Research Report
KTC-07-10/SPR244-02-1F

KENTUCKY TRANSPORTATION CENTER

EVALUATION OF GEOPHYSICAL METHODS AND GEOPHYSICAL CONTRACTORS ON FOUR PROJECTS IN KENTUCKY

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Research Report
KTC-07-10/SPR244-02-1F

EVALUATION OF GEOPHYSICAL METHODS AND GEOPHYSICAL CONTRACTORS ON FOUR PROJECTS IN KENTUCKY

By

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College of Engineering
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In cooperation with

Transportation Cabinet
Commonwealth of Kentucky

And

The Federal Highway Administration
U.S. Department of Transportation

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16. Abstract

This report details four geophysical testing projects that were conducted in Kentucky for the Kentucky Transportation Cabinet. The four projects were as follows: KY 101, Edmonson and Warren Counties, US 31-W, Elizabethtown Bypass, Hardin County, KY 61, LaRue County, and US 27, Pulaski County.

Two contractors conducted the investigations for this study: P.E. LaMoreaux and Associates (PELA), and The Center for Cave and Karst Studies, Western Kentucky University (CCKS).

The geophysical methods and the contractor that were used on each project was as follows: KY 101 – (PELA) Electrical Resistivity and Microgravity, US 31-W – (CCKS) Microgravity, KY 61 – (CCKS) Electrical Resistivity and Microgravity, and US 27 – (CCKS) Electrical Resistivity and Microgravity.

These two methods preformed well and this report recommends that these geophysical methods be used in Kentucky on a regular basis. One contractor (PELA) did not perform well. Although his report was well written and his analysis clearly illustrated, he was over a year behind schedule in finishing his report and he was over budget by $15,000. This report recommends that this contractor not be permitted to do further geophysical work in Kentucky.

The second contractor (CCKS) performed very well. His report was also well written and his analysis was clear. He finished each of his projects on time and within budget. This report recommends that this contractor be permitted to do more geophysical work in Kentucky.

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EXECUTIVE SUMMARY

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INTRODUCTION

The highway system is aging at a rapid rate and construction and maintenance dollars are always critical. Rehabilitation of older, in-service pavements and construction of new highway facilities often require knowledge of subsurface conditions. This information is expensive, time consuming and often very difficult to obtain. In addition, The Commonwealth of Kentucky possesses problem geologic formations (karst) that often limit the effectiveness of traditional subsurface techniques. The use of non destructive testing (NDT) and geophysical methods may prove to be a valuable tool in gaining a better understanding of these conditions and provide further information for the design, construction and rehabilitation of highways.

Many states throughout the country have been using NDT and geophysical techniques to assist in the design, construction, and maintenance of their transportation systems for decades. Various techniques have been successfully utilized to identify potential collapse zones in karst terrain, locate voids under pavements and bridge approaches, identify in-filled scour pockets around bridge foundations, and for a number of other transportation related applications.

BACKGROUND

Geophysical Methods

As experienced engineers know, geologic conditions at a particular proposed construction site can be very complicated – with wide variability over short spatial distances. To develop the optimum amount of geotechnical data for design would require numerous bore holes scattered over the site. Unfortunately, generating geotechnical data for a site, using drilling and logging techniques can be very expensive. For this reason designers are many times forced to develop designs that are based on insufficient data. This can cause problems during construction which often results in expensive change-orders and budget overruns.

Geophysical methods and non-destructive testing (NDT) methods can help to supply more complete data, at more closely spaced intervals, than borehole data. In the last two or three decades, numerous geophysical and NDT methods have been developed and used in various industries to provide more complete geophysical data at construction sites. Richard Benson(1) of Technos, Incorporated, presented a paper to the First International Geophysics Conference in St. Louis, in December of 2000. In that paper, he provided an excellent summary of many of the geophysical and NDT methods currently in use. Much of the following discussion is based upon information in that paper.

Airborne Geophysical Methods are commonly used to develop data over a wide area of interest. These can include information obtained from satellites. It can also include data taken from aerial photography, infrared photography and thermal imaging. These methods can provide fairly “coarse” data of a particular region at reasonable cost. This information can then supplemented with more precise data obtained from other geophysical methods, if necessary. A summary of airborne methods is listed in Table 1 which has been taken directly from Reference 1.

Table 1. Airborne or Satellite Measurements.

Method	Parameter/Condition Measured
Satellite Imagery Multispectral and radar	Surface image documentation and terrain interpretation
Aerial Photo and Video Imagery	Surface image documentation and terrain interpretation
Thermal Imagery	Temperature of surface (moisture/seeps/karat)
Airborne geophysical measurements	Subsurface characterization (e.g., magnetic data, electromagnetic, conductivity or resistivity data and radiometric measurements of natural radiation)

Surface Geophysical Methods can provide total site coverage in a relatively short period of time at reasonable cost. Depending upon the method used, great sample density can be obtained at fairly high speed, to collect data for total site coverage. These methods can provide information at depths of up to 100 feet. With this type of resolution and coverage, very small geologic or subsurface anomalies can be detected. Table 2 (from Reference 1) lists some of the major surface geophysical methods.

Table 2. Surface Geophysical Methods.

Method	Parameter/Condition Measured
Ground Penetrating Radar	Dielectric constant (stratigraphy/top of rock/karst)
Electromagnetic Frequency and Time Domain	Electrical conductivity (lateral variation in soil and rock/ inorganic contaminants)
VLF	Electrical resistivity (lateral variations in soil and rock, fractures, contacts)
Resistivity	Electrical resistivity (spatial variation in soil and rock/ inorganic contaminants)
SP (spontaneous potential)	Electrochemical and streaming potential (seepage/karat)
Seismic Refraction	Seismic velocity (top of rock/rippability)
Seismic Reflection	Seismic velocity (stratigraphy)
Seismic Surface Wave Analysis	Seismic velocity/dispersion (S-wave/stratigraphy)
Microgravity	Density (bedrock channels/karat)
Magnetics	Magnetic susceptibility (location of ferrous minerals, utilities/tanks/ drums/metal debris)
Metal Detector	Electrical conductivity of metal (location of utilities/tanks/metallic debris)
Thermal Imagery	Temperature of surface (moisture/seeps/karat), location of pipelines
Radiation	Natural gamma radiation (exploration for ores, fracture patterns)

Downhole Geophysical Methods yield very localized geophysical information using (as the name implies) existing boreholes or monitoring wells. If the borehole does not already exist, this method can be fairly expensive. However, unlike surface geophysical methods, resolution does not decrease with depth. As can be seen from Table 3 (Reference 1), there are many different borehole methods.

Table 3. Borehole Logging/ Measurements (Single Hole).

TYPE OF LOG	PARAMETER/CONDITION MEASURED
Nuclear	
Gamma	Natural gamma radiation/stratigraphic correlation, relative clay content.
Gamma Spectrometry	Natural gamma radiation/characterize mineralogy based upon radio-isotopes
Gamma-Gamma (Density)	Relative density/Bulk density of strata sometimes used as a cement bond log.
Neutron-neutron	Relative moisture/moisture content above the **water** table, porosity below the water table.
Electrical/Electromagnetic	
Induction	Electrical conductivity of soil, rock, and pore fluids
Resistivity	Electrical resistivity of soil, rock and pore fluids
Single Point Resistance	Resistance/Stratigraphy/vods/fractue/flow
Spontaneous Potential (SP)	Electrochemical effects at wall streaming potential due to movement of pore fluids/Stratigraphy/voids/fracture/flow
Magnetic susceptibility	Magnetic susceptibility of soil and rock for stratigraphic purposes, also responds to presence of ferrous metals for location of steel casing, drilling hazards, or other well problems
Radar	Travel time of the electromagnetic wave/Identification of anomalous conditions, far-field from the borehole, such as fractures, cavities, tunnels and mines
Fluid	
Water level	Water level of fluids in borehole
Conductivity	Electrical conductivity of borehole fluids/Provides a measure of borehole fluid, specific conductance (or total dissolved solids). Assess movement of water into or out of borehole locating permeable or fracture zones. Determine salt water interface.
Temperature	Borehole fluid temperature (groundwater flow)
Flow Meter (Fluid **Movement)** Impeller Heat Pulse	Fluid **flow** within borehole (groundwater flow)
In-Situ Chemical Sensors (Minimum diameter borehole 2 to 6 inches)	Borehole fluid electrical conductivity (flow/contaminantByoonduchvity, pH, oxygen, Eh, specific ion electrodes, tracers.
Mechanical	
Caliper	Borehole diameter (voids/cavities)
Deviation (inclinometer)	Borehole deviation from vertical
Acoustic/Sonic/Seismic	
Sonic or Full **Wave** Sonic	P and S wave velocity (near borehole)
Borehole **Imagery**	
Television	TV image of borehole wall/geologic strata, voids and fractures
Acoustic Televiewer (ATV)	Acoustic image of borehole wall/geologic strata, voids and fractures
Borehole Image processing Systems (RIPS)	Electrical image of borehole wall/geologic strata, voids and fractures
Scanning Sonar	Acoustic travel time/measurements of large voids **and cavities** intersecting the borehole

Surface to Borehole Measurements are summarized by Benson[1] as "typically seismic measurements made to provide P and S wave velocities to calculate bulk modulus. Resistivity and radar measurement may also be made between the surface and borehole, but are less common." Table 4 (Reference 1) summarizes those methods.

Table 4. Surface-to-Hole Measurements.

Method	Parameter/Condition Measured
Seismic P and S wave measurements	Spatial variation in travel time of seismic waves to identify spatial anomalies P and S wave velocities used to calculate elastic moduli
Ground Penetrating radar	Spatial variation in travel time (dielectric constant) to identify spatial anomalies
Resistivity	Spatial variation in resistivity to identify anomalies

Measurements Between Two or More Boreholes are similar to surface to borehole measurements except larger volumes of material can be characterized by these hole-to-hole methods. Table 5 (Reference 1) lists the details of those methods.

Table 5. Hole-to-Hole Measurements.

Method	Parameter/Condition Measured
Seismic P and S wave measurements	Spatial variation in travel time of seismic waves to identify anomalies, P and S wave velocities used to calculate elastic moduli between holes
Ground Penetrating radar	Spatial variation in travel time (dielectric constant) to identify anomalies
Resistivity	Spatial variation in resistivity to identify anomalies

Other methods were summarized in Benson's paper but are not discussed here as they were not considered relevant to this study.

GENERAL OBJECTIVES AND SCOPE OF WORK

In general, the objectives of this study were as follows:

- To review NDT and geophysical techniques (resistivity, conductivity, micro gravity, ground penetrating radar, seismic reflection/refraction, cross hole tomography, electro magnetic, and etc.) currently being used by other DOTs and other agencies.

- Determine the NDT and geophysical methods and equipment to be utilized in test projects for the Kentucky Transportation Cabinet.

- Evaluate test projects and consultants utilizing various NDT and geophysical techniques and compile results.

- Develop recommendations for the use of NDT and geophysical methods.

The general scope of work was to develop a number of field projects that would permit the evaluation of a number of geophysical methods. To evaluate these methods, a request for proposals (RFP) would be issued to various contractors on differing field projects. Contracts would be awarded on the basis of the evaluation of their proposals. It was decided to ask contractor to propose at least two geophysical methods. The various geophysical methods and the contractors used on these projects would be evaluated with recommendations being developed from the results. Although a number of other project have been performed in the state using geophysical methods, this report addresses only those projects conducted under the scope of this study.

CHOOSING A CONTRACTOR

Request for proposals (RFP)

The originally intended project for this study was to be US 231 in Warren County. An RFP (listed below) was issued to five prospective contractors inviting them to submit proposals. The contractors were then evaluated based on the information included in their proposals. The RFP issued by the Kentucky Transportation Center is as follows.

Request for Proposal
Kentucky Transportation Center, University of Kentucky
Lexington, Kentucky

General

The Kentucky Transportation Center at the University of Kentucky, under contract to the Kentucky Transportation Cabinet is requesting, by this notice (RFP), a proposal for geophysical testing and analysis on a proposed new highway alignment in south central Kentucky. The Cabinet and the Center are interested in the locations and descriptions of all subsurface features in this area. Site descriptions, scope of work, deadlines for proposal submittal, and contact personnel are listed below.

Site Description

The proposed new highway alignment is US 231, located in Warren County, Kentucky approximately 10 miles southeast of the City of Bowling Green. The total project length is approximately 5,360 meters. However, the area of interest is approximately 500 meters in length. The limits of this area are from Station 8+600 to Station 9+100, as noted on the accompanying plans.

The bedrock in and around the city of Bowling Green is a highly calcareous limestone which is highly susceptible to Karst formation. The overlying residual soils consist of heavy clays. From preliminary borings, the limestone bedrock is from 10 to 25 meters in depth. Details of borings, highway profile, alignment, and soil types can be obtained from the plans enclosed with this RFP.

Scope of Work

Task A. *The vendor is responsible to review the enclosed plans in detail, and from this review, propose (in the vendor's opinion) the* **two** *best geophysical methods for estimating the depth and lateral extent of the underground features of interest – in the area of interest. The proposal shall include the reasons for the vendor's recommendations for a particular method.*

Task B. *The successful vendor will be required to conduct all field testing to define all the underground features in the area of interest. The limits of the field investigation shall be confined to the stations listed above (along the centerline) and laterally, from the outside edge of the shoulder to the outside edge of the opposite shoulder (approximately 32.4 meters). Please see the enclosed typical section. The vendor will be required to perform all data processing necessary for completion of this task.*

Task C. *The vendor will be required to submit a detailed report describing all methods used to collect field data, and the methods used to process the data. The report should include all underground features that were found, including their location, extent and depth. The report should include color maps describing the subsurface features as interpreted by the contractor.*

Budget Estimate

The vendor shall submit a detailed budget with the proposal. Costs for field testing, data processing and reporting shall be broken out individually. The costs for each method shall be listed separately. The budget shall include an overall total for each method.

Time Estimate.

The proposal shall include an estimated completion date for this project. Also, estimated personnel hours for each task listed above shall be included.

Proposal Evaluation

The proposals will be evaluated on the following items, listed in order of importance:

Technical Content,

Budget Estimate,
Time Estimate.

Deadline for Submittal of Proposal

All proposals will be due in the offices of the Kentucky Transportation Center by 5:00 p.m. on July 31, 2002.

False or Misleading Statements

If in the opinion of the Kentucky Transportation Center, a proposal contains false or misleading statements or references that do not support a function, attribute, capability or condition as contended by the vendor, it may be rejected.

Proposal Submission

Proposals should be submitted to the following address:

Kentucky Transportation Center
University of Kentucky
Lexington, KY 40506-0281

Attention: David Allen

In the other field projects in the study (to be described later), only one contractor was invited to submit a proposal. A general RFP was not issued.

Proposals Received (US 231)

The following firms or agencies submitted proposals.

Blackhawk Geoservices, Inc.
Oak ridge, TN

Schnabel Engineering, Inc.
Greensboro, NC

Center for Cave and Karst Studies
Western Kentucky University
Bowling Green, KY

Technos, Inc.
Miami, FL

P. E. LaMoreaux & Associates, Inc.
Oak Ridge, TN

Technical Proposals and Evaluation

In this section of the report, the technical portions of each of the proposals are listed. It should be noted that these portions of the proposals were electronically scanned into this report from the hardcopies that were provided by the prospective contractors. Therefore, font size, font type and format will vary from proposal to proposal.

PELA Technical Proposal

APPROPRIATE GEOPHYSICAL METHODS FOR AN ENGINEERING INVESTIGATION OF KARST

Engineers commonly investigate subsurface conditions using Standard Penetration Test borings on a grid pattern. However, in order to document the complex variability of karst, or to identify the location and size of irregular cavities, such borings must be spaced so closely as to be economically impractical. Indirect techniques such as geophysics give a cost effective, non-invasive method of continuously investigating the variation in the karstic subsurface. Limited drilling at sites specifically identified by the geophysical investigation is then used for confirming and refining the interpreted data, rather than as a primary search technique.

Geophysical investigation techniques involve the measurement of the physical properties of the shallow rock and soil strata and the interpretation of the underlying geologic structure based on the values of, and variations in, those properties. As mentioned, karst terrane is infamous for its complex subsurface geology. Karst is characterized by a highly irregular bedrock surface on a small scale, broad depressions in the bedrock on a large scale, solutionally-widened fractures in the bedrock that may be filled with soil, and solution cavities and larger caves transmitting water vertically downward and laterally to springs.

