey was in line 080, with a high of 329.9 nano-Tesla. This response corresponds
fairly well with the low resistivity values in the resistivity profile as well as the high
amplitude variation in the GPR survey (figure 6.2). Magnetic data were collected at
various time intervals on different days. Magnetic survey data was collected on August
10th, October 16th, October 23rd, November 7th, and November 13th of 2004. The
collection of magnetic data at different times and days could affect the results of the
survey. The final results could also be influenced by the natural fluctuations in the
Earth’s magnetic field.
Figure 6.2. Line 080 composite figure. A very high magnetic response of 329.9 nT is interpreted as the water pipe. This magnetic response is probably related to a high-amplitude GPR response and a low resistivity anomalous feature in the resistivity data.
Metal objects in the study site affected magnetic values during data collection. In lines 000 and 100, erroneous data is the result of steel goal posts inside the study area. A similar false anomaly occurred in line 125 due to a steel backstop from an abandoned baseball diamond. The false anomalies were removed from the data set.

**Interpretation of Results**

Some of the magnetic anomalies present in the data did not correspond to the anomalies found with the other geophysical resistivity. Large anomalies were sometimes caused by unrelated steel objects in the survey area (such as the goal posts in line 000) and were removed from the final data set. However, magnetic did help to validate the other geophysical methods used in this survey. Three-dimensional wireframe (Figure 6.3) and shaded relief maps were created with the diurnally corrected magnetic data. In lines 000 and 125 very high magnetic anomalies were falsely created because of above surface metal objects. The magnetic anomaly in line 000 was truncated for the purpose of exhibiting more detail in the remaining magnetic data set.

Magnetic surveys are especially useful in archeological studies. These surveys are effective because of the high susceptibility of iron objects often found in ancient sites, and the thermoremnant magnetism produced when bricks and other clay-based artifacts were fired and manufactured (Burger, 443). Although this is not an archeological survey it is possible that fill material, including clay-based objects, was previously used to fill in the sinkholes. Materials such as bricks, field drainage tile, asphalt, and other used construction materials may skew interpretations of the magnetic survey data.
Figure 63. 3D wireframe map of the magnetic diurnal correction data. Notice the elevated “flat spot” in line 000 between 20 and 40 meters (red arrows). This is the result of the removal of erroneous data due to the steel goal posts in the survey area. Note the deep depression in line 125 (black arrow). This is believed to be the result of a steel chain link batter’s cage adjacent to survey line 125.

It is also possible that disturbances in the soil due to the construction of Herman Street, and then the destruction of Herman Street, could cause fluctuations in the magnetic data. It was observed through the course of data collection that residual asphalt, most likely material associated with Herman Street, was resting inside the study area. It is not determined what type or how much construction material is present in the shallow subsurface of the study area.
Chapter 7: Electromagnetic Surveying

Data Acquisition

Electromagnetic surveying data collection began on December 18\textsuperscript{th}, 2004 and was completed the same day. Data was collected at 5 meter intervals and was very simple and time efficient. Once the operator eliminated himself of all metallic items, the GEM electromagnetic surveying unit was donned. A strap fits over the shoulder of the user, while the GEM rests by the operator’s hip (figure 7.1).

![Figure 7.1. A GEM-2 electromagnetic surveying unit in use (from Geophex).](from Geophex)

Orange, non metallic traffic cones were positioned at both ends of the survey. The cones were used as guides, so the operator could walk in a straight line. Data was collected in the same manner as the GPR data (i.e. north to south then south to north until complete). Once a 166- meter path was completed, the operator moved 5 meters east,
turned 360 degrees and began collecting data parallel to the last path. Data collection began on line 000 and continued every 5 meters eastward until the end of the survey area was attained.

**Data processing**

Electromagnetic data was downloaded from the GEM-2 apparatus into Surfer version 8. A personal computer was connected to the GEM-2 via an RS-232 cable and WinGEM (a windows-based program) was used to download the data. Four frequencies were collected by the GEM-2 simultaneously during the survey. The frequencies used were 1170Hz, 3930Hz, 13590Hz, 42150Hz. These frequencies are determined by the user.

