

# KARST MAPPING WITH GEOPHYSICS AT MYSTERY CAVE STATE PARK, MINNESOTA

By Todd A. Petersen and James A. Berg  
Geophysics Program  
Ground Water and Climatology Section  
DNR Waters  
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## 1.0 Summary

A new visitor center is planned for Mystery Cave State Park on a known karst area. Geophysical surveys were conducted to locate existing karst features and to help site the building away from known sinkholes and caverns. Resistivity imaging, seismic refraction, drilling, and rock coring methods were all used for this project.

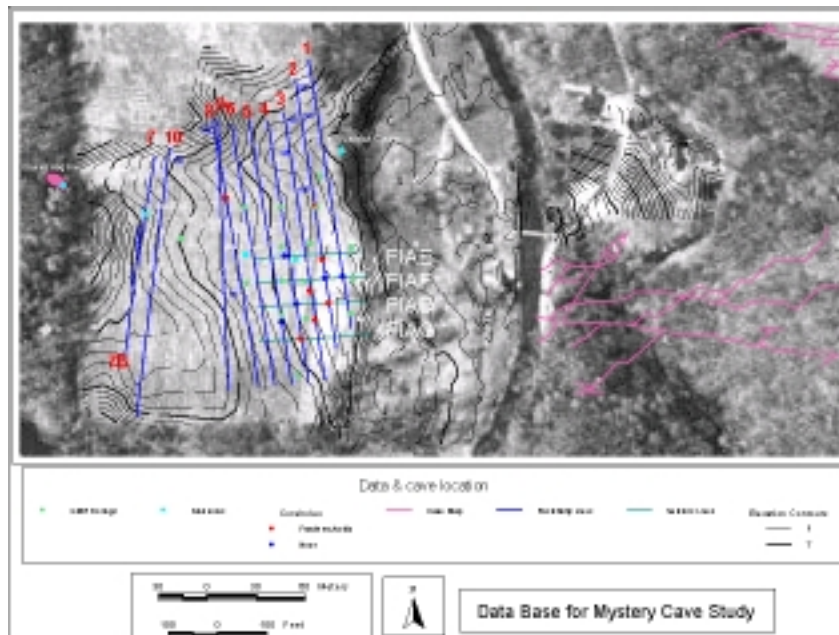
The data collected at Mystery Cave demonstrate that seismic and boring information worked well in mapping the bedrock surface, but did not detect potential sinkholes very well. Surface resistivity followed by rock coring, did a much better job of defining existing conduits and potential sinkholes.

The trend of possible voids and collapse features suggests that they follow the same fracture systems that controlled the development of Mystery Cave. The mapped features are mostly shallower than Mystery Cave.

The resistivity data provided essential information to DNR Parks both for mapping the karst resource and for siting its new visitor center.

## 2.0 Introduction

Geophysical investigations were conducted at Mystery Cave to assist in determining the most promising foundation location for a new interpretive center for the park. The proposed site is in an area that has previously been farmed and is now mostly open field with some areas overgrown with trees. Figure 1 shows the location of all the data collected during this project. The plan view of Mystery Cave (which shows the main bedrock fracture trends) is plotted on the eastern side of the Root River. The locations of the resistivity lines, seismic lines, and boring data are shown on the left side of this figure.



*Figure 1. Database for Mystery Cave Study*

We initially made four seismic refraction lines to get a general picture of the bedrock surface in the proposed area of the new park building. Subsequently, the DNR Bureau of Engineering ordered a series of borings to bedrock to confirm and expand the seismic data.

Because the potential for underground conduits was high in the area, we decided that a different set of techniques was necessary to locate potential sinkholes before siting a building. We chose the relatively new technique of resistivity imaging (Loke, 2000), followed by bedrock coring of any resistivity anomalies, to better define the geology of the area. This resistivity method records both lateral and vertical changes in the unconsolidated material and in the bedrock. It does not resolve the top of bedrock as well as seismic refraction: depth to bedrock estimates can be off by 5 to 10 feet when the bedrock is shallow (10 to 15 feet). But it is a very good method for measuring sand versus clay or void versus limestone.

### 3.0 Methods

The seismic surveys were conducted using two linear spreads of 24 geophones each, with an overlap of two to three geophones where the spreads met. The distance between geophones was 10 feet. A 12-pound sledgehammer was used as the seismic source for these lines.

The resistivity imaging method uses standard arrays developed as sounding techniques and modifies them to create two-dimensional resistivity profiles. A line of electrodes is placed at equal 3-meter intervals along the desired profile. Four electrodes are used at one time. Two inject current into the ground and two read the electrical potential between them. The resistivity meter and switch box automatically read many combinations of current and potential electrodes from short offsets to long offsets starting at one side of the electrode spread and moving toward the opposite end. The short offsets analyze the shallow earth, and the longer offsets penetrate more deeply.