Karst terrane in the Appalachian Province and the Interior Plateaus is characterized by a cover of clayey sediment overlying the soluble bedrock, which is usually limestone or dolomite. The uppermost part of the limestone is highly weathered and riddled with solution openings developed along bedding planes and fractures. These are frequently filled by the overlying sediment, which has migrated downward. This upper zone of highly weathered limestone is called the epikarstic zone and is generally estimated to be approximately 10 meters thick. On a larger scale the limestone surface is marked by broad basins (10's to 100's of meters across) drained by vertical drainage channels or shafts which penetrate downward from the epikarstic zone to the true karst, where groundwater moves laterally through cavernous conduits.

The geophysical techniques that are appropriate for this investigation must be able to resolve the details of this complex geological variation in a setting where the clayey overburden sediments are 10 to 25 meters thick, as specified in the RFP. Because of the complexity, most geotechnical investigations of karst terrane utilize two geophysical techniques in combination. One technique alone may not provide an unambiguous interpretation of the complex structure, but when two different geophysical techniques, making use of variations in two different physical properties, are utilized on the same area, the combined information can limit the interpretation. Geophysical investigations are interpretations, and are not absolute in nature. PELA's staff, and almost all responsible geophysicists, insist on several exploratory borings at representative locations to confirm the interpretation of the geophysics. PELA recommends that significant planning decisions involving financial investment or risk to the public safety not be made based on geophysics alone, without confirmatory boring data. As specified, borings will not be a part of this proposal.

Ground Penetrating Radar (GPR) provides rapid results and is effective in most settings, except in thick clay. Radar waves are radiated into the ground as an antenna is towed across the ground surface while simultaneously recording the reflections from subsurface features. The resulting two-dimensional cross-sections can be interpreted to predict where sinkholes may develop, to map the top of bedrock, or to locate man-made features such as underground storage tanks or graves, among other tasks. GPR has been used extensively for geotechnical investigations of karst in Florida, in areas where the surficial sediments are sandy. Clayey sediments have a high electrical conductivity and attenuate the radar signal after only one or two meters of penetration. Therefore, at the proposed site in Warren County, Kentucky, with 10-25 meters of clay covering the limestone, GPR would not provide any useful data.

The measurement of **electromagnetic conductivity (EM)** is a rapid technique that has been widely applied in karst areas. The instrument generates an electromagnetic field and measures the electrical conductivity of the shallow subsurface materials based on how they interact with this field. The simplest, most rapid version of EM (using the EM-31 instrument) makes one composite measurement representative of shallow conditions, approximately 5 meters in depth. If shallow rock is present, the conductivity will be very low; if the clay overburden is more than 5 meters thick, the conductivity will be high. Thus, this composite measurement will respond to variations in the thickness of the clay, within this five meter zone. More complex EM instrumentation is sensitive to greater depths, on the order of 60 meters maximum, but the actual contribution of material at the depth limits is very small. Moreover, this technique is much more time consuming. The EM-34 instrument utilizes two loop antennas that are usually carried by two operators, as much as 40 meters apart. Where the depth to limestone is shallow, EM is a useful, rapid screening technique. At greater depths the sensitivity is lower and the effort is considerably higher. Because of the depth of the

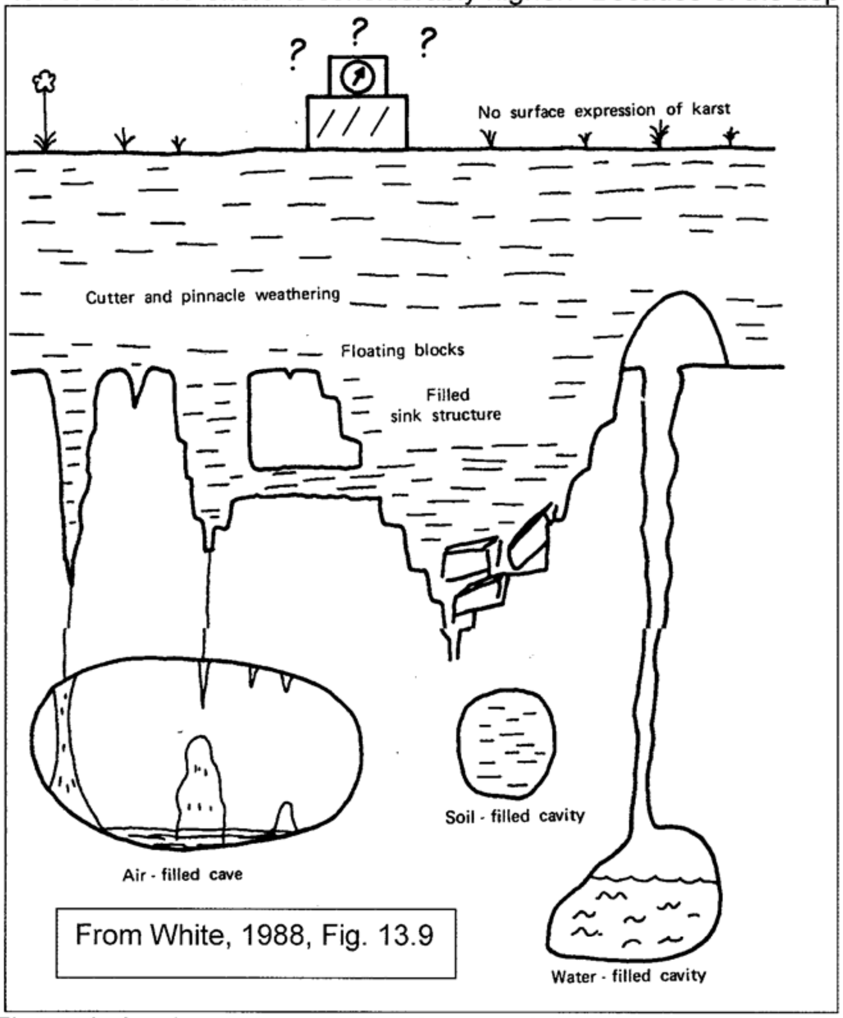


Figure 1: A schematic example of some of the complex subsurface conditions present in karst terrane.

rock at this site, and the limited sensitivity at that depth, PELA concludes that EM would not be the best technique for this investigation.

Seismic reflection is often used in geotechnical engineering investigations. A seismic wave is generated by an energy source, such as a hammer blow or small explosion, and radiates downward. The wave energy is reflected off geologic boundaries and travels back to the ground surface where the two-way travel time is measured by a string of sensors (geophones) at various distances from the source. This data is then interpreted. Seismic reflection is most useful for profiling the top-of-rock. It has not been widely used to provide detailed information on solution features within the bedrock. It is a potentially useful technique in karst investigations. The **Spectral-Analysis-of-Surface-Waves (SASW)** is a new seismic technique that can provide much more detail than the interpretation of simple reflection data. However, the SASW technique is much more sophisticated, complex, time-consuming and costly. It is probably not cost-effective at this time for investigating large, linear sites such as highway corridors. While a simpler seismic reflection survey might provide useful information at this site, PELA believes that other techniques are preferable, as explained below.

P.E. LaMoreaux & Associates, Inc. (PELA) proposes to conduct this investigation using two surface geophysical techniques: **electrical resistivity tomography** (ERT), and **microgravity**. The measurement of the electrical resistivity of the earth is a relatively simple process. Electrical resistivity is a measurement of the resistance of earth materials to the flow of electricity. This property correlates most strongly with the electrical properties of the pore water, the amount of pore water, and the presence of clay materials in the matrix. Surface resistivity measurements can be used to study lateral changes in the subsurface geology and to produce vertical cross sections of the natural hydrogeologic setting.

The microgravity method is a geophysical technique that measures minute differences in the earth's gravitational field at different locations due to mass differences in the ground beneath the measurement, such as the missing mass caused by dissolved voids. In the past, such minute differences were difficult to measure reliably, and any source of extraneous vibrations that disturbed the instrument made accurate measurements almost impossible. However, microgravity surveying has developed significantly over the last ten years, and with the development of modern high-resolution equipment, careful field acquisition techniques and sophisticated data reduction and analysis, these anomalies can be detected and interpreted.

The Electrical Resistivity Method

Electrical resistivity is an intrinsic property of all materials. The properties that affect the resistivity of soil or rock include: porosity, water content, composition (clay mineral and metal content), dissolved solids in the pore water, and grain size distribution. Therefore, electrical resistivity is ideally suited for geologic investigations. However, it must be noted that totally different geologic materials may not be distinguished by this technique, if the end result of all these properties is that the materials have similar electrical resistivity.

In an electrical resistivity investigation, an electric current is applied to the ground surface through two electrodes. Two or more additional electrodes are placed in the ground to measure variations in the potential of the electrical field (voltage) that is set up within the earth. The successful application of this technique for delineating karst features depends on understanding karst terranes and the selection of the appropriate electrode array (Zhou, Beck & Adams, 2002). The commonly used arrays are the Wenner array, Schlumberger array, and Dipole-dipole array (Reynolds, 1997). These different electrode configurations have particular advantages, disadvantages and sensitivities, to either vertical or horizontal change in the subsurface materials. Because of the three-dimensional nature of karst features such as sinkholes, cavities, and depressions on the bedrock surface, it is important to have an array that is sensitive to *both* vertical and horizontal changes. The dipole-dipole array produces the most detailed data distribution and is therefore PELA's preferred method. PELA has extensive experience with this application.

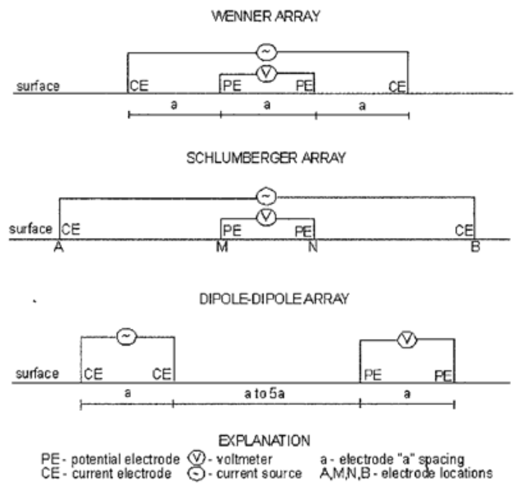


Figure 2. Electrode configurations used in electrical surveys.

Two basic field procedures that are commonly used in electrical resistivity exploration are:

1. **Constant separation traversing** (CST) in which the electrode separation remains constant while the measurements move laterally during the survey; and
2. **Vertical electrical sounding** (VES), in which the center of the electrode spread is maintained at a fixed location and the electrode spacing is increased in increments.

CST is normally employed when a rapid survey of an area is desired. It is particularly suited for *prospecting for sand, gravel and ore deposits* and for *locating fault zones* or contacts between steeply dipping layers of earth materials. **VES** is designed to provide information on the variation in subsurface conditions with depth. VES is typically used to help determine the *depth to the water table, the thickness of sand, gravel and rock layers, and the actual value of electrical resistivity versus depth.*

Traversing and sounding can be combined using a multi-electrode system, known as **Electrical Resistivity Tomography** (ERT). In principal, ERT is very similar to the traditional resistivity techniques that have been applied for decades, but were little used because they were so labor intensive. However, modern electronics, computerized instrument technology, and computer modeling of the data dramatically increases field efficiency while making it possible to interpret the dense array of data that is now collected. Using a linear array of fifty-six electrodes, which are variously selected by the computer program as current or measurement electrodes, it is possible to obtain approximately 700 data points for the dipole-dipole technique in three hours. Unlike the traditional methods (which provide data at various depths below one point on the ground surface), resistivity tomography produces a geo-electric cross-section which can be used to define the topography of the bedrock surface and identify fracture zones, and underground cavities or conduits. Multiple parallel cross-sections may be combined to produce three-dimensional block diagrams of the subsurface.

The ERT method is especially valuable in areas where ground penetrating radar is inapplicable due to the clayey, conductive overburden. In such areas, which include most karst terrane, the resistivity method is the only real alternative for 2D and 3D mapping of the shallow subsurface. In karst terranes, the common subsurface materials have very different resistivities, thus facilitating the data interpretation. Clay is very conductive (low resistivity), whereas limestone is highly resistive. An air-filled void has a theoretically infinite resistance.

The field instrumentation measures the apparent resistivity at numerous locations and depths. The electrode array may be either linear (2-D) or in a grid pattern (3-D). 3-D data collection is a relatively new technology. Because of the complexity of combining measurements at each point in three-dimensions, the data collection technique is restricted to using the pole-pole array and it is still extremely time consuming. The pole-pole array is not as sensitive as the dipole-dipole array. Maule, Nyquist and Roth (2000, p. 969) conclude that **"combining multiple 2D resistivity profiles, inverted assuming 2D geology, produced a better image of the subsurface than a single 3D sounding that covered the same area,** but with fewer and more widely spaced electrodes in each horizontal direction."

The measured data are analyzed using a 2-D or 3-D inverse modeling computer program[1]. In the program, a non-linear least-squares optimization technique is used to automatically determine the best fit to the data. It is important to remember that due to the inherent properties of modeling, the pseudosection gives an approximate (and sometimes deceptive) interpretation of the subsurface geology. When a simple, idealized cross-section is modeled in the forward sense to calculate an array of apparent resistivity data, and that data is plugged into the inverse modeling program as if it were field data, the resulting interpretation is not a one-to-one re-creation of the original cross-section (see Zhou, Beck and Adams, 2002). Therefore, the data should be evaluated and interpreted by an *experienced geologist who understands both the underlying geophysical theory and the complexities of karst.* An example of a two dimensional electrical resistivity cross-section is shown in Figure 3.

[1] The inverse modeling software preferred by PELA is RES2DINV.

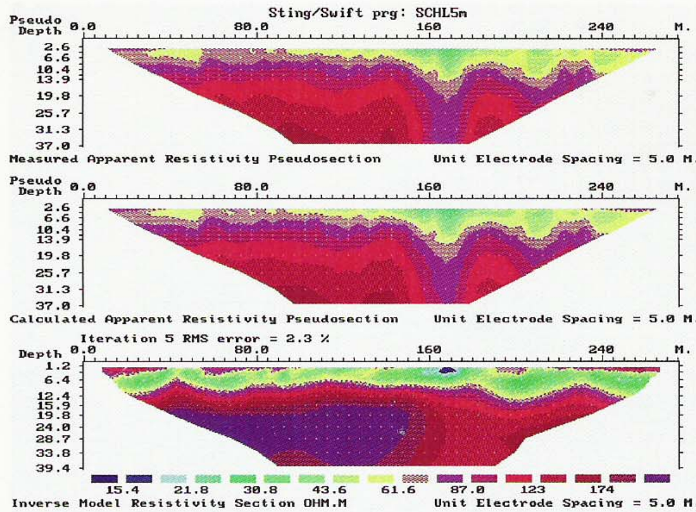


Figure 3. Dipole–dipole resistivity transect, 5 m spacing, showing measured apparent resistivity (top), inverted model (bottom) and apparent resistivity section calculated from the model (middle).

Inasmuch as the complexities of 2-D resistivity data interpretation are documented, and inasmuch as 3-D resistivity data are collected using a less sensitive array and are significantly more time consuming, and obviously must be even more complex and deceptive to interpret, therefore PELA proposes to utilize 2-D data collection and interpretation in their investigation, and to later combine closely spaced 2-D cross-sections to produce a 3-D model of the subsurface as recommended by Maule, Nyquist and Roth (2000).

Electrical resistivity profiles can be most effectively used when coordinated with ground truth data from test holes to further constrain the model. Figure 4 shows an ERT pseudosection with coordinated test hole data from a site located in Middle Tennessee. The interpreted resistivity pseudosection indicated two sub-surface anomalies characterized by a vertical zone of low apparent resistivity (100 ohm-m as compared to about 500 ohm-m). The subsequent test holes verified the interpreted bedrock topography and presence of karst features, which are similar to those shown in the photo of Figure 4. Another way to report ERT data uses CAD to quickly and easily superimpose geophysical drawings, for example contour maps and profiles, onto basemaps so that the findings can be evaluated with respect to known conditions (Figure 5).