Next a plan view map of each frequency, along with the GPS coordinates, was created in Surfer 8 and saved as a *.BMP file extension. A GPS unit collected location data simultaneously as the electromagnetic survey data was collected to ensure the correct position of the collected EM data.

**Results and Discussion**

The electromagnetic (EM) survey indicates large anomalous features in the same proximity as the electrical resistivity anomalies. The four EM frequencies collected have differing depths of penetration. As with GPR, the greater the frequency is the shallower the depth penetration. The 1170 Hz frequency contains several lineages and anomalous features. The 3930 Hz frequency has some stronger features that are prevalent in the data set. The 13590 Hz data set contains several strong features, and the 42150 Hz data set has the strongest anomalous features of the four frequencies (Figure 7.2).
Figure 7.2 a. EM data base map Key. The four frequencies collected with the GEM-2: 1170 Hz, 3930 Hz, 13590 Hz, and 42150 Hz (Figures 7.4a, 7.4b, 7.4c, and 7.4d respectively). The sinkholes, long lines, short lines, sewer lines, water lines, and resistivity anomalies are included for reference.

<table>
<thead>
<tr>
<th>Key</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goal Posts</td>
<td>Red</td>
</tr>
<tr>
<td>Group of Trees</td>
<td>Light green</td>
</tr>
<tr>
<td>Single Tree</td>
<td>Orange</td>
</tr>
<tr>
<td>Sinkhole</td>
<td>Blue</td>
</tr>
<tr>
<td>Filled Sinkhole</td>
<td>Yellow</td>
</tr>
<tr>
<td>Manhole Cover</td>
<td>Pink</td>
</tr>
<tr>
<td>Long Lines</td>
<td>Green</td>
</tr>
<tr>
<td>Short Lines</td>
<td>Gray</td>
</tr>
<tr>
<td>Resistivity Anomaly</td>
<td>Black</td>
</tr>
<tr>
<td>Sidewalk</td>
<td>Yellow</td>
</tr>
<tr>
<td>Cement Pads</td>
<td>Orange</td>
</tr>
<tr>
<td>Ball Field Backstop</td>
<td>Yellow</td>
</tr>
<tr>
<td>Borehole Location</td>
<td>Green</td>
</tr>
<tr>
<td>8&quot; Sewer Pipe</td>
<td>Blue</td>
</tr>
<tr>
<td>1&quot; Water Line (probable location)</td>
<td>Purple</td>
</tr>
</tbody>
</table>

Figure 7.2b. Base map of 1170 Hz EM data.
Figure 7.2c. Base map of 3930 Hz EM data.

Figure 7.2d. Base map of 13590 Hz EM data.
Interpretations of Results

Electromagnetic surveying proved useful in determining the location of the known anomalies. Plan view maps of each frequency: 1170, 3930, 13590, and 42150 Hz, were created from the raw data. The plan view map of the EM acquisition corresponds extremely well with the resistivity anomalies on the base map. Each figure was created showing the correlation between the electrical resistivity anomalies and the anomalous features found in the EM data.

The strong EM anomaly running east-west in the data is interpreted as the 8-inch sewer line that ran under Herman St. The section of the sewer line that runs north-south in the northwest corner of the survey is not represented in the EM data set. This may be
because the actual location of the line is several meters to the west. The goal posts in this corner of the survey are visible as anomalous features and found all four frequencies.

The second strong anomaly that correlates well with resistivity data and runs diagonally through the study area is interpreted as the 1-inch water line. It is not known why the anomaly forks or splits in the southeast corner of the data set. The north-south trending anomaly on the far east of the survey boundary correlates well with the sidewalk, and is most pronounced in the 42150 Hz data (Figure 7.2d). It is possible that this anomaly is caused by the asphalt used in the construction of the sidewalk.
Chapter 8: Seismic Refraction

Data Acquisition

Seismic refraction data was collected in early May, 2005. Data collection was completed in one day. Seismic refraction data was collected using a 48 station geophone array. The geophones were spaced at 1 meter intervals. Two geophone arrays were proposed, one on line 100 and one on line 125. Due to time constraints, only one geophone array was established. This array is located along line 100 (Figure 8.1).