At Mystery Cave, the resistivity data were collected with a Sting R1 Resistivity Meter in conjunction with the Swift automatic multi-electrode system. Fifty-six electrodes spaced 3 meters apart (for a total length of 165 meters) were used to collect one segment of data. Two array types were selected: dipole-dipole and Wenner-Schlumberger.

The dipole-dipole array gives good horizontal resolution but may have a poor signal to noise ratio (S/N) because the potential electrodes are outside of the current electrodes. The Wenner-Schlumberger array is more directed for vertical resolution, but it also gives reasonable horizontal resolution. This method has greater S/N than the dipole-dipole method because the potential electrodes are placed between the two current electrodes. The dipole-dipole method worked well for most lines. Lines 6 and 10 were collected with the Wenner-Schlumberger array for comparison purposes.

### 4.0 Data Processing

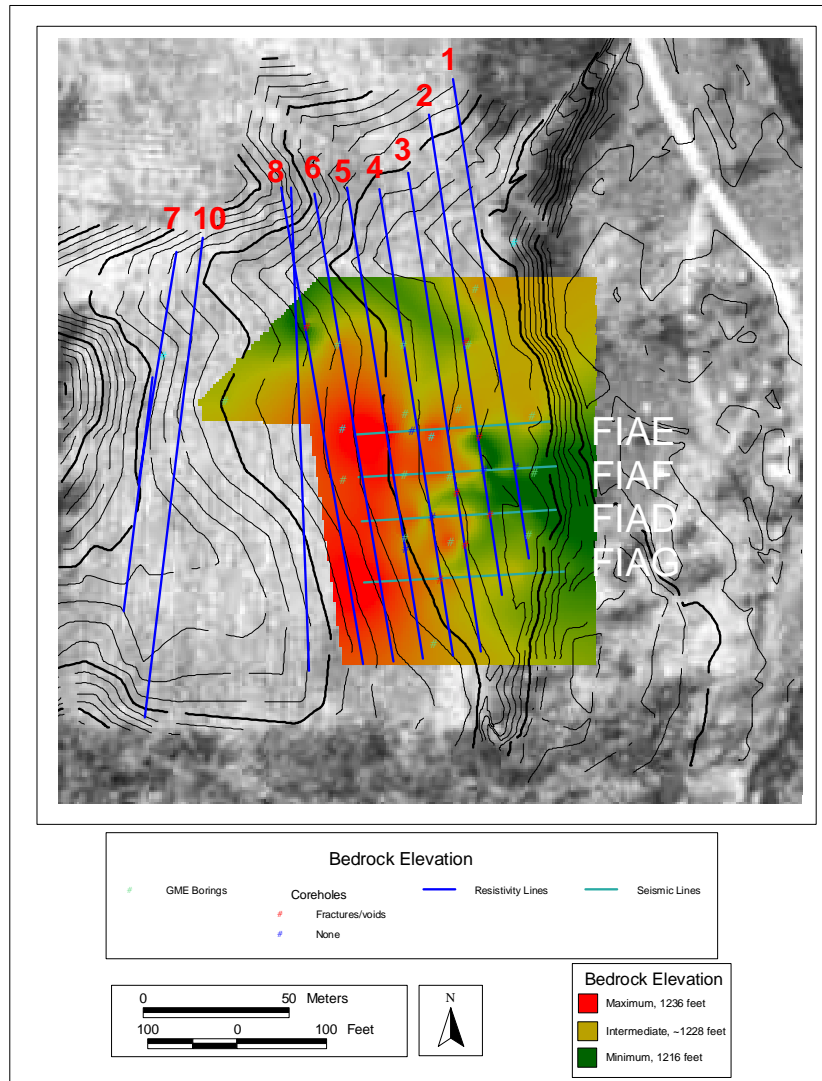
Standard refraction analysis was applied to the seismic data to determine the depth to bedrock and the bedrock velocity. Data analysis was done with Rimrock Geophysics SIPT2 program, which uses the delay time method refined by up to three passes of ray tracing.

The resistivity field data comprise resistance measurements between various electrodes and related geometry information. An apparent resistivity value is calculated, which depends only on the resistance measurements and the array geometry. These data are plotted as a pseudosection, which is a plot of the apparent resistivity values based on the geometry of the electrodes. Each apparent resistivity value is plotted midway between the set of electrodes used in making the measurement. The pseudo depth of each point is plotted at the median depth of investigation for the particular array. Pseudosections are difficult to work with and are not very meaningful to nongeophysicists. For these reasons, a data inversion is done to help with the interpretation. The inversion produces a plot that shows a resistivity value for each horizontal and vertical node. This resistivity inversion section is then used to interpret subsurface lithology.

These data were inverted with RES2DINV, a commercially available program. Programming steps include editing out bad data points, setting up appropriate horizontal and vertical filters, selecting the inversion method, and then interpreting the data.