PELA

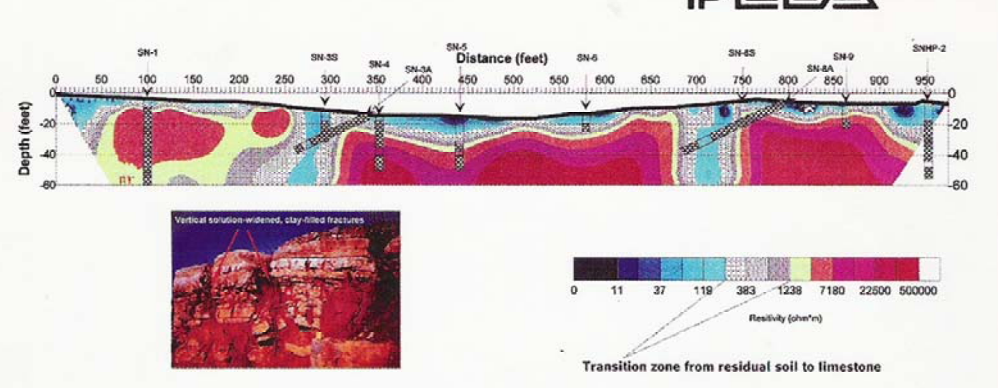
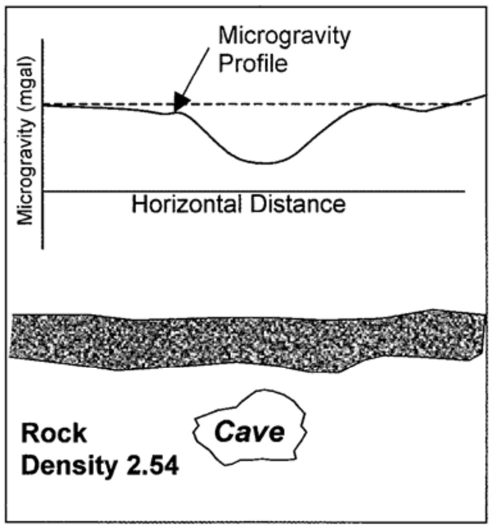


Figure 4. Electrical resistivity tomography pseudosection with schematic ground truth test hole data showing the presence of two sub-surface solution widened fractures.

Figure 5. The generalized elevation of the bedrock surface as interpreted from Electrical Resistivity Tomography. Contour lines show the ground surface; bedrock surface elevation is color-coded.

The Microgravity Method

The microgravity method measures the earth's gravitational field at specific locations on the earth's surface to determine minute variations of the subsurface density. Microgravity data in engineering and environmental applications must be collected in a grid or along a profile with stations spaced less than 5 meters apart. The measured microgravity at any given location will generally be influenced by the density of the material beneath the location, the elevation of the ground, the topography around the measuring point, and the latitude. In order to relate gravity data to subsurface density, the other factors must be accounted for. Measured microgravity data is processed to remove the other predictable components of the gravitational field of the earth. The processed data are known as Bouguer gravity anomalies, measured in μGal.



The principle of the gravity method is illustrated by the simple model of Figure 6. The earth's gravitational field is usually described by the vertical component of the gravitational acceleration g_z. The mean value of the field at a point on the surface of the earth is primarily determined by the mass of the earth, but small local variations in mass perturb this mean value. In Figure 6 the cave, presumed to be filled only with air, represents a mass deficit in the measurement of g_z. The plot shows the associated lowering of the field in the vicinity of the cave.

Figure 6: Idealized cross-section through a cave and the resulting gravity profile.

Finally, this model illustrates the non-uniqueness of the interpretation of gravity variations. The anomaly for a sphere is that of a point mass where the mass is the product of the sphere volume and the density contrast. If the sphere is air-filled and if the surrounding formation is uniform and of known density, then the anomaly can be interpreted in terms of the radius of the cave. However if the cave were partially water filled, exactly the same anomaly would be found for a cave of some larger radius. Later it will be shown that any anomaly can be reproduced by variations in the density of a near surface layer so that there are no unique properties that define depth or size of such targets.

This method is indirect in the sense that the measurements themselves do not directly yield the distribution of the physical properties. Rather the measurements must be interpreted using some assumptions about the subsurface, and it is this interpretative step in which it is vitally important to use an experienced geophysicist who also understands the complexity and variability of karst terrane.

Based on Newton's Law if the measurement accuracy of the gravimeter is 0.001 mgal we must know our elevation to **.32 cm or .125 inches**. It is evident that accurate surveying of gravity stations, especially elevation, is critical to this technique.

DATA COLLECTION

Data collection for this project will take a two phased approach in order to more accurately target specific parts of the new highway alignment. It is PELA's professional opinion that by using the ERT to first survey the entire study area and then measuring a microgravity grid in areas where more detail is warranted, that a very accurate 3D understanding of the area will be obtained.

Two-dimensional (2-D) electrical imaging surveys are widely used to map areas of moderately complex geology where conventional resistivity sounding and profiling techniques are inadequate. PELA will first measure four parallel, closely-spaced lines of ERT along the proposed route of the new highway. PELA will use the industry standard Sting R1 Memory Resistivity Meter with the Swift "Smart" Electrodes. The ERT data will be collected to image a depth of at least 40 meters, providing the necessary information to accurately map the top of rock and the epikarstic zone. To do this while preserving detail in the data, 56 electrodes will be used, spaced 5 m apart. Due to the inability to cross current Route 231 we will also conduct 4 lines parallel to current Route 231, in order to more accurately represent the 3 dimensional nature of the study area.

Apparent resistivity is measured in the field. The recorded data are then interpreted using an inversion program, which models real geo-electric configurations that might produce such apparent resistivity values. RES2DINV is the software program that is used to interpret the resistivity measurement data as a 2-dimensional electrical cross-section. Upon completion of the initial processing of the ERT data, areas indicating karstic anomalies will be delineated for further investigation using the microgravity method.

The microgravity surveys will be conducted using the industry standard in high precision land gravity meters, the Scintrex CG-3M. PELA will initially investigate three topographic areas noted on the route map where karst features are obvious on the surface. In addition, microgravity grids will also be measured over any other anomalous areas as identified by the ERT method. Each area of microgravity investigation will cover approximately 550 square meters. By using small station spacing within the grid (3 m) it will be possible to generate a contour map of the residual Bouguer gravity. Collection of data on a regular grid results in improved data detail that can be used to separate the effects of karstic features from the geological or topographical background effects. This is more accurate than using data measured only along discrete profiles, which can often fail to adequately sample the anomaly caused by a mass deficiency at depth. A transect can only provide a two-dimensional understanding of a three-dimensional subsurface feature, and may misrepresent the size and orientation of such a feature.

Due to the need for accurate elevation measurements, PELA will contract professional surveyors to obtain the necessary latitude and topographic correction data, rather than using technicians or students to gather the data. This is imperative, because for a measurement accuracy of 1 μgal it is necessary to know the N-S position to within 1.2 meters, and the elevation to 0.32 cm. Experienced gravity crews can obtain observations with an accuracy of 1 μgal and a standard deviation of <5μgals, far smaller than the errors observed in the data collected by the novice. The microgravity data will be reduced to take into account topography, free air, and the Bouguer slab effect. Since the latitude and free air effects, and to a good approximation the Bouguer effect, are accurately predictable, it is common practice to correct the data to a reference level. This essentially removes the large first order variations along the profile and permits the identification of subsurface anomalies due to the geologic variation.

ESTIMATED COST

Because of the two phased approach, the field work has been scheduled for two separate periods. The ERT cross-sections will be measured first and then interpreted. Data reduction and interpretation of 12 ERT transects will require approximately one week. The microgravity investigation will initially concentrate on the three areas showing karst features on the ground surface, and will be conducted over up to four additional areas showing karst features based on the ERT interpretation. The microgravity data will then be reduced, modeled and interpreted in the office. Final report preparation will summarize the data and methodology. If the client agrees that a comprehensive technical review of each of these techniques is an important part of a research report, then Optional Task 7 will be added to the report.

The estimated total cost of the project is $36,574. The optional comprehensive technical review will cost an additional $7,600. A detailed budget breakdown is included as Appendix II . PELA's **Schedule of Fees** and **General Conditions** are included in Appendix III.

TIME AND SCHEDULE

In order to insure that the field work does not conflict with the highway construction, which is already under contract, PELA will insure that both the ERT and microgravity fieldwork are completed by the end of September, 2002. Data reduction and interpretation, and **preparation of the final report will be completed by November 15, 2002**. If the optional comprehensive technical review is added, PELA will deliver the final report no later than December 6, 2002.

2.0 BACKGROUND INFORMATION

2.1 Site Description

Based on the information provided by the KTC, the geophysical survey area will be approximately 500 by 33 meters. Specifically, the limits of this area are from Station 8+600 to Station 9+100, and laterally between the proposed outside shoulders of the new highway alignment (approximately 32.4 meters). Based on boring log information, subsurface conditions consist of heavy clays (CL, CH) from surface to bedrock. Limestone bedrock is estimated to occur at a depth of 7 to 9 meters below ground surface (bgs).

According to KTC personnel, the site conditions consist of an open, grassy field that is described as former pastureland. However, the possibility exists that some waist-high grass and/or minor brush may need to be cleared (included in costs).

2.2 Purpose

Based on information provided by the KTC, the purpose of the geophysical survey is to estimate the depth and lateral extent of underground features of interest using what the geophysical contractor believes are the two best geophysical methods. It's our understanding that the geophysical "targets" of this investigation can best be addressed by approaching the investigation as follows:

- Providing continuous two-dimensional (2D) profiles that show variations in bedrock topography and the depth to limestone bedrock (~10 to 25 feet bgs) to:
    - Map individual bedrock "lows" (~5-meter nominal diameter) and linear bedrock channels (~5 meters across) that may be associated with sinkhole development and/or dissolution features along the bedrock surface prone to sinkhole development.
    - Map bedrock "highs" or outliers that could impede construction progress of planned road cuts.
- Providing continuous 2D profiles that variations in the bedrock and overburden such that anomalies can be "linked" across the interface.
- Providing data from two geophysical techniques that can be correlated between the two and hence provide a more conclusive overall geophysical interpretation of subsurface conditions.

Blackhawk has carefully evaluated the survey objectives along with existing information on subsurface conditions. We've looked at the technical feasibility of employing several different geophysical methods and have ruled out gravity and microgravity, spontaneous potential (SP), electromagnetic (EM) and very low frequency (VLF) EM, ground penetrating radar (GPR), spectral analysis of surface waves (SASW), and compressional (p-wave) seismic reflection due to non-uniqueness problems, lack of adequate depth penetration and/or resolving power at the target depth, or lack of additional site-specific information.

The shear-wave seismic reflection method (either 2D or 3D) is the geophysical technique that ***would*** provide the highest subsurface resolution (i.e., detection of ~1-meter diameter voids at 25 feet), however, at an increased level of effort compared to the two techniques we recommend below. Costs for 3 variations of the s-wave seismic reflection approach are included in the Optional Approach Attachment.

Based on site conditions and project objectives, Blackhawk strongly believes that those two techniques that are most likely to succeed and that also provide a cost-effective approach to screening the subsurface are high-resolution seismic refraction profiling using the "roll-along" approach and electrical resistivity profiling using a capacitively-coupled system in "walking" mode.

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3.1 General Considerations

The assumption is that data from the seismic refraction survey will be used to provide information on variations in bedrock topography and to map the lateral extent of the target features. A schematic diagram showing seismic refraction principles is presented as **Figure 1**. High resolution bedrock profiles will provide data on local deviations in the bedrock topography, which will indicate potential areas of concern. The localized dips in bedrock imaged by the refraction survey will be correlated with electrical resistivity profiles collected coincidently. Good correlation between seismic and resistivity data will indicate whether karst processes, such as bedrock weathering, groundwater channeling, or weakened soils prone to sinkhole development exist on site.

To accomplish the survey objectives, Blackhawk will use a 60-channel seismic acquisition system coupled to an accelerated weight drop (AWD) as the energy source. We have a great deal of experience utilizing the AWD method as a source for seismic refraction and reflection surveys. This method has been successfully applied in high noise environments or in situations where the target was sufficiently deep.

Blackhawk proposes the innovative approach of using a 60-channel split-spread data acquisition method for the refraction project. Simply put, most refraction surveys are conducted with an average of 3 to 7 shotpoints per spread (including off-end shots). The split-spread method deploys a sufficient number of transducers (i.e., geophones) that are simultaneously recorded to provide the entire range of offsets needed for the refraction survey on both sides of the source within a single shot. This method eliminates the inefficient move ups of an entire spread after walking a source through that spread, and eliminates the necessity of re-occupying the same source position for multiple spreads. An example of this technique is shown as **Figure 2**. This figure also shows a 3-D net diagram of a bedrock channel derived from multiple parallel split-spread refraction profiles, which is the refraction approach proposed for this investigation. Another example (**Figure 3)** shows a Blackhawk example data set of split-spread refraction data acquired across the Mississippi River. The redundancy of refracted information received at each transducer is obvious. This enhanced redundancy provides for a more accurate interpretation because identifying bad data points is relatively simple.

The following summarizes some of the advantages to using a large recording system, acquiring data along multiple parallel lines, and employing the split-spread "roll-along" refraction method:

- Greater data multiplicity than conventional refraction surveys (often with as few as 3 shots per spread) resulting in improved statistics and depth to refractor estimates.

- Greater field efficiency since the trailing end of the survey line is continually advanced ahead of the "active" portion of the seismic spread.

- Psuedo-3D diagrams, such as net diagrams can be constructed from refraction data collected along parallel lines resulting in improved ability to see subsurface trends in the data.

The assumption is that the electrical resistivity survey approach proposed can be used to continuously map changes in the subsurface electrical properties from near the surface in the overburden section to depths of approximately 10 to 12 meters (~33 to 39 feet). Bedrock anomalies may be evidence of sinkholes, voids, and variations in bedrock features prone to sinkhole development. With the depth of exploration provided by the resistivity survey, correlations can likely be made with anomalies seen in the seismic refraction data.

Resistivity data will be collected using Geometrics, Inc. TR1 OhmMapper resistivity meter (**Figure 4**) or the Model TR5. The OhmMapper is a capacitively-coupled, towed resistivity array. The TR5 model is not yet available to the public, though is available to Blackhawk through intra-company exchange. The TR5 contains 5 receiver units, compared to 1 receiver unit in the TR1 model. Since the OhmMapper depth of penetration can be affected by highly conductive soils, the possibility exists that exploration depth could be less than desirable at the site. For this reason, we've included costs to conduct a fixed-electrode resistivity survey using an AGI Sting/Swift 56-electrode resistivity system (**Attachment B-1**). If the OhmMapper results were inconclusive, this would be determined on the first day of fieldwork.

3.2 Geophysical Survey

3.2.1 Light Brush-Clearing

Prior to conducting the investigation, Blackhawk will clear any light brush that might impede the progress of the survey crew. If required, this is expected to be a minimal effort.

3.2.2 Land Surveying

Prior to collecting seismic data, Blackhawk will establish the line locations and conduct a land survey. Accurate elevations are critical for proper refractor depths. Note: This task will not required for the resistivity survey. Land survey work will be performed by Blackhawk staff experienced in total station land surveying methods. The land survey will be conducted using a total station laser theodolite instrument, such as a Sokkia SET500.

The land survey will include the following items of work:

- Line Layout and staking on 30-meter centers,
- Station chaining with pinflags and/or surveyor's paint on 2-meter centers,
- Collecting X,Y, and Z survey data using the total station at the 30-meter stakes, all line starting and ending points, and off-end shotpoints.
- Collecting survey data at all downline stations where variations in elevation (Z) exceed 0.5 feet relative to stations on either side of that point.
- Collecting survey data at all surface cultural features that could potentially affect the seismic and/or resistivity data.

All survey points will be tied to permanent benchmarks or existing site monitoring wells referenced to the local U.S. State Plane Coordinate System.

3.2.3 Seismic Refraction Survey

The recommended seismic refraction survey will be comprised of six continuous and parallel profile lines spaced approximately 6 meters apart, for a total survey distance of 3,000 meters. To correctly accomplish the objectives of this survey, the geophone group interval needs to be small enough to increase redundancy, thus enhancing subsurface coverage. We feel that a 2-meter geophone group interval will provide the resolution requirements of the Highway 231 site investigation. We recommend the following seismic refraction survey equipment and field parameters for the survey:

- Geometrics Strata-Visor; 60-channel seismograph,
- Refraction geophones; 8-Hz,
- Accelerated weight drop; seismic source,
- Hammer and cylinder (initial source test),
- 2-meter geophone group interval,
- 12-meter (6-station) source interval with a minimum of 4 off-end shots per seismic line,
- 30/30 symmetric split-spread recording configuration. This would result in 59 meters (~194 feet) to the far offset and provide good statistical information for GRM refraction processing and/or tomographic analysis.

Initially, a seismic source test will be conducted using a hammer/cylinder and the AWD. Based on these test results and the results of field parameter optimization testing, the seismic source and field geometry to be used for the remainder of the investigation will be chosen. Note: Blackhawk is prepared to conduct the survey with the hammer/cylinder at the same price as that shown for the AWD source if test results indicate the hammer provides better data.