Six different shot point locations were used for the array. The geophones were aligned so that geophone 24, also the center of the array, was directly adjacent to the middle sinkhole. Each shot point was separated by a length of 12 meters.

Data processing

The principal purpose of the seismic study was to determine the location of attenuation due to the suspected joint or joints related to the sinkholes. The secondary purpose of this method was to locate possible areas of further study. This geophysical survey method was intended to be brief.

This method was simply used as an experiment to demonstrate the location of the joints and to correlate these locations with the previous four methods. This preliminary study was intended to act as a catalyst for future geophysical studies by Wright State
graduate students, and was not designed to be a processed in detail. For these reasons, the seismograms were printed directly from the Stratoview system and interpreted. No in depth data processing was performed for this geophysical method.

Figure 8.1. Base map of the seismic survey line and shot points. The long lines, short lines and sinkholes are included for reference. Notice that attenuation occurs directly adjacent to the middle sinkhole.
Results and discussion

The 48 geophone array was purposely set to center over the sinkholes and the cavernous joint beneath. As expected, strong attenuation of seismic energy is clearly observed in the data between geophones 23 and 24. This strong attenuation clearly indicates the presence of a cavernous void in the bedrock that disrupts the transmission of seismic energy. A small amount of seismic energy passes through the discontinuity, but the energy is insignificant (Figures 8.2a and 8.2b).

In figures 8.2a and 8.2b, attenuation is indicated by the location of two parallel red lines located at geophones 23 and 24. The short blue horizontal lines in the seismograph identify the onset of refracted seismic wave energy. These refracted waves are hardly detectable beyond geophone 24.
Figure 8.2a. Seismograph of north shot point. A seismograph display of a 48 geophone array centered over the middle sinkhole on line 100. The shot point is located 12.5 m from center on the north end of the survey. Notice that attenuation occurs between geophones 23 and 24. Diagram modified from Reynolds, 1997.
Interpretation of Results

The use of seismic refraction proves that there is indeed attenuation in the subsurface. Attenuation occurred at the location it was expected between geophones 23 and 24. It should be noted that a cable break occurs between geophones 24 and 25. The attenuation that is present is not related to a defective connection between the cables. It is interpreted that attenuation is most the result of a geological feature, such as a collapse zone or a joint. A pipe or water line buried in the glacial till would not likely cause such sharp attenuation of seismic energy because normally these buried utilities would not breach the bedrock.
Chapter 9: Conclusions

The primary goal of this geophysical study is to determine if the anomalies discovered were indeed associated with the known karst features on the Antioch University Campus. The secondary goal of this study was to determine the extent and location of these anomalies.

The most successful methods for determining geometry were electrical resistivity and GPR. The most useful method for determining an accurate location of a void or joint was seismic refraction. The best method for reconnaissance, ease of use, and speed was the electromagnetic method. The electromagnetic method was helpful in confirming locations of anomalies in the GPR and resistivity methods. The magnetic method was useful as a complimentary survey in establishing the location of anomalies detected by the other methods. However, some outlying anomalies were discovered with the magnetic method that were not established with the other four methods.

Some resistivity anomalies of much higher conductivity than the surrounding bedrock are most likely not associated with the karst features in the study area. The low resistivity anomalies in the northern section of the survey that run east-west are believed to be the result an 8-inch steel sewer pipe that is below what was an extension of Herman Street. A 1-inch abandoned water line is buried under the soil and glacial overburden. The water line trends northwest-southeast through the study area, and is most likely the cause of a low resistivity anomaly in the resistivity data. It is interpreted that the low resistivity anomalous feature adjacent the sinkholes (lines 080 through 125) is the result
of a water line. A separate low resistivity anomaly is present at the bottom of these resistivity profiles. This anomaly is believed to be a cavernous void filled with low resistivity materials such as soil and clay.