5.0 Discussion

Figure 2 is a bedrock surface elevation map derived from the boring and seismic data that are plotted on top of this map. The resistivity lines are shown for location purposes only. They were not used to make this map. An approximate bedrock surface was picked from the resistivity data for comparison with the seismic and boring information. It is not shown because the results were unsatisfactory; the resistivity imaging data did not sufficiently resolve the bedrock surface. The bedrock surface estimates from the resistivity data did not correlate well with seismic and boring information.



**Figure 2. Bedrock Elevation from Seismic and Borehole Data**

Note that the bedrock surface generally slopes toward the Root River (which is just off the right edge of this figure) and also slopes toward the swale just north of the mapped area.

Figure 3 shows surficial and buried resistivity anomalies. Some of these anomalies appear to be isolated and not necessarily in communication with other anomalies. Most of them, however, form trends that are parallel with or on line with known karst features. The five major lineaments that are shown on Figure 3 are all parallel with the main axis of Mystery Cave.

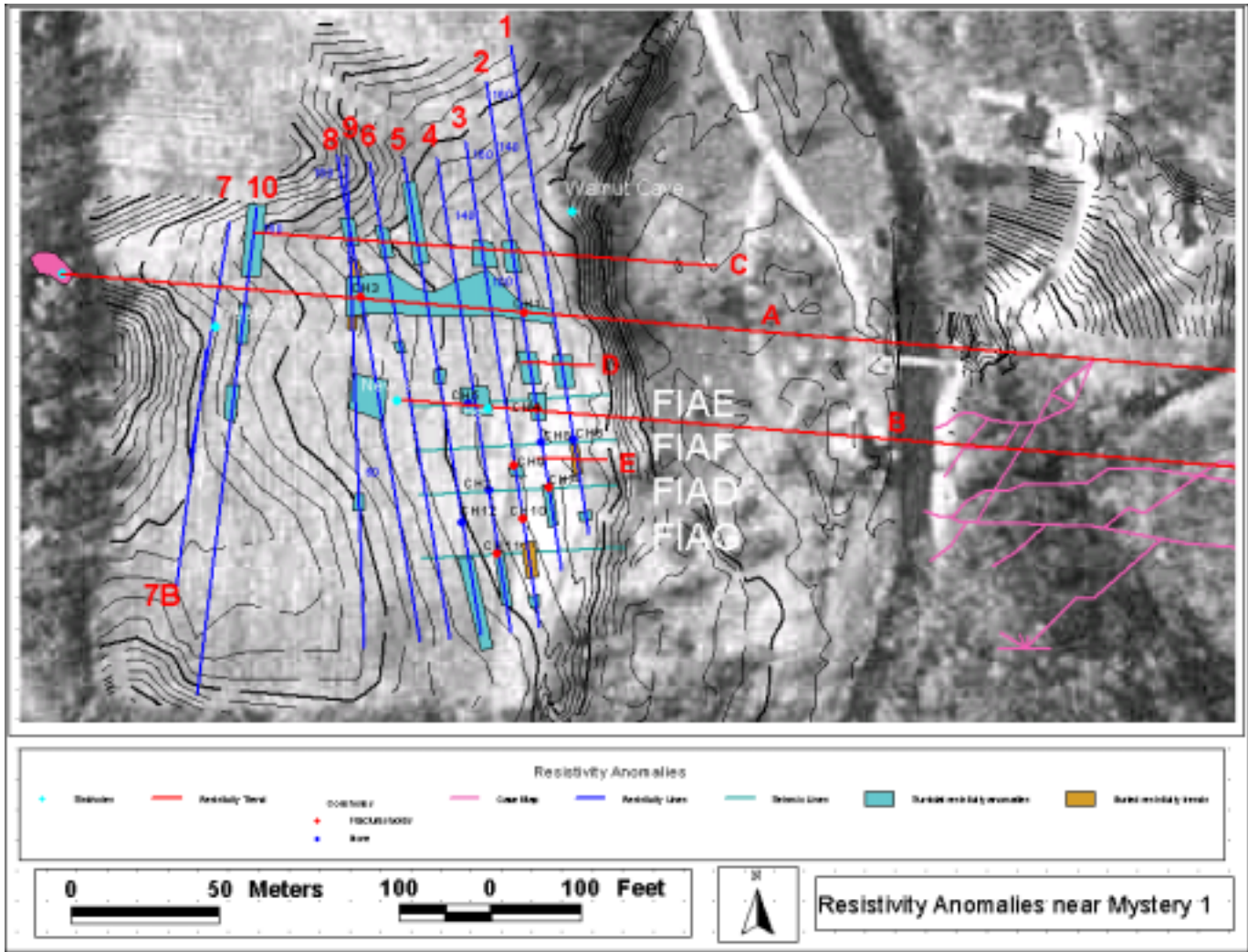
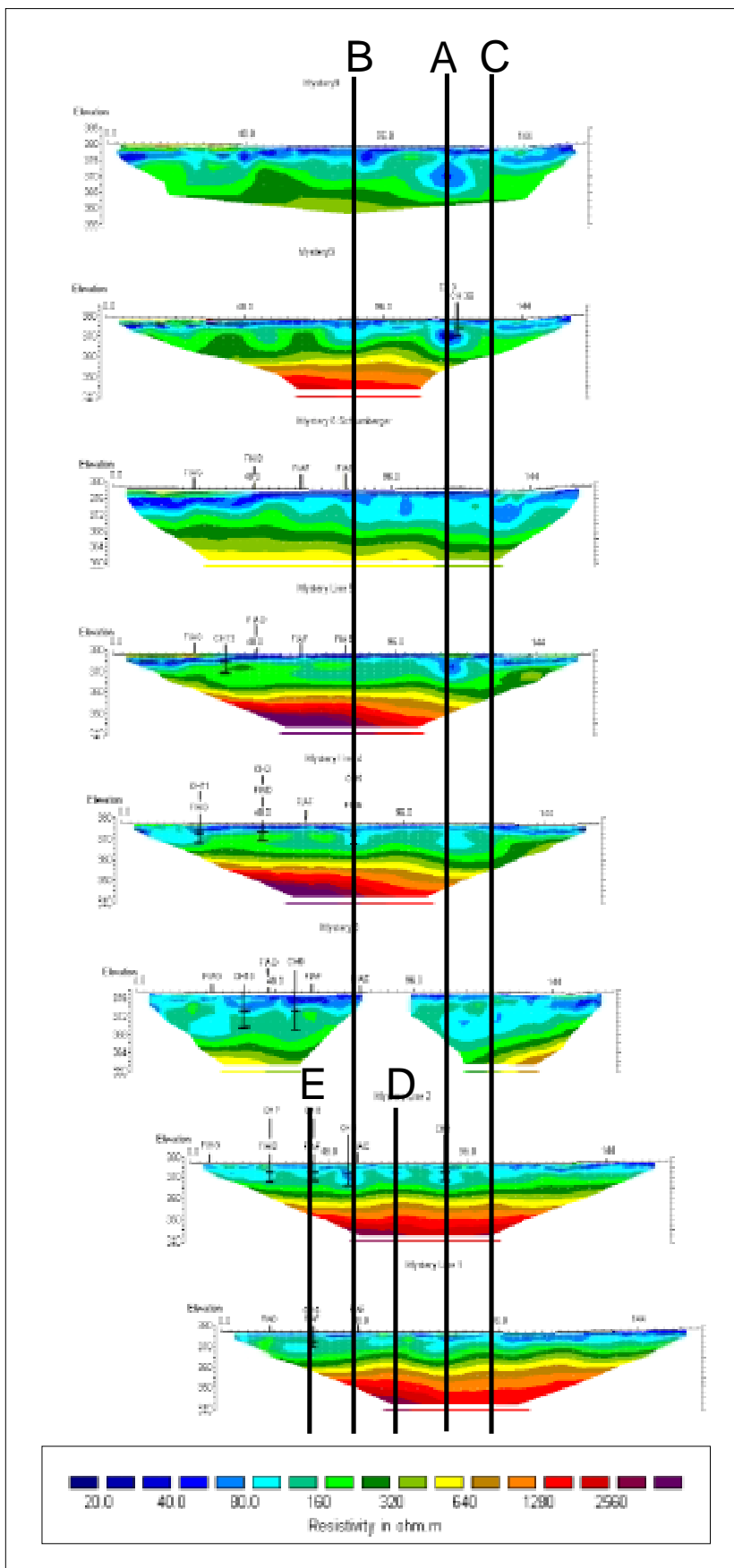