Following these tests, seismic refraction data will be collected along each of the proposed survey lines for an estimated total of 3,000 linear meters of surface coverage.

3.2.4 Electrical Resistivity Survey

The recommended electrical resistivity survey will be conducted along the same six parallel profile lines as those used for the seismic survey. Each line will be 500 meters in length, for a total survey distance of 3,000 meters. The electrical resistivity data will be used to generate continuous 2D profiles across the survey lines investigated. In conventional resistance, a specified current is injected into the ground using probes connected to a DC power source. The resulting measured voltage is used to calculate the ground's resistance to current flow by Ohm's Law,

$$\mathbf{R = V/I,}$$

where R = resistance, V = voltage, and I = current.

Resistance will vary depending on the distance and geometry between the probes so it is normalized with the addition of a *geometric factor* that converts the measurement to resistivity, (expressed in ohm-meters), where

$$\rho_a = 2\Pi \text{ a } V/I,$$

[for equally spaced galvanic electrodes (Wenner array)]

Data will be acquired with the Geometrics OhmMapper TR1 or TR5. As the OhmMapper streamer is towed across the ground (**Figure 5**), an AC current is coupled into the earth by the transmitter and measured at the receiver. This measured voltage is proportional to the resistivity of the earth between the dipoles. Apparent resistivity is calculated using the appropriate geometric factor for the capacitively-coupled antenna array. A data comparison of OhmMapper TR1 data and conventional fixed-electrode resistivity data collected with a Sting/Swift system is presented as **Figure 6**.

The depth to which OhmMapper data can be reliably interpreted depends on the dipole length and the distance from the transmitter dipole to the receiver dipole. The practical distance at which the receiver can detect the transmitter depends on the resistivity of the earth. Typical depths of investigation are 10 to 20 meters. However, skin depth effects on EM measurements often determine the practical limit of the depth of investigation in highly-conductive areas. The approximation of skin depth, in meters, is 500 times sq. rt. (ρ/f) where ρ = resistivity and f = frequency. Based on review of the site-specific soils described in the boring logs and target depth information, the OhmMapper should be successful in imaging to an estimated depth of 10 to 12 meters for the U.S 231 highway project. If local soil conductivity values are high and limit depth penetration with the OhmMapper this will be apparent during the first day of fieldwork, and the AGI Sting R1/Swift 56-electrode resistivity system could be used to collect the resistivity data (**Attachment B-1**). The electrode array and spacing will be chosen in the field to optimize survey parameters for site-specific conditions/targets.

Resistivity data will be acquired along 6 parallel profiles providing a Psuedo-3D image of the subsurface. Average resistivity values recorded will provide enough overlap in data to have continuous subsurface resistivity coverage.

3.3 Data Processing

3.3.1 Seismic Data

The processing begins by determining or "picking" the time of the first arrival (onset) of energy at each receiver for each shot record. The source and receiver geometry is then applied for each shot record in the refraction spread and the data is then corrected for elevation. This data is then combined to produce a time-distance plot of the first arrival times for each refraction spread (**Figure 2**). Blackhawk will use ViewSeis software for generalized reciprocal method (GRM) processing, which represents the "standard" conventional approach to calculating refractor depths. Plots of 2D depth sections representing each survey line will be generated from GRM processing. In addition to GRM processing, we'll also process select refraction data using GeoTomo2D software that represents the tomographic inversion approach to data analysis. Plots of color-enhanced 2D depth sections of these select data will be compared with GRM depth sections and 2D inverse model resistivity sections for the purposes of correlation and to determine which refraction data processing method provides the most useful results.

After refraction analysis of the seismic profiles is complete and final depth to bedrock information is obtained, Blackhawk will import bedrock topography data into Geosoft's Oasis Montaj software and prepare a color-enhanced contour map and/or a 3D net diagram depicting bedrock topography and anomalies identified.

3.3.2 Resistivity Data

Electrical resistivity data will be 2D inverse modeled and interpreted using the RES2DINV program, by Loke. The inversion in RES2DINV is based on the smoothness-constrained least squares method. The 2D model used in the inversion process divides the subsurface into a fine mesh of rectangular blacks from shallow to deep that are limited at depth by the largest surface electrode spacing. In an iterative process, the program determines the resistivities of the model blocks that will produce an apparent resistivity pseudosection that agrees with the measured data pseudosection. The difference between the model inversions and the measured data is presented as root-mean-squared (RMS) error. Typically RMS error of 10 percent or less represents good correlation between modeled results and measured data. Data will printed and analyzed using linear and logarithmic color amplitude scales. Forward modeling will be performed using RES2DMOD to support resistivity anomaly interpretations.

3.4 Data Interpretation

Data interpretation will be coordinated and led by Jeff Hackworth, R.Gp., P.G., the Project Manager. He will delegate as he deems necessary certain tasks to those individuals referenced in the Key Personnel section (**Attachment C**).

3.4.1 Seismic Data

The first arrival times of the direct wave and refracted waves from flat-lying uniform layers plot as a straight line for each layer. A best-fit line is drawn through the points associated with each layer on the travel-time plot and the slope is then calculated for each best-fit line. The velocity of each layer is then determined by calculating the inverse of the slope of each best-fit line. The intercept time, in conjunction with the layer velocities, is used to calculate the thickness of each layer.

The GRM depth calculation will then be applied to the seismic data to provide better resolution of the layer interfaces by detecting variation in the topography of the surface of the refracting layers and variation in layer velocity across each layer. Since the GRM is a statistical method, great care is required in data acquisition and editing to provide sufficient data for accurate depth calculations representing the bedrock surface and individual short-period anomalies potentially representing sinkholes, channels, and dissolution features.

Select refraction data will also be processed using the tomographic method. Tomography in seismic refraction uses the first arrival times of the direct wave and refracted waves determined from the shot records. The first arrival times, array geometry, and elevations are imported into the tomography modeling software. Unlike the more routine GRM and slope intercept methods, first arrivals are not assigned to specific layers prior to modeling. The tomographic modeling program uses ray-trace fitting to produce the best-fit velocity model for the field data. Smoothing functions are often applied to produce a more realistic and constrained velocity model, and minimize artifacts in the results.

3.4.2 Resistivity Data

Resistivity data can typically be used to identify a void(s) and/or zones of significantly weakened soils several feet in diameter at the target depth required of the U.S. 231 investigation. This assumes the resistivity profile is located near the target features and cultural noise sources (e.g., buried pipelines, metal fences, and structures) are minimal or nonexistent. A resistivity anomaly caused by a void would likely be evident as a localized high response in the inverse model resistivity section. A zone of loosely consolidated would most likely be evident as a decreased resistivity (i.e., increased conductivity) response locally, although some field conditions would lead to an increase in resistivity over the target.

Site resistivity data will be printed and analyzed using linear and logarithmic color amplitude scales, and converted to an apparent conductivity display. Color amplitude scales will be selected to enhance features of interest and keep constant comparison between profiles.

3.5 Deliverables

Project deliverables will include two copies of the Geophysical Survey Report that will include the following maps and data:

- 2D Seismic Refraction Depth Sections for each of the six profiles,
- First break picks and shot records for select shotpoints,
- Color enhanced contour map and/or 3D net diagram showing bedrock topography and anomalies evident in the seismic refraction data,
- Color-enhanced 2D tomographic sections of select refraction profile data,
- 2D inverse model resistivity sections showing anomaly interpretations for each of the six profiles,
- Resistivity forward models used to support resistivity data interpretations,
- Plan view geophysical interpretation map of the site showing survey line locations (referencing State Plane Coordinates) and indicating the locations of significant geophysical anomalies.

Blackhawk GeoServices will prepare a geophysical report that will include select shot records, and 2D cross-sections depicting GRM refraction solutions, seismic velocities, first break information, and depth to bedrock information for each seismic profile. The profiles will be interpreted to indicate the locations of anomalies that represent the target features of this investigation. Blackhawk will provide 2D inverse modeled resistivity sections for all resistivity profiles, which will be interpreted and correlated to refraction anomalies. The report will also include a color-enhanced contour map and/or 3D net diagram of bedrock topography based on the seismic refraction solution. All maps contained in the report will be referenced to the local State Plane Coordinate System and indicate geographical information and features that can be used to relocate the seismic and resistivity profile lines and/or the locations of anomalies.

Schnabel Technical Proposal

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July 30, 2002

David L. Allen
Kentucky Transportation Center
176 Raymond Building
Lexington, KY 40506-0281

SUBJECT: US 231 New Alignment, Warren County, Kentucky
Proposal for Geophysical Services

Dear Mr. Allen:

We are pleased to provide this proposal to conduct surface geophysical surveys along the planned alignment for the new US 231 in Warren County, Kentucky. This proposal is in response to your request for proposal dated July 2, 2002 with supplemental information provided in a letter dated July 19, 2002.

Schnabel Engineering is highly interested in performing this work. We have worked extensively with the state transportation agencies in Maryland and Virginia to locate karst features beneath existing and proposed highway alignments using geophysical methods. In addition to the highway investigations, we have conducted numerous other geophysical surveys for karst investigations for public and private clients.

This proposal provides our understanding of the project, a discussion of available geophysical methods, our proposed scope including some optional surveys, our estimated costs, and our draft Agreement. At requested, we have not included any qualification materials with this proposal. Client references, example project materials, and resumes can be provided at your request.

1.0 UNDERSTANDING OF PROJECT

Based on our review of the RFP and from discussions with Mr. David Allen, we understand that the Kentucky Transportation Center (Center) and the Kentucky Transportation Cabinet plan to evaluate geophysical methods for locating karst-related features along the proposed new alignment for US 231 in Warren County, Kentucky. The Request for Proposal asks for the two "best" methods for estimating the depth and lateral extent of the underground features. One of the goals of this work is to demonstrate applicable methods to be used on future highway projects.

The work is to be conducted along a 500-meter (1,641-foot) portion of the alignment from Station 8+600 to Station 9+100. The site has not been cleared for construction but is reported to consist of grass-covered fields. No clearing should be required for this work. The study area is limited to the area between the outside shoulders of the road, a width of approximately 32.4 meters (106 feet). The maximum depth of interest is about 25 meters (82 feet) but the Center is primarily interested in the features within 10 meters (33 feet) of the ground surface. No intrusive investigations are required as part of this work.

2.0 AVAILABLE METHODS

A number of surface geophysical methods are available to investigate karst-related features. Schnabel Engineering has experience in each of these methods and has worked with other state transportation agencies to apply selected methods. The application of a particular method depends on desired resolution, size of survey area, budget, and site conditions, among other factors. The primary geophysical methods used to evaluate karst terrain are discussed below with comments on their suitability for this particular project.

2.1 2D Resistivity Imaging

As a stand-alone method, resistivity imaging is arguably the most cost-effective technique for locating karst-related features in the top 30 meters (100 feet) of the subsurface. Data is acquired by placing a linear array of electrodes in the ground, generating a current in the ground between two electrodes, and measuring the voltage differences between a second pair of electrodes. Various array types are used with the dipole-dipole method being the most common. Depth imaging is conducted by changing the electrode spacings used for each measurement. A high number of measurements can be made very rapidly using multi-channel equipment and programmable resistivity meters. The data is inverted to produce a 2D resistivity model that matches the observed data.

We have used this technique on numerous projects to locate karst features for the Maryland State Highway Administration (MSHA), the Virginia Department of Transportation (VDOT), and for other clients. The depth of investigation and resolution of the resistivity method depends on the array length and electrode spacing. The benefit of using 2D resistivity is that it is a proven, cost-effective technique that can provide the geometry of karst features more rapidly than other geophysical methods. The limitations of the 2D method are that analysis assumes a 2D structure and that out-of-plane features may not be detected. While 2D resistivity imaging is limited by the assumption of 2D structures, parallel 2D data sets can be combined into a 3D data set and inverted to produce a quasi-3D model. An example 2D model from one of our highway projects is shown below.

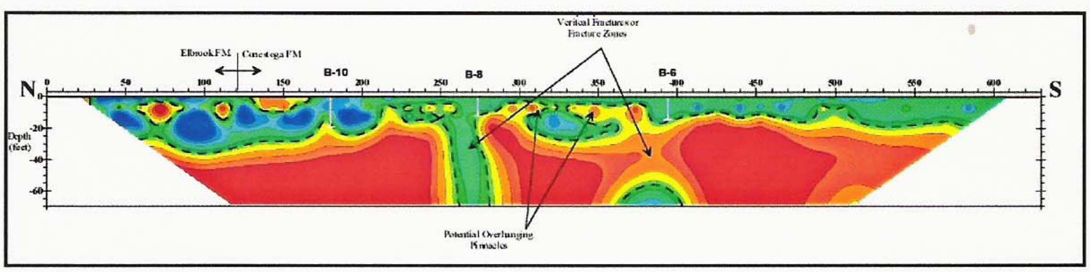

Figure 1 - Example 2D resistivity image showing karst-related features

2.2 3D Resistivity Imaging

The 3D resistivity method uses the same basic technique and equipment as the 2D method but the electrodes are placed in 2-dimensional array to cover the area of interest. Measurements are made in at least two directions. At least twice as many electrodes are needed for 3D field work as compared to 2D surveys and the data acquisition takes at least twice as long. The data is inverted to produce a 3D model that can be displayed as a data cube or as depth slices.

While 3D imaging can provide more reliable geometry of karst features, it is more time-consuming than the 2D method and may be better suited for determining the geometry of specific karst features that have already been identified using other methods. An example 3D image from one of our Virginia highway projects is shown below.

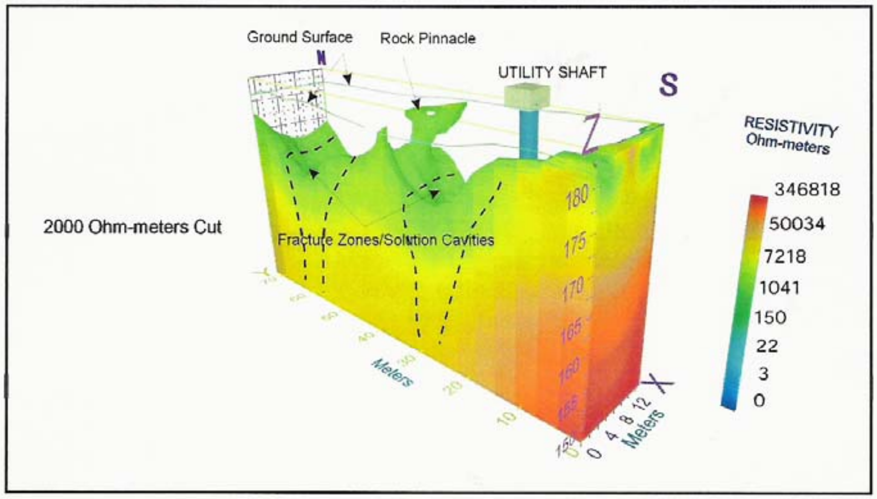

Figure 2 - Example 3D Resistivity data from highway investigation

2.3 Electromagnetic Induction

The use of EM instruments to locate water-bearing and clay-filled solution features is well documented. It is also possible to locate near-surface voids using EM methods. Near-surface voids provide a low conductivity response while water and clay-filled features are more conductive than the surrounding bedrock. The depth of investigation and resolution depend on the coil spacing of the particular EM instrument. The EM-31, for example, has a coil spacing of 3.66 meters (12 feet) and provides a maximum depth response of about 20 feet. The data can be displayed in a profile form for a single line, or gridded and contoured for an area survey.

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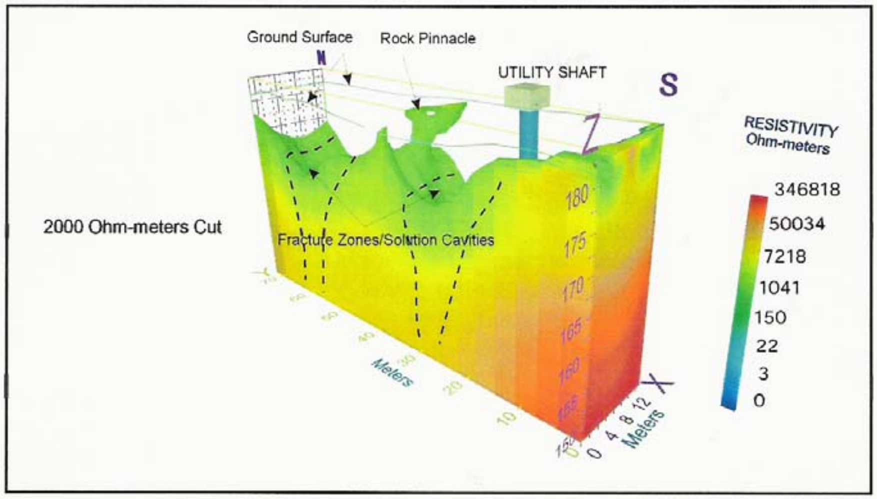

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The EM method is a relatively rapid field method that can provide complete coverage of a survey area at a relatively low cost. The EM method can also complement other data sets such as 2D resistivity, providing a data set that helps with interpretation of shallow features and that allows correlation between 2D survey lines. An example plot from an EM survey we conducted for karst features is shown below.