A collapse feature is present in the GPR data (lines 080 and 125) and is probably caused by the developing sinkholes. The bedrock joint that is located in the westernmost sinkhole is trending, N45W. This is the same angle that the two joints in the gorge trend. For this reason, it is likely that the “trough shaped” features adjacent to the surface expressions of the sinkholes are the result of a karst related collapse. This collapse feature was probably induced by a joint in the Cedarville Dolomite.

The results of this study indicate that the five geophysical methods utilized were successful in determining if the anomalies were associated with the karst in the survey area. It is concluded that the anomalies with the highest conductivities are the result of a steel sewer line and a steel water line. Secondary anomalies in the data are believed to be the result of filled voids in the bedrock. It is also concluded that the extent and location of geologic anomalies were successfully determined with the geophysical methods utilized.

**Suggestions for Future Surveys**

Perhaps a more detailed GPR survey should be performed near the sinkholes and especially in between the easternmost and the westernmost sinkholes. It may be effective to use a higher frequency GPR antenna for better resolution in the vicinity of the karst features. It may also be appropriate to perform additional detailed seismic surveys surrounding the sinkholes to determine exactly where joints and collapse features exist and how far they extend.
References


Hansen, Michael C., 1997. The Ice Age in Ohio, Educational Leaflet No. 7.


Loke, M. H. 1999. RES2DMOD Version 3.01, Distributed by Advanced Geosciences, Inc.

Ohio Department of Natural Resources, Division of Geological Survey, Ohio Karst Areas Map.


Appendix A: Composite Figures (Magnetic Profiles, Ground Penetrating Radar Profiles, and Resistivity Profiles)
Figure A.1. Line 000 composite figure. From top to bottom: magnetic profile, GPR profile and resistivity profile.
Figure A.2. Line 025 composite figure. From top to bottom: magnetic profile, GPR profile and resistivity profile.
Figure A.3. Line 035 composite figure. From top to bottom: magnetic profile, GPR profile, and resistivity profile.
Figure A.4. Line 040 composite figure. From top to bottom: magnetic profile, GPR profile, and resistivity profile.
Figure A.5. Line 045 composite figure. From top to bottom: magnetic profile, GPR profile, and resistivity profile.
Figure A.6. Line 050 composite figure. From top to bottom: magnetic profile, GPR profile, and resistivity profile.
Figure A.7. Line 055 composite figure. From top to bottom: magnetic profile, GPR profile, and resistivity profile.
Figure A.8. Line 060 composite figure. From top to bottom: magnetic profile and GPR profile.
Figure A.9. Line 065 composite figure. From top to bottom: magnetic profile and GPR profile.
Figure A.10. Line 070 composite figure. From top to bottom: magnetic profile and GPR profile.
Figure A.11. Line 075 composite figure. From top to bottom: magnetic profile, GPR profile, and resistivity profile.
Figure A.12. Line 080 composite figure. From top to bottom: magnetic profile, GPR profile, and resistivity profile.
Figure A.13. Line 085 composite figure. From top to bottom: magnetic profile, GPR profile, and resistivity profile.
Figure A.14. Line 090 composite figure. From top to bottom: magnetic profile, GPR profile, and resistivity profile.
Figure A.15. Line 095 composite figure. From top to bottom: magnetic profile, GPR profile, and resistivity profile.
Figure A.16. Line 100 composite figure. From top to bottom: magnetic profile, GPR profile, and resistivity profile.
Figure A.17. Line 125 composite figure. From top to bottom: magnetic profile, GPR profile, and resistivity profile.
Appendix B: Electromagnetic Data
Figure B.1. Base map of 1170 Hz EM data.

Figure B.2. Base map of 3930 Hz EM data.
Figure B.3. Base map of 13590 Hz EM data.

Figure B.4. Base map of 42150 Hz EM data.
Appendix C: Seismic Data
Figure C.1. Seismograph of north shot point.

Figure C.2. Seismograph of south shot point.
Appendix D: Study Site Map
Figure D.1. Study site map. The solid red lines indicate the long survey lines collected and processed by Parkman (2006).