Figure 3. Resistivity Anomalies



**Figure 4. Resistivity Lines 1-6, 8, and 9**

This figure shows the continuity of resistivity anomalies along fracture zones A through E.

Figure 4 shows the two-dimensional resistivity inversion for resistivity lines 1 through 6 and 8 through 9. The data are aligned such that a vertical slice through this figure forms the west-northwest to east-northeast trends shown on Figure 3. These trends parallel the main Mystery Cave passage orientation. The two other cave passage trends (northeast-southwest and northwest-southeast) are more difficult to see in these data because the resistivity lines are more parallel to those trends. The ideal method to see anomalies is to orient the resistivity lines perpendicular to the expected anomaly trend. Figures 5 and 6 are larger scale versions of Figure 4 containing resistivity lines 1 through 4 and 5, 6, 8, and 9, respectively.

All of the coreholes that intersect resistivity lines are plotted on the resistivity sections. The horizontal ticks represent the top of bedrock and the bottom of the corehole for each hole.

Trend A is the strongest trend in the resistivity data. It transects a low resistivity zone in all of the resistivity lines and it directly passes through Ground Hog Sink to the west of the study area. It is very prominent on all of the data except for line 6. This is probably because line 6 was gathered with the Wenner-Schlumberger method and all of the other lines in this figure were gathered with the dipole-dipole method. The dipole-dipole method is much more sensitive to horizontal changes than the Wenner-Schlumberger method. Because of its physical array, the Schlumberger method does more horizontal averaging. Thus, the anomaly is not as well constrained horizontally on line 6.