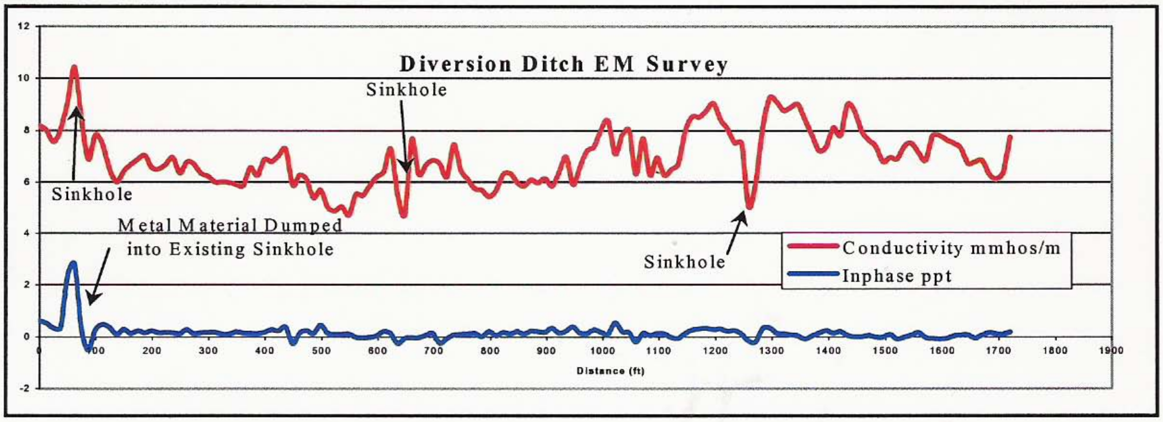

Figure 3 - Example EM-31 Profile from sinkhole investigation

2.4 Multi-Channel Spectral Analysis of Surface Waves (MASW)

Another method that has potential application in karst investigations is multi-channel spectral analysis of surface waves (MASW). The MASW method uses the analysis of the dispersion of surface waves to estimate the shear wave velocity depth profile at a series of surface locations. An array of geophones is used to record the surface wave energy and then this array is extended in roll-along method to record data along a survey line. The individual shear wave profiles are combined and contoured to provide a 2D cross-section of the subsurface shear wave velocity. Low density zones and air or water-filled voids should appear as low velocity anomalies in the 2D cross-section.

MASW is a relatively new technique that should be useful in the evaluation of karst features. Insufficient examples are available to determine the expected resolution of this method but it will depend on the geophone spacing, specific energy source, array length, and other factors. The rate of data acquisition is slower than 2D resistivity but it is expected to improve as MASW is used more regularly. The MASW technique is not recommended as a primary survey method for this project, due to the relatively higher cost and unknown resolution but it could be used to evaluate specific features identified using other methods. An example image produced by a MASW survey is given below.

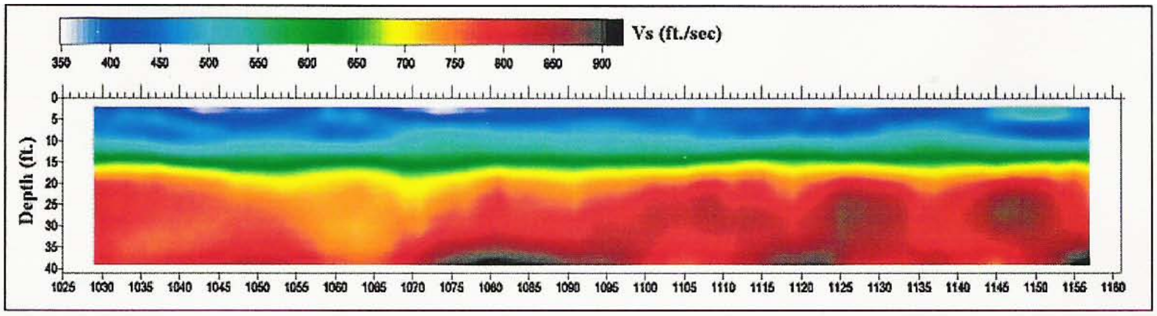

Figure 4 - Example 2D shear wave velocity cross-section from MASW survey

2.5 Other Methods

Other methods that have been used to locate karst-related features include micro-gravity and ground-penetrating radar. Historically, micro-gravity has been used successfully to locate voids and low density zones in the subsurface. However, gravity data acquisition and analysis is much more time-consuming than other methods and the method does not provide a unique solution. The amount of time required for each reading can limit the resolution of a survey for a given budget. Micro-gravity is not recommended for this particular project.

Ground penetrating radar (GPR) has been used in some cases to locate anomalies in karst terrain. However, the GPR signal is limited to a few feet of penetration in clayey soils, such as are found at this site. GPR is not recommended for this particular project.

3.0 PROPOSED APPROACH

We have developed our approach to address the specific objectives of the current project while addressing the needs for future cost-effective surveys for Kentucky highway projects. In addition to providing a proposal to conduct surveys using two recommended methods, we have included options for evaluating additional methods at the Center's discretion.

3.1 Method 1 – 2D Resistivity Imaging with 3D Processing

We propose to conduct parallel 2D resistivity lines along the new highway alignment using the dipole-dipole method. The dipole-dipole array provides a good combination of lateral and vertical resolution compared to other arrays. The surveys will be conducted using an array of 56 electrodes and an electrode spacing of 3 meters (10 feet) for an array length of 165 meters (541 feet). The maximum expected depth of investigation is 20 percent of the array length, so we expect to obtain images to a depth of about 33 meters (108 feet).

The roll-along technique will be used to extend the array to cover the total survey line length. In the roll-along technique, a portion of the electrodes from the beginning of the array are moved to the front of the array to collect additional data, and then the process is repeated as needed. Each survey line will be approximately 500 meters (1641 feet) in length.

For this work, we recommend an initial line spacing of 10 meters (32.8 feet) from shoulder to shoulder to provide 4 parallel survey lines. Disregarding the data gap that will be caused by the existing US 231 roadway, the total linear coverage for the 4 initial lines will be about 2,000 meters (6,562 feet). Additional in-fill data can be collected along lines spaced between the initial survey lines, as needed to provide additional data over observed features. We have included an option for collecting 500 meters of in-fill data. Our cost proposal is based on the initial data acquisition parameters stated above. The data acquisition parameters may change based on discussions with the Center prior to mobilization. In this case, our costs may need to be adjusted.

The data will be acquired using either our Sting/Swift system or a leased equivalent. Stainless steel electrodes will be used for the dipole-dipole measurements, with salt water added at each electrode location as needed to reduce contact resistance between the electrode and the ground. Level surveys will be used to determine the relative elevations of each electrode and will be tied to a temporary benchmark (TBM) or to a known elevation if one exists within the survey area. Wooden stakes will be placed at the beginning and end of each survey line and at intervals along each line. It will be the Center's responsibility to survey the location of each stake, if needed.

The recorded data from the initial array on each line will be downloaded to a laptop computer in the field and reviewed for quality control prior to proceeding with the rest of each line. A preliminary depth model of each line will be generated during the field work to determine if karst features may be present. These preliminary results will be used by us and by the Center representatives to determine if and where additional in-fill lines are needed.

The resistivity data will initially be processed using Res2DInv to produce independent 2D models. Then, the 2D data sets will be combined into a 3D data set and inverted to produce quasi-3D models of the subsurface resistivity. The quasi-3D data will be presented in various formats (3D data block, depth slices, etc.) as needed to show the extent of suspected karst features.

Expected Results of Resistivity Surveys

In general, the resistivity images should show the residual clayey soils as a surficial unit of lower resistivity and the underlying limestone bedrock as a higher resistivity zone. Air-filled voids of sufficient size may be observed as very high resistivity anomalies while water and clay-filled solution features within the bedrock will have a low resistivity compared to the general bedrock values.

The resistivity surveys should provide images of laterally extensive features that cross the survey lines, have an equivalent diameter at least as large as half the electrode spacing (1.5 meters or 5 feet), and are at least as large as they are deep. For example, it is expected that this method will allow a void that is 3 meters (10 feet) in diameter to be imaged if the top of the void is no deeper than 3 meters below ground surface and the survey line is approximately centered over the void. Karst-related features not meeting these criteria and features located between the survey lines may not be imaged using the proposed resistivity method.

3.2 Method 2 – Electromagnetic Induction

We propose conducting electromagnetic induction (EM) surveys over the study area to supplement the results of the 2D resistivity surveys and provide near-surface information in the area between lines. The data will be collected using a Geonics EM-31 terrain conductivity meter that has a maximum investigation depth of about 6 meters (20 feet) when operated in the vertical dipole mode. The peak response for the vertical dipole mode is from a depth of about 1.5 meters (5 feet).

The EM-31 data will be collected at approximately 0.5-meter (1.6-foot) intervals along parallel survey lines with a spacing of 2.5 meters. Thirteen survey lines will be required to cover the study area for a total linear coverage of about 6500 meters (21,327 feet or 4.0 miles). The wooden stakes placed during the resistivity survey will be used for location control with additional stakes and pin flags placed as needed.

The data will be reduced using DAT31, a proprietary software program published by Geonics for this purpose. After the data are adjusted for position, they will be exported for contouring and annotation in Surfer, a common gridding and contouring software package. The data will be displayed as a color contour plot. Individual profile lines can also be plotted above the 2D resistivity models to aid in the interpretation.

Expected Results of EM Surveys

The EM-31 provides both conductivity and in-phase values for each measurement. The conductivity plot will be used to identify possible karst related features, such as near-surface voids and water or clay-filled solution zones in shallow rock. The conductivity values can also be used to distinguish between areas of shallow limestone bedrock (low conductivity) and thicker residual soils (higher conductivity). In addition, the in-phase data will help identify buried metal objects such as utilities and waste material that can often cause false anomalies in the resistivity data.

4.0 OPTIONAL SERVICES

At the discretion of the Center, Schnabel Engineering can provide one or more of the following services, in addition to the proposed scope of work. These additional services could improve the overall evaluation of this particular site and provide additional information for selecting survey methods for future sites.

4.1 Lineament Analysis

Our typical approach to investigating an area with karst activity is to conduct a lineament analysis using topographic maps and aerial photographs prior to conducting the field investigation. Solution activity in limestone is often associated with a particular joint or fracture pattern. Lineament analysis can determine the dominant orientations of karst activity in a particular area and be used to select line locations and orientations, and aid in the data interpretation. The estimated cost for this optional service is provided in this proposal.

4.2 3D Resistivity Imaging

The results of the 2D resistivity survey may indicate the presence of karst-related features in some locations within the study area. Additional detail on the geometry of these features could be obtained by performing a 3D resistivity survey over a specific area. The 3D data also would allow a better estimate of the volume of a particular feature, if needed for grouting purposes. The 3D survey would be conducted using the pole-pole or the pole-dipole method with an electrode spacing of 3 or 5 meters (16.4 feet), depending on the specific survey objectives. The cost for a 3D survey would depend on the specific acquisition parameters and the extent of the survey.

4.3 MASW

Critical areas underneath the planned roadway containing a complex geometry of karst features could be further evaluated using MASW. We assume that the MASW work would be conducted following the initial 2D analysis of the resistivity data so that an appropriate area can be selected. The cost for a MASW survey would depend on the acquisition parameters and the extent of the survey.

5.0 STAFFING

We propose conducting the field work using a 3-person crew. We have found that a 3-person crew is more efficient than a 2-person crew when conducting multi-channel resistivity surveys. The project will be staffed in the field using one of our Project-level Geophysicists, a staff-level Geophysicist and a Technician. The project will be managed by our Associate Geophysicist, Mr. Edward D. Billington, P.G., of our Greensboro, NC office. Resumes for these personnel can be provided upon request.

6.0 ASSISTANCE TO BE PROVIDED BY THE CENTER

It is assumed that the Center, as the representative of the Kentucky Transportation Board, will be responsible for obtaining permission for us to be on the site properties and will indicate the alignment boundaries and shoulder limits to us in the field. We also assume that the Center will be able to provide available aerial photographs and topographic maps to assist us in the lineament analysis, if that analysis is conducted.

7.0 PLANNED SCHEDULE

We understand that the work needs to be completed prior to beginning of construction, which is currently scheduled for mid-fall of 2002. Assuming that a notice to proceed is given to us by August 19, 2002, we could mobilize to the site by about September 2. We have estimated that the field work will require about 10 days to complete, allowing 7 days for the 2D resistivity survey, 2 days for the EM-31 survey, and one day for weather. Given this field schedule, we assume that the field work will be completed by about September 13. Data analysis and report preparation will require approximately 2 to 3 weeks. We anticipate submitting our report by October 7, assuming draft reviews are not required by the Center.

Please note that selection of any of the optional geophysical methods would extend the length of the field work and the associated time required for analysis and report.

8.0 ASSUMPTIONS

We have made the following assumptions in addition to those stated above in preparing our estimated costs for this work.

1. Clearing of brush will not be required for this work.
2. The site can be easily walked and can be driven using a 4-wheel drive vehicle.
3. There are no paved areas within the survey area.
4. The Center will arrange to have the centerline of the planned alignment staked every 25 meters.
5. Delays from inclement weather will not exceed more than one field day.
6. Only one mobilization will be required for the 2D resistivity and EM-31 surveys.

PROPOSED KARST SUBSURFACE GEOPHYSICAL INVESTIGATION ALONG A SECTION OF US 231, WARREN COUNTY, KENTUCKY

INTRODUCTION

The Center for Cave and Karst Studies (CCKS) Applied Research and Technology Program of Distinction (Appendix I) proposes to assist the Kentucky Transportation Center with a karst subsurface geophysical investigation along a 500-meters section of the new highway alignment for US 231 located in Warren County, Kentucky approximately 10 miles southeast of the City of Bowling Green.

Over the past 17 years the CCKS has performed numerous subsurface geophysical investigations in karst areas and many of them have been along existing or proposed highways. Appendix II contains two publications that demonstrate the Center's ability to detect karst subsurface features and depth to bedrock. The second article, presented at the First International Geophysics Conference on Highways, deals only with the Center's work along proposed or existing highways in Kentucky.

The Center has recently performed an electrical resistivity and microgravity investigation for Florence and Hutcheson along a one-half mile section of proposed Route 27 north of Somerset, Kentucky. It is presently involved in an investigation along the mile long section of US 31-W in Bowling Green which is to be widened. The CCKS has also recently investigated the sinkhole collapse under Dishman Lane in Bowling Green and is presently performing a geophysical investigation for the widening of Cave Mill Road for the City of Bowling Green.

SCOPE OF WORK

Task A

Many geophysical techniques have been used in karst regions to investigate subsurface conditions, and the CCKS over the years has tested most of them. Some geophysical techniques, such as ground penetrating radar, that work quite well in sandy soils such as Florida, provide very poor results when applied in the high clay soils of Kentucky. Other common geophysical techniques, particularly seismic, do not provide good results in most karst areas because of the very irregular soil bedrock interface and complicated subsurface features such as caves and existing sinkhole collapses. Spontaneous potential (natural potential) is a very cheap and easy technique, but the results are very difficult to interpret and the interpretations are often very subjective. The Center believes that these techniques have been greatly overstated in the literature and have not provided good results in Kentucky.

Beginning in 1985, the CCKS started using microgravity, a geophysical technique primarily used for oil exploration to measure low-gravity anomalies in karst terrain. These low-gravity anomalies virtually always are indicative of caves, collapsed caves and areas of deep regolith surrounded by solid limestone (large deep cutters). The Center has drilled approximately 150 wells into microgravity low anomalies, and its success rate is well above 90% for identifying these karst features. For many years it was virtually the only geophysical tool that the Center used to investigate karst subsurface conditions. However, with the development of the new Swift/Sting Electrical Resistivity Meter over the last four years, the Center has started to use electrical resistivity to determine depth to bedrock, cutters (areas of deep regolith between bedrock pinnacles), sinkhole collapses and caves. The Center now prefers to use both electrical resistivity and microgravity for karst subsurface investigations. This facilitates interpretation as follows:

1. A low microgravity anomaly that corresponds with a high resistivity anomaly is indicative of an air-filled cave.

2. A low microgravity anomaly that corresponds with a low resistivity anomaly is indicative of an area of deep regolith surrounded by bedrock (clays tend to be good conductors of electricity).

The Center believes that knowledge of karst subsurface features is critical in the interpretation of the geophysical data. For example, dry limestone bedrock, surrounded by areas of moist limestone bedrock will often appear to be a cave on the modeled data due to its high resistivity. Several geophysical firms have made this mistake and drilled wells into solid bedrock when attempting to intersect caves.

Task B

The Center owns a significant amount of geophysical equipment. It also has personnel with several years of experience using the instrumentation and interpreting the results. The Center proposes to use its Sting/Swift Electrical Resistivity Meter and its Scintrex CG3 Microgravity Meter to perform the subsurface investigation.

The Center has two layouts for performing this investigation and therefore submits two proposals and two budgets.

1. Traverse layouts. The layout often used by the Center involves performing traverses above and parallel to the proposed highway alignment. Often one traverse using both resistivity and microgravity is performed along the center of each proposed lane of traffic. This layout requires the least amount of work, but it does not provide the 3D data requested under Task B of the Request for Proposal.
    a. Advantages: The traverse layout requires less time and less expensive equipment; therefore, it is less expensive.
    b. Disadvantages: The technique of using a series of traverses and then contouring the values using Slicer Dicer or some other contouring program will not provide accurate resistivity data. Unfortunately, the modeling

program only shows variation in resistivity along the traverse. It then scales the data and prints it out as a color with each color representing a resistivity range. Unfortunately, the range and subsequent color will be different for each traverse. This technique does not provide true, 3D resistivity data.

2. Grid Layout. In order to provide 3D data and 3D color maps, a grid system is needed along the approximately 32.4 meters wide by 500 meters long proposed alignment. Therefore, the Center prefers to provide 3D electrical resistivity data instead of 2D (traverse data). This will provide a much better representation of the true subsurface conditions since it measures the electrical resistivity between all stations within a grid, not just those along a traverse. The following diagrams show the advantage of 3D over 2D:

   2D measures resistivity between electrodes along each individual traverse but not between traverses. Each traverse is independent.

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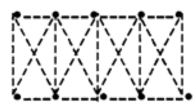
   •---•---•---•---•

   3D measures resistivity between all electrodes in a grid, even diagonally.



   The Center proposes to measure microgravity in a grid system measuring the true microgravity at each point (not modeled data). These microgravity data will then be contoured using Slicer Dicer software.

   The Center proposes to use six-meter spacing for the grid system for both resistivity and microgravity. In areas where the resistivity and microgravity data indicate a subsurface anomaly that needs to be further investigated, microgravity will be repeated using a two-meter spacing interval.

   a. Advantages: The grid layout provides true 3D resistivity data over the entire area while the traverse method provides only 2D data along each traverse. It provides better subsurface data than the traverse method.

   b. Disadvantages: The grid layout requires more time, more expensive equipment and therefore is more expensive.

Task C

The Center will provide a detailed report describing methods used to collect and process the data. The data should provide good estimation of depth to bedrock when calibrated using **existing borings.**

TECHNOS

Proposal
For New Highway Alignment Along US231
Near Bowling Green, Kentucky
for
Kentucky Transportation Center
University of Kentucky
Lexington, Kentucky

July 23, 2002

BACKGROUND

The Kentucky Transportation Center at the University of Kentucky, under contract to the Kentucky Transportation Cabinet is requesting a proposal for geophysical testing and analysis on a proposed new highway alignment in south central Kentucky.

The proposed new highway alignment is US231 located 10 miles southeast of the City of Bowling Green. The area of interest is approximately 500 meters in length. The limits of the field investigation will be confined to Stations 8+600 to 9+100 (along the centerline) and laterally, from the outside edge of the shoulder to the outside edge of the opposite shoulder (approximately 32.4 meters).

The bedrock in and around the city of Bowling Green is a highly calcareous limestone which is highly susceptible to karst formation. The overlying residual soils consist of heavy clays. From preliminary borings, the limestone bedrock is between 10 and 25 metes in depth.

TECHNICAL APPROACH

We are proposing 2D resistivity imaging and microgravity measurements to characterize the subsurface and identify karst features. We recently successfully used this approach to characterize karst conditions along I-65 northeast of Bowling Green.

2D Resistivity Imaging Measurements

Electrical resistivity measurements are made by placing electrodes in contact with the soil or rock. A current is caused to flow in the earth between one pair of electrodes while the voltage across the other pair of electrodes is measured. The resistivity measurement represents the apparent resistivity averaged over a volume of the earth determined by the soil, rock, and pore fluid resistivity, along with the electrode geometry and spacing.

A Sting resistivity meter in conjunction with the Swift multi-electrode switching system manufactured by Advanced Geosciences, Inc allows a two-dimensional (2D) resistivity image of the subsurface to be acquired relatively quickly. An array of electrodes are set into the ground and an automated system controls which two act as the potential electrodes and which two act as the current electrodes. By switching to different electrode separations and positions, a resistivity cross-section can be calculated using a two-dimensional inversion program (RES2DINV).

DEPTH AND RESOLUTION

The depth and resolution of 2D resistivity measurements are related to the electrode spacing and the distribution of current, which is influenced by the relative resistivity and thickness of the subsurface layers. A single measurement of apparent resistivity at a given electrode spacing represents a weighted average of the resistivity and geometric effects over a relatively large volume of material, with the shallow portions contributing most heavily.

DATA ACQUISITION

For this investigation, we propose 2D resistivity measurements along three survey lines located along the centerline and both shoulders. The measurements will be made with a 6-meter electrode spacing, providing relatively high resolution data to a maximum depth of approximately 30 meters.

The data will be digitally recorded and downloaded to a PC for processing. The data will be processed using RES2DINV software and contoured as resistivity cross-sections along each survey line.

EXPECTED RESULTS

The proposed data will provide three (3) parallel 2D cross-sections along the proposed right-of-way. Depth of measurements will be approximately 30 meters and will show the thickness and variation in overlying unconsolidated materials along with the top of rock. Localized lows in the bedrock (cutters) will be identified.

LIMITATIONS

Resistivity data can be adversely affected by grounded metallic objects such as large metallic pipelines and guard rails. We will make an effort to make measurements in areas not affected by these features.

Microgravity Measurements

A microgravity survey provides a measure of change in subsurface density. Natural variations in subsurface density include lateral changes in soil or rock density, buried channels, large fractures, faults, dissolution-enlarged joints and cavities. The microgravimetry method comes closest of all the geophysical methods for allowing a positive statement to be made regarding the presence or absence of subsurface cavities at a site (Butler, 1984).

A microgravity survey consists of making sensitive gravity measurements at the microGal (μGal) level (1/1000 of a milliGal or 10^{-9} of the earth's gravitational field) with a gravimeter. Most gravimeters are relative instruments which measure differences in gravity from station to station and not absolute values. Gravity measurements are acquired at discrete points along a profile line or within a grid, and are corrected for instrument drift, tidal effects, elevation changes, and latitude. The corrected measurements are known as the *simple Bouguer gravity.* Spatial changes in the Bouguer gravity are referred to as gravity anomalies, and are directly related to subsurface density changes.

MAXIMUM DEPTH OF DETECTION

As a rule of thumb, compact structures that can be approximated as spherical in shape, can be detected at a depth to center of about two times the effective diameter at the 10 microGal threshold level (Butler, 1980). In reality, if the sphere (cavity) developed due to dissolution of rock it must have at least one input and one output tunnel. In addition, it is associated with highly weathered fracture zones and bedding planes. This results in a halo effect that increases the magnitude of the gravity anomaly by a factor of 2. Similar arguments can be made for other geometries.

DETECTABILITY THRESHOLD

The magnitude of a gravity anomaly is dependent on the depth, size and density contrast of a subsurface feature. In order to be detected in the gravity survey, a subsurface feature must be large enough or shallow enough to produce an anomaly above the noise threshold. Under normal field conditions, anomalies ≥10 microGals should be routinely detectable (Butler, 1984).

DATA ACQUISITION

Microgravity measurements will be made with a Scintrex CG-3M gravimeter. Data will be acquired at stations spaced 6 meters apart along three survey lines located along the centerline and both shoulders. Survey lines may be extended beyond the area of interest to maximize the depth of investigation. We estimate that data will be acquired at a total of 300 stations.

The data will be processed using standard gravity reduction software and presented as survey lines and/or contour maps.

EXPECTED RESULTS

The three parallel lines of gravity data will be located along the same lines as the resistivity data and will provide a more detailed assessment of lower density zones across the width of the right-of-way.

A decrease in density can be related to increased depth to rock or major weathered fracture systems or cavities. The resistivity data will be used to constrain models developed from the gravity data. The combination of both methods will yield a more accurate and complete model of subsurface conditions than borings alone can provide.

LIMITATIONS

Variations in nearby topography can produce anomalies that are not due to subsurface features. Small cavities located at a depth greater than twice their diameter may not be detected.

SCHEDULE AND DELIVERABLES

Technos will be prepared to mobilize to the site within two weeks of notification to proceed. Fieldwork is estimated to require approximately 7 to 10 days depending upon staffing. A final report will be provided within 15 working days of completion of fieldwork.

A detailed report will be provided that describes all methods used to collect field data and the methods used to process the data. The report will include all underground features that were found, including their location, extent and depth. The report will include color maps and cross-sections models.

COSTS

The costs for the survey are provided as lump sum and have been broken down by method.

Mob/Demob/Equipment/per diem (3 persons crew)	$10,400.00
Fieldwork	
Resistivity data acquisition (4 days)	10,000.00
Gravity data acquisition (6 days)	15,000.00
Survey set up and elevations (1 day)	2,500.00
Resistivity data reduction and analysis	1,300.00
Gravity data reduction and analysis	1,300.00
Final report	$ 5,000.00
	$45,500.00

ASSUMPTIONS

Our costs are based upon the following assumptions:

- Client will coordinate site access, if necessary;
- Client will coordinate movement of vehicles, if needed;
- Client will provide traffic control and safety equipment, if needed;
- The survey will be run in accessible areas only (no brush clearing is included);
- All work completed during one mobilization;
- Three copies of a final report will be submitted.

Evaluation of Proposals

Each of the five proposals was evaluated on three major points --

Technical Merit,
Experience of the staff, and
Cost.

All of the prospective contractors seemed to have adequate experience. However, it appeared that the Center for Cave and Karst Studies at Western Kentucky University would use graduate students for much of the field work. Table 6 is a summary of the proposed methods and costs, plus the "pros" and "cons" of each contractor.

Table 6. Summary of Analysis of Contractors' Proposed methods and Costs.

Rank	Firm	Methods	Cost	Pros	Cons
1	PELA	• Microgravity • 2D Sting/Swift Resistivity (10 km) • OPTION - Tech Review	$36K $44K w/tech review option	• High data volume • Proven methods • Strong team	• Tech review is expensive
2	Blackhawk	• 2D OhmMapper Resistivity (3 km) • GRM Refraction • OPTION -- Sting/Swift Resistivity	$39K ($14K for OhmMapper, $30K for refraction) $52K total with Sting/Swift option	• Proven primary method • Try out new methods	• Expensive with Sting/Swift Option
3	Schnabel	• 2D Sting/Swift Resistivity (2 km) • EM31 Terrain Conductivity • MSASW • OPTION – 2D infill lines	$34K $41K with infill option	• Proven primary method • Try out new methods	• Secondary methods might not work
4	WKU	• Microgravity • 2D Sting/Swift Resistivity (2 km) • OPTION – 3D Sting/Swift	$13K $26K with 3D option	• Proven methods • Inexpensive	• Proposal cost inconsistent with other proposals • Contractor already known
5	Technos	• Microgravity • 2D Resistivity (1.5 km)	$47K	• Proven methods	• Expensive • Low data volume • Low proposal effort

From Table 6, the first four contractors proposed at least three methods, with Contractor 3 proposing four methods. Contractor 5 proposed only two methods. From Table 6, it is clear that costs varied widely. The comments in the "pros" and "cons" columns in the table were all issues that were discussed by the research team and the study advisory committee. In the end, the contractors were ranked as shown in Column 1 of Table 6. Table 7 is a summary of the top two methods that each contractor would perform, if awarded the contract, along with comments concerning brush clearing and surveying.

Table 7. Summary of Proposed Methods.

Vendor	Method 1	Method 2	No. of Lines	Cost	Comments
PELA	Resistivity	Microgravity	4	$36,574	
Blackhawk	Seismic	Resistivity	6	$39,166	Will do surveying and clear brush
CCKS (Crawford)	Resistivity	Microgravity	2-D Traverse (3 lines?) 3-D Grid	$13,347 $25,829	Both proposed methods can be done with 2-D Traverse or 3-D grid (6-meter grid spacing)
Schnabel	Resistivity	EM	4	$34,068	KTC responsible for surveying and brush clearing
Technos	Resistivity	Microgravity	3	$46,800	Assumes all brush has been cleared

From the evaluation and analysis of the proposals, it was decided to award the contract to P.E. LaMoreaux and Associates (PELA). However, a problem developed while the analysis of the proposals was under way. It was discovered that the letting and construction schedule for US 231 in Warren County had been moved up. Therefore, there was not going to be sufficient time to complete the geophysical study before the letting date. Consequently, the research team and the study advisory committee were forced to choose an alternate site for the study. KY 101 in Warren and Edmonson Counties was chosen as the alternate study site. This site was chosen because it had a sufficient time frame to conduct the study and because it had the same physiographic characteristics of US 231.

However, because of time and cost the research team and the study advisory committee decided not to go through the "full blown" proposal route a second time. Since PELA had been chosen to be awarded the contract on the first site, it was decided to ask them to submit a proposal for the second site. Therefore, PELA submitted a second proposal for KY 101. The cost for that site was $61,000, and the contract was awarded to PELA.

FIELD PROJECTS

Project No. 1: KY 101, Edmonson and Warren Counties

This project was awarded to PELA. An approximate two-mile section of KY 101 on the border of Edmonson and Warren counties was to be relocated (see Figure 1). Within the total project length there were two areas of interest, totaling approximately 3,000 feet. The first area was approximately 100 feet in length (Station 63+00 to Station 64+00). The second area was from Station 95+00 to Station 121+50 (2,650 feet in length). Figures 2 through 4 show general views of the two areas.

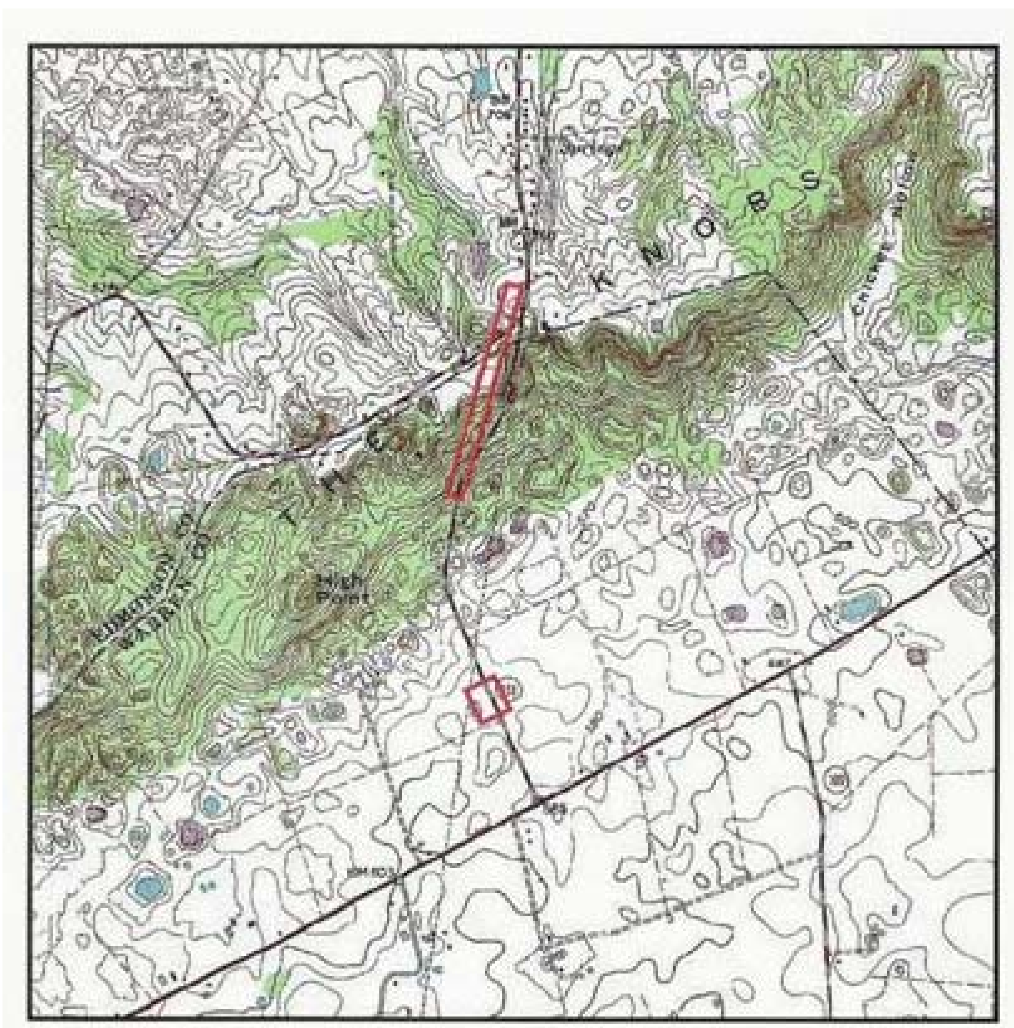


Figure 1. Location of Project No. 1, KY 101 (Areas of Interest).