Two anomalies along this trend were test drilled to ground truth the resistivity data. Corehole (CH) 1 was drilled at resistivity line 2 (Figure 5) and CH 3 was drilled at resistivity line 8 (Figure 6). CH 1 found 14 feet of overburden above very fractured bedrock. A 4-inch void was discovered at 25 feet and the drilling water was lost into the ground below 26 feet. The driller lost 400 gallons of water in a 5-foot run. This implies large fractures and a significant karst piping system.

CH 3 was drilled at the large resistivity anomaly at station 118, line 8. The depth to bedrock here is 24 feet. There was virtually no recovery of rock core here because the auger flights were heavily twisted due to penetrating weathered bedrock. The core barrel would not fit through them.

After a larger diameter auger was acquired from the home office, CH 3 was redrilled just north of the original hole. This has been labeled 3B to distinguish it from CH 3. CH 3B hit hard bedrock at 16 feet. Competent rock core was collected from 16 to 30.5 feet. This shows that the resistivity anomaly is wider than the physical void. The resistivity anomaly at resistivity line 8 is 9 or 10 meters wide, but the drilling data indicate a narrower feature. This discrepancy probably occurs because the resistivity stakes were placed 3 meters apart and the smallest dipole covers 9 meters of ground. Because these voids are at least partially clay and water filled, they are more conductive than the surrounding limestone and are preferred paths for the electrical current.

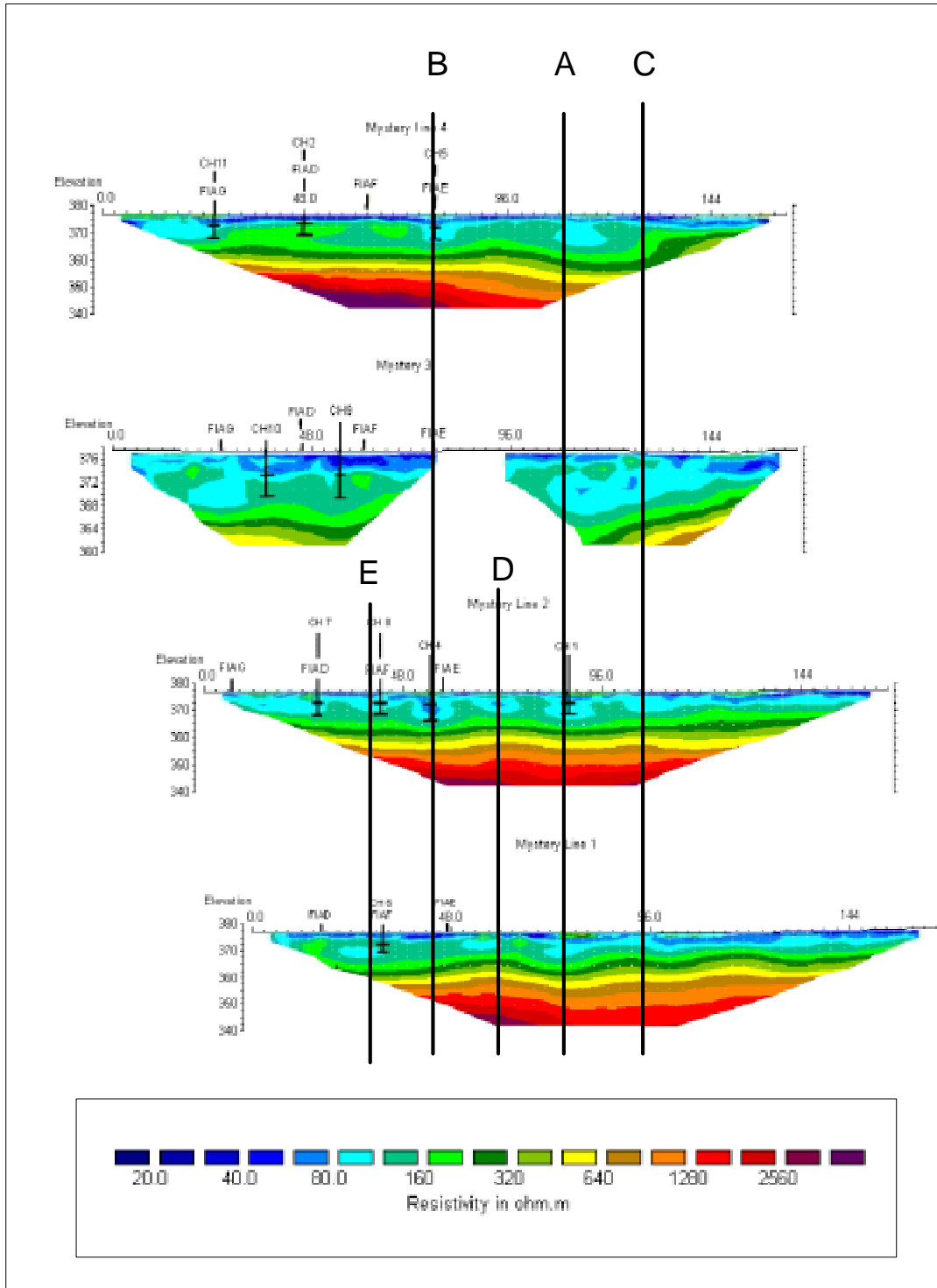
Trend B also connects a series of strong resistivity anomalies and passes through two known sinkholes. It passes through both the newly discovered sinkhole and a sinkhole seen on an old aerial photograph, called new sink and GPS sink, respectively, on Figure 3. Trend B also runs through CH 4, where a large void space was discovered beneath a thin limestone roof.