Figure 2. KY 101, Section 1.

Figure 3. KY 101, Section 2.

Figure 4. KY 101, Section 2.

According to the contractor's report, this site is located in the Western Pennyroyal physiographic which starts north of Elizabethtown at the Ohio River and go south and west towards Bowling Green and Hopkinsville, and then turning back north again to the Ohio River. This area is mostly Mississippian age rocks, starting with St. Genevieve limestone at the southern end of the project and concluding with outcrops of the Girkin and its overlying Golconda formations at the northern end. These formations are highly karst with sinkholes, solution features and caves scattered throughout.

Two geophysical methods were used at this site. The first was electrical resistivity tomography (ERT) using an AGI String R1 Earth Resistivity Meter with the Swift automatic multi-electrode switching system. The second method used on this project was the microgravity method, which measures variations of earth's gravity beneath the instrument at a particular point of testing. The variation of gravity is due to the density of materials at that point. The survey was conducted using a Scintrex CG-3M Autograv Microgravity Meter.

The full report submitted by PELA on this project is listed in Appendix A. Table 1 from that report (Table 8 in this report) lists numerous karst features along the project route, as determined from the ERT. These are described in Table 8. A total of 30 anomalies are listed along the approximate 3,000-foot section.

Table 8. Results of ERT for KY 101 (Table 1 in PELA's Report).

PELA

Table 1. Line by line description of karst features along the planned expansion of KY route 101. Features noted are those of specific concern to stability of the road. They are described based only on the data from one line.

Line No.	Start Point	End Point	Feature Start Point	Feature End Point	Length of Feature	Comments and Interpretation
1	62+10	64+80	63+00	63+25	25 feet	A bowl shaped depression or trough in the bedrock surface: a cutter.
1	62+10	64+80	63+80	64+15	35 feet	A bowl shaped depression or trough in the bedrock surface: a cutter.
2	62+10	64+80	63+35	63+65	30 feet	Wide, deeply-weathered zone to a depth of at least 80 feet. No material with resistivity in the rock range.
3	62+10	64+80	62+75	63+80	105 feet	A broad depression in the bedrock surface.
3	62+10	64+80	63+95	64+25	30 feet	A bowl shaped depression or trough in the bedrock surface: a cutter.
4	95+00	104+65	95+25	95+75	50 feet	A bowl shaped depression or trough in the bedrock surface: a cutter.
4	95+00	104+65	97+60	98+15	55 feet	A solution-widened fracture in the bedrock, infilled with clayey overburden.
4	95+00	104+65	98+90	99+50	60 feet	A bowl shaped depression or trough in the bedrock surface: a cutter.
4	95+00	104+65	100+50	101+50	100 feet	A broad, bowl shaped depression or trough in the bedrock surface.
4	95+00	104+65	101+70	102+20	50 feet	A bowl shaped depression or trough in the bedrock surface: a cutter
5	94+40	101+40	95+30	96+70	140 feet	Low resistivity material (range of clay) at depth, beneath continuous high resistivity (rock range) material. A depression in the limestone surface centered between 96+30 and 96+70. Interpreted as a clay-filled cave.
5	101+50	115+40	101+50	102+70	120 feet	Wide, clay-filled zone to a depth of at least 80 feet. No material with resistivity in the rock range.
5	101+50	115+40	106+80	107+15	35 feet	Narrow, deep (50' +) shaft or clay-filled fracture which appears to correlate with an open karstic shaft to the west of the line. This has a great probability of posing significant risk to the road.
5	101+50	115+40	112+50	113+70	120 feet	Thin, near-surface layer of high resistivity (rock range) underlain by an elliptical zone of low resistivity material. This area correlates with a surface depression and may be indicative of future subsidence. It may be a shallow, clay-filled solution feature beneath sandstone caprock.
6	94+30	101+20	96+20	96+50	30 feet	Minor depression or trough in limestone surface: minor cutter.
6	94+30	101+20	99+10	99+50	40 feet	Isolated zone of high resistivity material at surface. Interpreted as rock floater near or at surface underlain by clay, or possibly a rock pinnacle.

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Table 8. Continued.

PELA

6	102+50	116+40	105+00	105+65	65 feet	A bowl shaped depression or trough in the bedrock surface: a cutter.
6	102+50	116+40	106+25	106+55	30 feet	Narrow, deep (50' +) shaft or clay-filled fracture which appears to correlate with an open karstic shaft to the west of the line. This has a great probability of posing significant risk to the road.
6	102+50	116+40	107+05	107+70	65 feet	Low resistivity material (range of clay) at depth, beneath continuous high resistivity (rock range) material. Interpreted as possibly a clay-filled solution feature.
7	117+30	121+30				Appears that throughout the length of this transect competent bedrock is more than 50 feet below ground surface.
7	117+30	121+30	118+10	118+45	35 feet	Extremely low resistivity potentially indicative of a saturated zone or very clayey interval, may also represent a conductive body in the fill.
7	117+30	121+30	118+80	118+95	15 feet	Extremely low resistivity potentially indicative of a saturated zone or very clayey interval, may also represent a conductive body in the fill.
7	117+30	121+30	119+25	119+60	35 feet	Extremely low resistivity area underlying an area that may have bedrock near the surface.
8	117+65	121+65				Appears that beyond 118+15 of this transect competent bedrock is more than 50 feet below ground surface.
8	117+65	121+65	118+20	119+20	100 feet	Very low resistivity anomaly that is broad nearer to the surface and then as it deepens becomes more like a shaft. This area is within a depression in the surface that was reported to be a filled in sinkhole by the owner Texie Colley.
8	117+65	121+65	119+35	120+35	100 feet	Very similar to above except there is no surface expression.
9	117+40	121+40				Appears that throughout the length of this transect competent bedrock is more than 50 feet below ground surface.
9	117+40	121+40	118+20	118+75	55 feet	Very low resistivity pocket.
9	117+40	121+40	119+00	119+30	30 feet	Extremely low resistivity area underlying an area that may have bedrock near the surface.
9	117+40	121+40	119+50	120+20	70 feet	Extremely low resistivity area underlying an area that may have bedrock near the surface.

A bowl or cup shaped anomaly is one in which dissolution of the limestone surface has produced a depression which was filled with a less resistive clayey soil. These areas are not thought to represent a great risk for sudden catastrophic collapse but may represent areas of persistent gradual subsidence.

The shaft anomalies are best described as a shaft of unconsolidated sediment filling a fracture in the bedrock. These areas are a substantial hazard as they lack any support in the middle of the feature and as such are possibly unstable and subject to collapse.

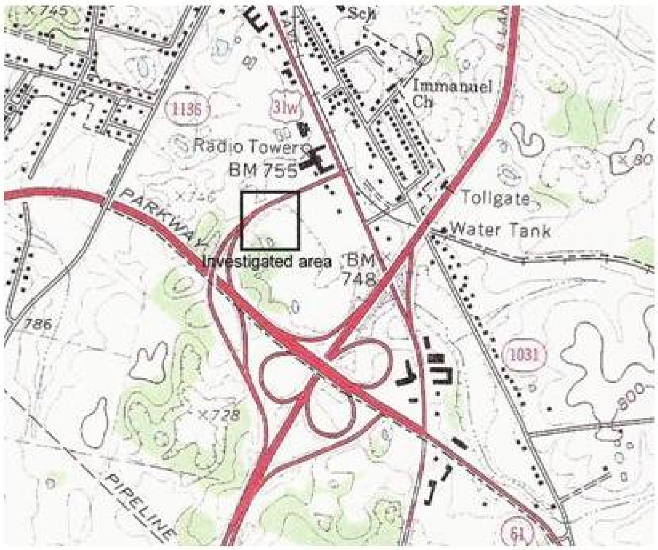
P.E. LaMoreaux & Associates

Two locations were tested using the microgravity method. As stated in the PELA report, "one was located in the fields in the lower portion of the site area where an existing sinkhole has been patched by DOT and a large sinkhole is present nearby in the field. A 300 by 300 foot grid was established on 20-foot station spacing, with a secondary 100 by 100 foot grid with 10-foot spacing in the center over the known sinkhole. This resulted in approximately 370 points being collected over the area. The second grid was located at the northern end of the area of interest, closer to the Edmonson-Warren County line on the property of Mrs. Texie Colley, over a filled sinkhole which penetrated through the sandstone caprock. A 300 by 330 foot grid was used, with 20-foot station spacing, giving a good compromise between resolution and site coverage. This resulted in approximately 260 points being collected over the area." The microgravity method indicated three low gravity areas at the first location, indicating three geophysical "anomalies" at that location. These are shown (dark blue-green areas) in Figure 11 of the PELA report (Appendix A). Figure 12 of the PELA report shows two possible geophysical "anomalies" at the second location, which are indicated by the blue-green areas on the map.

Project No. 2: US 31-W, Elizabethtown Bypass, Hardin County

This site is located off of the west side of a section of the southbound lane of 31-W Bypass extending around Elizabethtown, Kentucky. The sinkhole collapse is located approximately 85 feet to the west of the emergency shoulder of the roadway (see Figure 5).

Figure 5. Site Location.



Figures 6 and 7 are views of the collapsed area. Note the location of the highway in the background of Figure 7. The testing for this project site was conducted by the Center for Cave and Karst Studies (CCKS) at Western Kentucky University. They were awarded the study through contract negotiations, and an RFP was not issued.

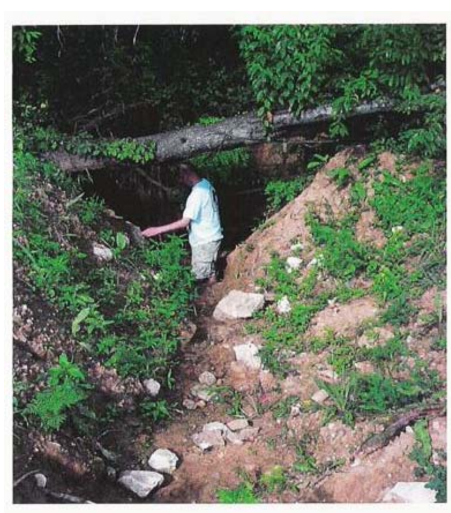


Figure 6. Location of Sinkhole.

Figure 7. Location of Sinkhole.

According to the final report submitted by CCKS (see Appendix B), the primary geologic units in the area are the Mississippian limestone and dolomite units. The most significant units are the St. Louis Limestone which overlays the St. Genevieve Limestone. This area and these geologic units are well known for having numerous karst features.

Microgravity was the only geophysical method used at this site. A Scintrex CG-3M Autograv Microgravity meter was used to conduct this study. Three parallel traverse lines were established at the site. The first traverse line was 100 feet in length, and Traverses 2 and 3 were 140 feet in length. The gravity readings were on 10-foot spacing intervals. Details of the testing locations and procedures are given in CCKS' report in Appendix B.

The three traverses tended from southwest to northeast. The gravity reading showed a decrease from west to east, indicating increasing depth to bedrock. According to the report, the sinkhole "is a result of a regolith (unconsolidated material lying on top of bedrock) arch collapse. It has been formed by downward movement of regolith into a crevice in the underlying bedrock." Detailed results can be found in the report in Appendix B.

Project. No. 3: KY 61, LaRue County

This project is located on KY 61 at approximate Milepost 12.9, between Elizabethtown and Hodgenville, in LaRue County. At this point the highway is a four-lane divided roadway, with a grassy median, running northwest to southeast (Figure 8). The southeast bound lanes have a noticeable dip (Figure 9). A general view of the area is shown in Figure 10.

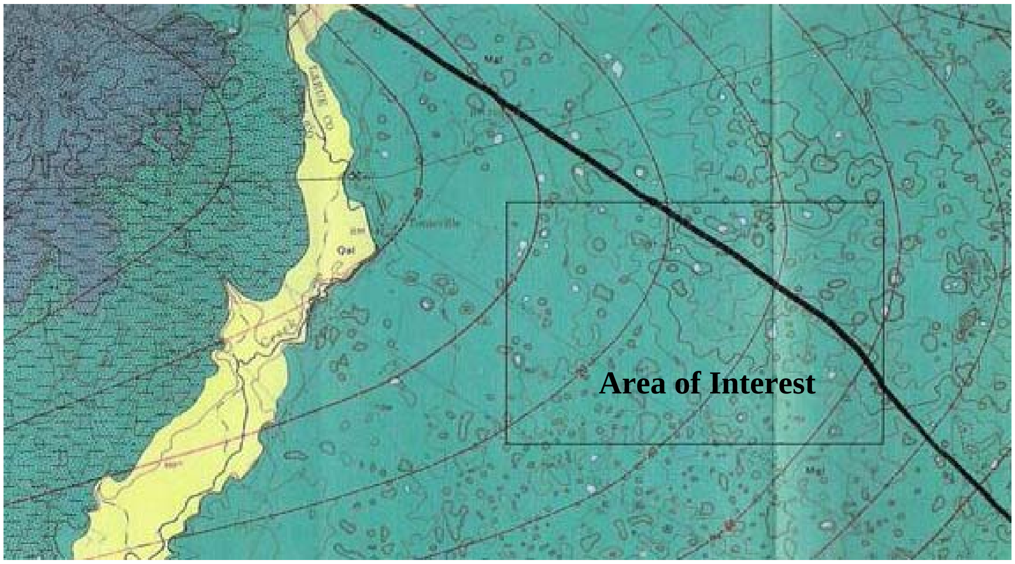


Figure 8. Location of Project No. 3, KY 61, LaRue County.

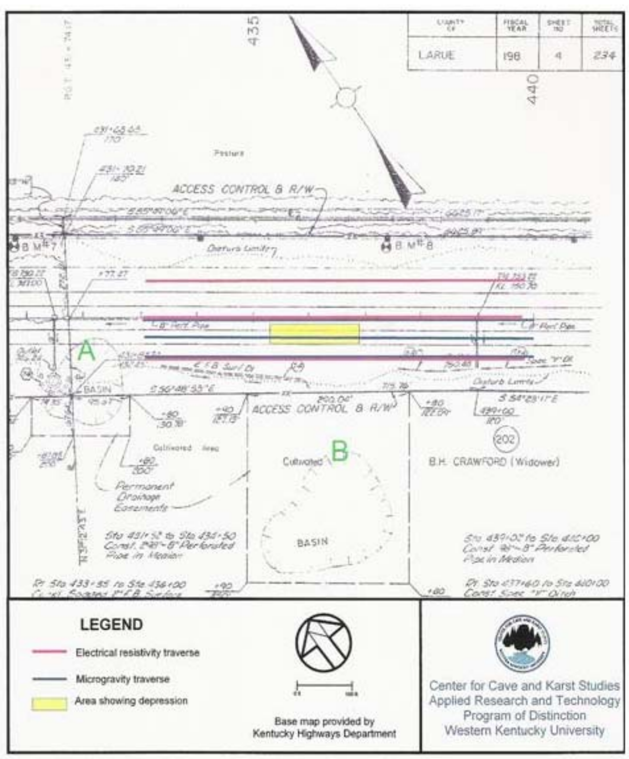


Figure 9. Detailed Location.

The main geologic units at this site are the St. Louis Limestone overlying the St. Genevieve Limestone. These are units of the Mississippian Age. These are highly susceptible to formation of sinkholes, solution channels and caves. The area under investigation is contains numerous funnel-shaped sinkholes (Figure 8).