Trend B also passes through areas on line 5 and line 1, which have no associated resistivity anomaly. Perhaps the solution cavities along trend B follow a fracture trace that has been unevenly weathered. The fracture may be very thin in some areas and widen out much larger in other areas. Alternatively, the different resistivity signature may be due to a different fill material in the voids (air, water, or clay). It may be due to variations in both void size and fill material.

Trend C also connects a series of low resistivity anomalies, especially on lines 3, 5, 6, 8, and 9. This trend may have influenced the location of the surface swale. Trend C is less developed than trends A and B.

Trends D and E connect features on resistivity lines 1 and 2 but do not seem to continue farther west.

All of these features trend east-southeast roughly parallel to the main passages of Mystery Cave. This suggests that these trends are fractured controlled conduits. The conduit has collapsed and been refilled near CH 3 on trend A. On trend B, there are two known sinkholes plus the cavern found at CH 4.



*Figure 5. Resistivity Lines 1–4 with Fracture Zones A through E*

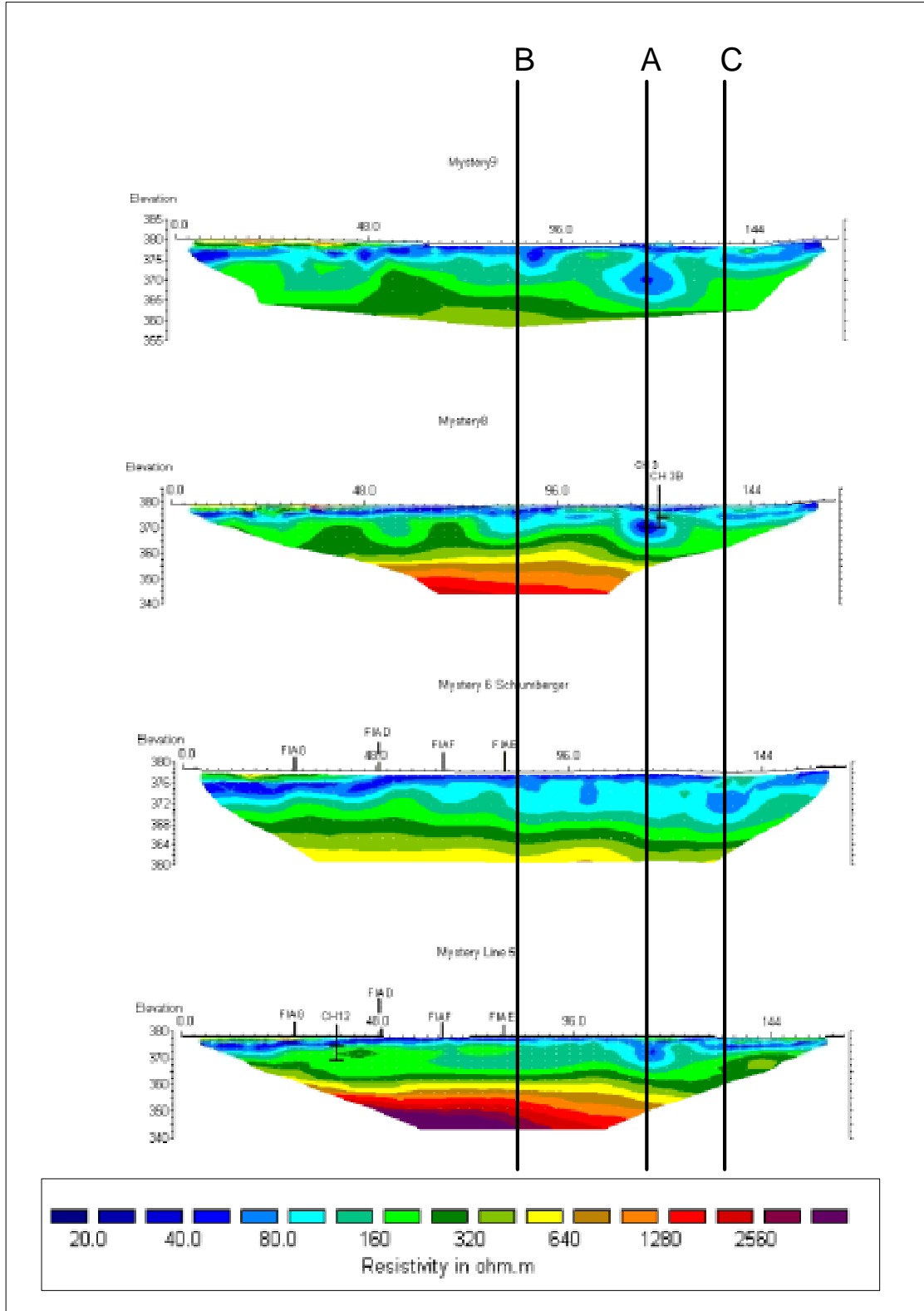


Figure 6. Resistivity Lines 5, 6, 8, and 9 with Fracture Zones A, B, and C



Figures 7–10 are the seismic line cross sections for FIAD through FIAG. The locations where the resistivity lines cross the seismic lines are plotted across the top of the seismic cross sections. The locations and depths to bedrock of nearby borings and coreholes are plotted at the appropriate elevations. The coreholes were usually located on the seismic line, but the borings were located off line. On these figures, the borings (labeled with a B) were projected into the seismic line, and the coreholes (labeled CH) were located on the seismic lines. Both the boring and the corehole bedrock picks all matched quite well with the seismic data. The match between the seismic and corehole information was especially good on line FIAD.

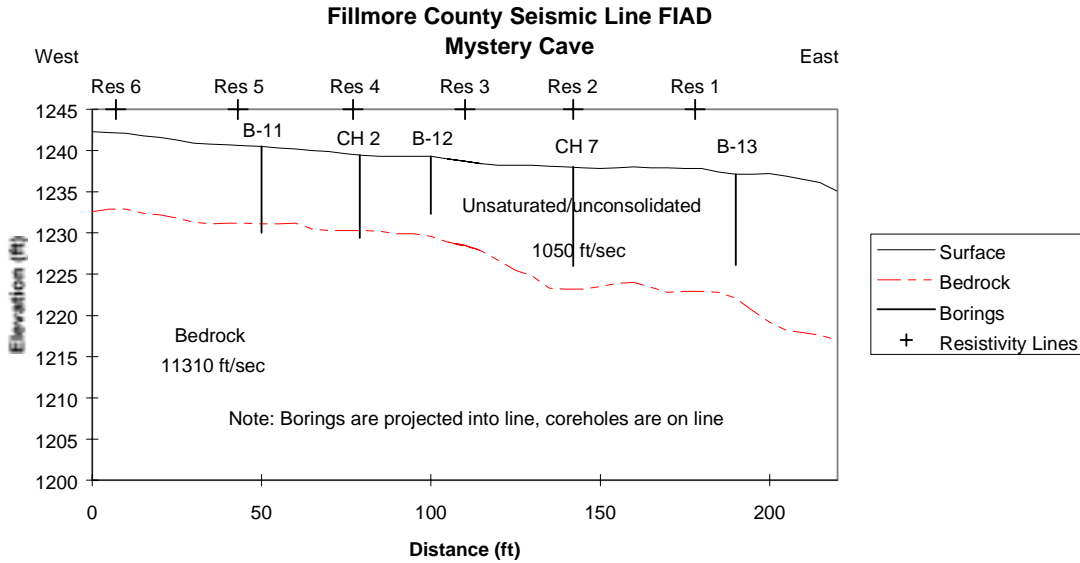


Figure 7. Seismic Line FIAD

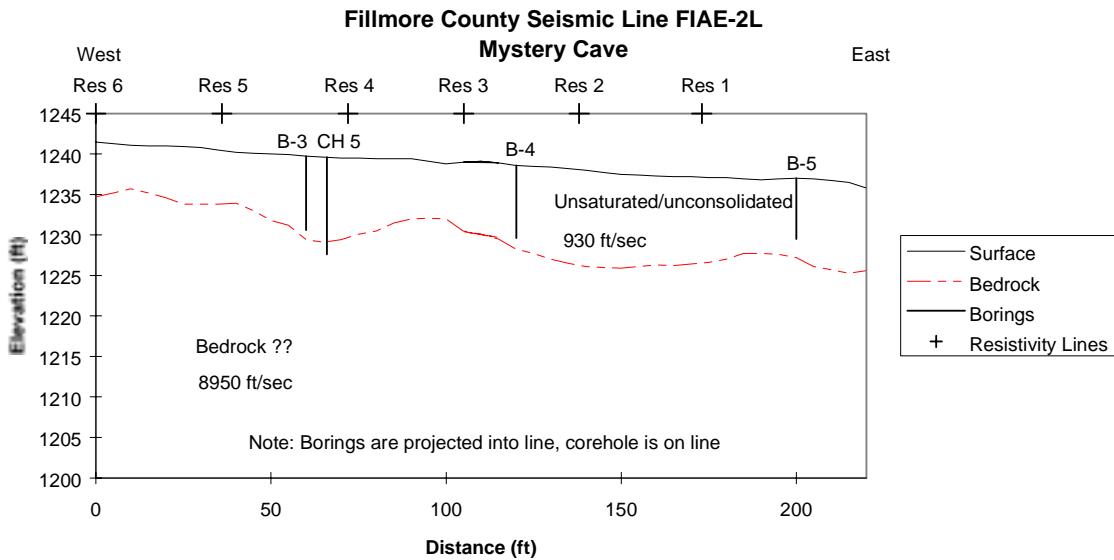
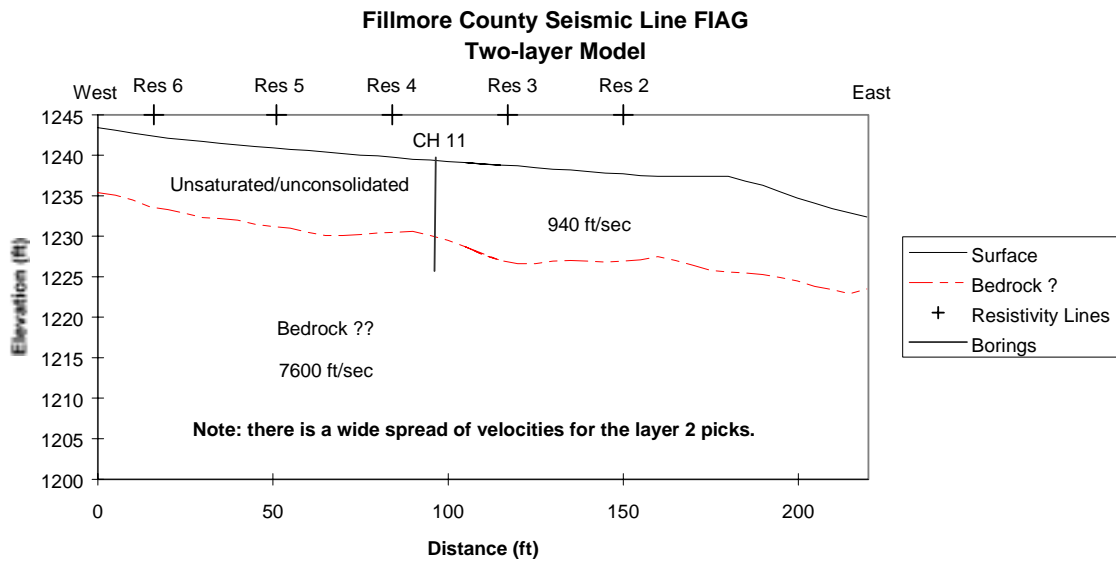
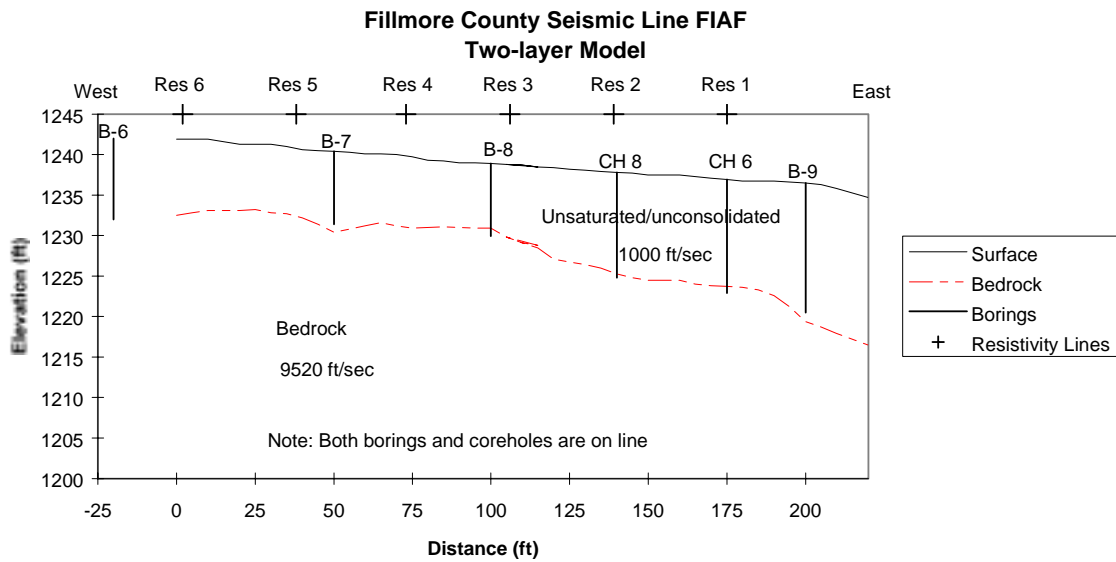


Figure 8. Seismic Line FIAE



6.0 References

Loke, M. H., 2000, Electrical imaging surveys for environmental and engineering studies:  
[www.agiusa.com/literature.shtml](http://www.agiusa.com/literature.shtml)