This project was conducted by CCKS. Two geophysical methods were used at this site. The first was microgravity and a Scintrex CG-3M Autograv Microgravity Meter was used to collect gravity measurements. Resistivity was the second method used at this site. The resistivity survey used the Sting/Swift resistivity system to collect data. Three traverses were taken at this site – one north of the highway, one in the median, and one south of the highway (see Figure 9). The electrodes had 20-foot spacing on each traverse.

In general, the results from both methods indicated that the dip in the roadway may have been an extension of the karst feature (sinkhole basin) just south of the roadway (labeled B in figure 9). Also, the sinkhole basin labeled A in figure 9 may be a part of the same karst feature. Details of this investigation are listed in CCKS' report located in Appendix C.

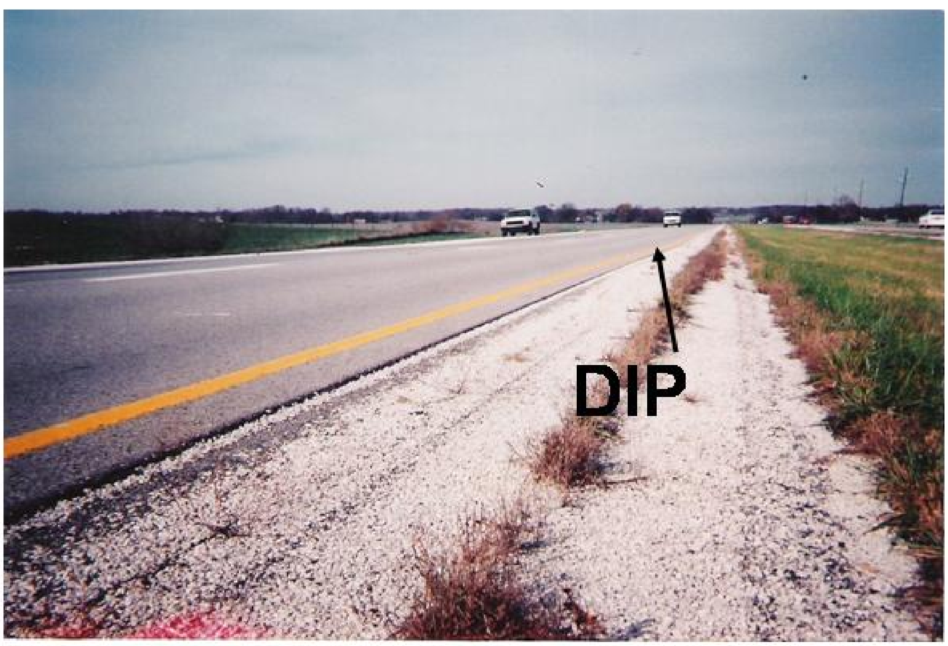


Figure 10. General Site View, KY 61.

__Project No. 4, US 27, Pulaski County__

This project is located on US 27 in Pulaski County, near Somerset, Kentucky. The site is located on a section of proposed relocated US 27 from Station 1064+00 to Station 1088+00 (see Figure 11). The geologic units at this site are the same as at the other three sites previously discussed in this report. The St. Louis Limestone is the dominant unit.

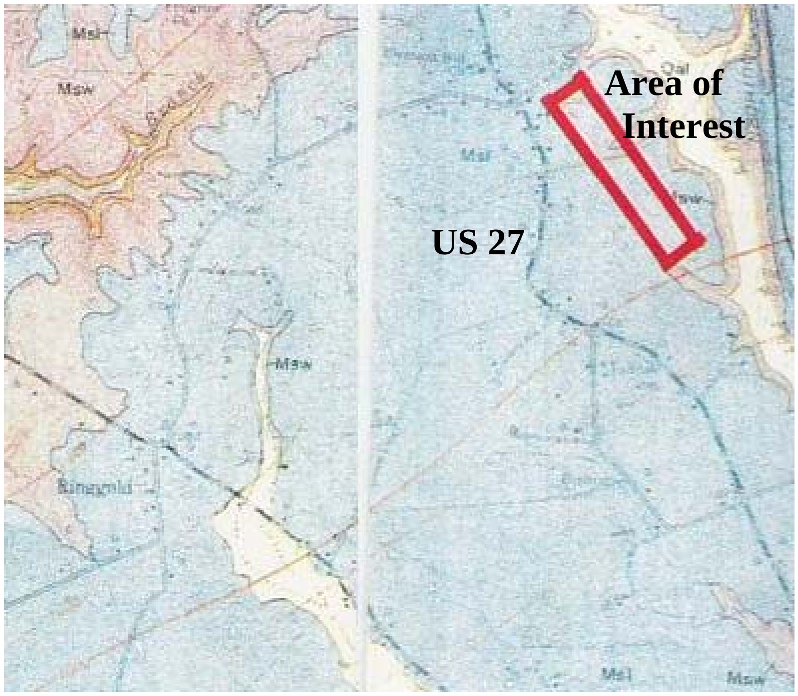


Figure 11. Location of Project No. 4, US 27.

Four traverse lines were run in the area of interest. The lines were 64 feet apart. Both microgravity and electrical resistivity were conducted along each traverse. Known caves in this area (Fisher Cave and Sweet Potato Cave) crossed under the traverse lines in this study. None of the cave sections were larger than three feet in height. Although not a part of this study, these cave sections were physically mapped by cave explorers.

The conclusions of the contractor's report stated that "after examination of electrical resistivity and microgravity data gathered over the areas containing Fisher Cave and Sweet Potato cave, it appears that the caves are located with the underlying bedrock. This portion of the bedrock containing the cave passageways, according to the resistivity profile, is approximately 80 feet below ground level. Both caves are too small and too deep to be detected either as low gravity or high resistivity anomalies. The third cave under investigation, Natural Bridge Spring, did not cross under the proposed highway site."

Detailed information on site conditions and methods along with the contractor's conclusions can be found in the contractor's report listed in Appendix D.

EVALUATION OF METHODS AND CONTRACTORS

One of the most important aspects of geophysical testing is to choose the right method for the particular site. All of the methods have advantages, disadvantages and limitations. There is on one method that is universally applicable to all situations. Therefore methods should be chosen after careful consideration of the site and objectives of the testing, and should be made in conjunction with the advice of experienced professionals. The only two methods used in this study were electrical resistivity and microgravity.

Electrical Resistivity

Crawford et al[(2)] state that "resistivity surveys provide an image of the subsurface resistivity distribution. Features that are not good conductors of electricity, such as air-filled voids in the overburden or a cave in the bedrock, result in high resistivity anomalies. This makes the resistivity method a good exploratory technique for investigation karst subsurface features, or where depth to bedrock is needed." Electrical probes are inserted into the ground at various distances, as shown in Figure 12 (shorter distances yield results from shallower depths).

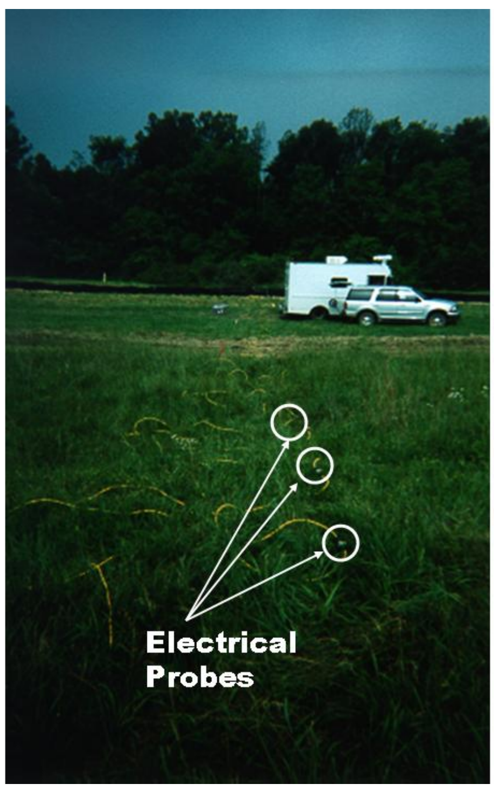


Figure 12. Electrical Resistivity Probes.

From the three projects tested in this study (KY 101, KY 61 and US 27) using electrical resistivity, results were good at each of the three sites. Collecting data at the sites is very time-consuming and complex. In addition, post-processing of the data is intensive and time-consuming. However, much more detailed information can be developed and analyzed at a much lower cost than what can be obtained from core drilling.

Microgravity Method

Microgravity surveys are used to measure the variation in density of subsurface materials. Gravity readings that are higher than normal indicate subsurface materials that have higher densities and lower gravity readings indicate less dense materials. Each gravity reading must have the following corrections made during post processing of the data.

- Instrument Drift (short term),
- Earth Tides,
- Reference Ellipsoid (latitude),
- Free-Air Effect (elevation, and
- Bouguer Slab Density (refers to the attraction of the slab material, which is caused by variation in density, between the station elevation and sea-level).

Microgravity measurements were obtained on all four projects included in this study. Two contractors, PELA and CCKS, used the microgravity method. As stated earlier in this report, gravity measurements were made by a Scintrex CG-3M Autograv Microgravity Meter. Figures 13 and 14 show gravity measurements being collected.

Figure 13. Microgravity Measurements Being Collected.

Figure 14. Close Up Of Microgravity Measurements.

As in the case of electrical resistivity, collecting readings in the field was very time consuming and complex. Also, post processing of the data in very intensive and subject to some interpretation by an experienced operator. However, the reports submitted by the contractors were very clear and easy to understand. Like electrical resistivity, much detailed information can be gained from this method at a cost considerably less than coring and drilling. Consequently, it was concluded that this method was very successful in characterizing the subsurface materials at the sites included in this study.

Evaluation of Contractors

PELA

P.E. LaMoreaux and Associates was the contractor on the KY 101 project. They were well qualified with many years of experience on their staff. Their technical proposal was in-depth and well-written. Their proposal clearly identified the scope of work and the approaches that were to be taken in conducting the study. Their field data collection techniques were excellent. Their final report was also well-written. It explained fully how the work was conducted and how data was collected. In addition, their analysis and recommendations were clearly explained. However, the research team can not recommend this contractor be used for future geophysical projects, without the assurance the problems which were encountered during the project can be addressed. The reasons for this lack of recommendation are explained in the following section of this report.

CCKS

The Center for Cave and Karst Studies at Western Kentucky University conducted three of the projects in this study. These were US 31-W, KY 61 and US 27. Like PELA, all of their technical proposals were well written and clearly defined the problem. Their proposals clearly explained their proposed approach to conducting the study. Their reports were well-organized and well-written. The presentation of their data was clear and easy to understand. Each of their project reports were received on time, and each of the projects were completed within budget. The research team most certainly recommends that this contractor be used on future geophysical project sites.

PROBLEMS ENCOUNTERED DURING THE STUDY

1. PELA had considerable problems completing the KY 101 project. They first indicated that the weather prevented them from completing the field data collection phase on time, and fell several months behind in that phase of the study. The original budget was for $61,000. However, they had used all of their budgeted funds and the report still had not been written. They were forced to ask for and additional $15,000 in order to complete the study. The final report was also late, which was partially blamed on personnel issues, including the fact that the P. I. developed health problems during the study.

2. The University of Kentucky Research Foundation was extremely slow in processing the necessary contract documents, causing a delay of several weeks getting the project started.

3. There was considerable conflict between the University of Kentucky research Foundation and the Western Kentucky University Research Foundation over regulations and contracting procedures. Several weeks of negotiations were required before all of the regulations for both agencies were satisfied.

CONCLUSIONS

- Both the electrical resistivity method and the microgravity method required extensive data collection in the field, which, in turn, requires a considerable amount of time to conduct a field investigation.

- Both the electrical resistivity method and the microgravity method requires extensive post processing of the data, and both require considerable experience in interpreting the data.

- Both methods appeared to define and delineate underground features fairly clearly and would indicate to a designer areas that would need further investigation.

- Four of the five prospective contractors provided good technical proposals. The fifth contractor (Technos) did not provide a very complete proposal and his estimated cost was considerably greater than the other contractors.

- The two contractors (PELA and CCKS) provided good final reports that were well-written and complete. The reports explained the methods used very well, and clearly explained and displayed the data well. Their interpretations were well documented.

- One contractor (PELA) was over a year late in providing the final report and over ran their budget by $15,000.

- The second contractor (CCKS) performed very well. His reports were on schedule and he completed the work within budget on each of the projects.

- Contracting procedures and regulations with the University of Kentucky Research Foundation and the Western Kentucky University Research Foundation were very difficult and required an excessive amount of time.

RECOMMENDATIONS

- Both the electrical resistivity method and the microgravity method should be used more extensively, in the future, in the preliminary stages of design. This will allow designers to more accurately choose areas for further, and more detailed, investigation – such as drilling and coring.

- Other methods of geophysical testing should be tried in Kentucky, as the situation might warrant.

- Due to problems outlined above, one contractor (PELA) should not be permitted to work for Kentucky Transportation Cabinet unless the problems associated with this project can be eliminated on future projects.

- As stated previously, the second contractor (CCKS) did an excellent job in his investigations and should be given further contracts in the state.

REFERENCES

1. Benson, R. C., *An Overview of Methods and Strategies Assessing Subsurface Geologic Conditions and Structural Testing of Road and Bridges,* The First International conference on the Application of Geophysical Methodologies and NDT to Transportation facilities and Infrastructure, December 11-15, 2000, St. Louis, Missouri.

2. Crawford, Nicholas, et. al., *Microgravity and Electrical Resistivity Subsurface Investigation at Mile Point 12.9 on Kentucky Highway 61, LaRue County, Kentucky,* Report by the Center for Cave and Karst Studies, University of Western Kentucky, Bowling Green, Kentucky, Report to the Kentucky Transportation Center, University of Kentucky, Lexington, Kentucky, October 2003.

APPENDICES (A through D)

APPENDIX A

KY 101 Report

Results of an Integrated Geophysical Investigation Over the Route of the Rt. 101 Expansion Through Edmonson and Warren Counties, Kentucky

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Dr. Barry F. Beck, P.G.

PELA Project No. 654600 **June 24, 2004**

PELA

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EXECUTIVE SUMMARY

On December 15, 2002, the Kentucky Transportation Center (KTC-UK) at the University of Kentucky, under contract to the Kentucky Transportation Cabinet, and P.E. LaMoreaux and Associates, Inc. (PELA) entered into an agreement to conduct geophysical testing and analysis on a proposed new highway alignment in south central Kentucky. The objectives of the geophysical studies were to:

- Use an integrated geophysical approach to identify the absence or presence of karst conditions underlying the proposed new highway alignment.

- Use a combination of two geophysical techniques to provide a 3-D understanding of the complex geology often associated with karst terranes, and a top-of-rock estimate.

- Evaluate the need for future ground modification.

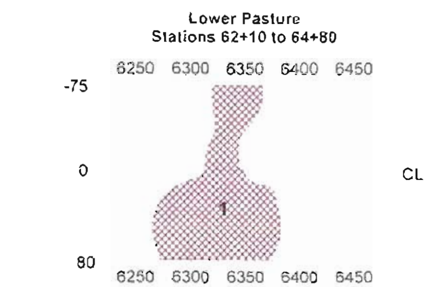
An integrated survey using microgravity and electrical resistivity tomography (ERT) was conducted to locate existing subsurface karst features and to help guide ground modification along the proposed alignment through known sinkholes, and over solution widened fractures and possible caverns. In most studies, surface geophysical methods are used in combination. We acquired nine ERT profiles and completed two 300 square foot microgravity grids to cover the areas of highest interest, including areas with visible sinkholes at the time of the survey. Wherever possible, three parallel resistivity transects were obtained along the alignment and the interpretations combined to yield a 3-D model. The gravity coverage was confined to only two limited areas because of the high cost of 3-D data, which was required by the contract.

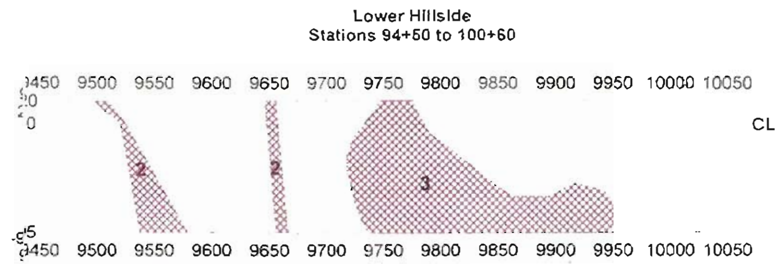
The resistivity models have an average maximum depth of approximately 80 feet. The 2D-ERT data outlines irregular features within the overburden and the bedrock,

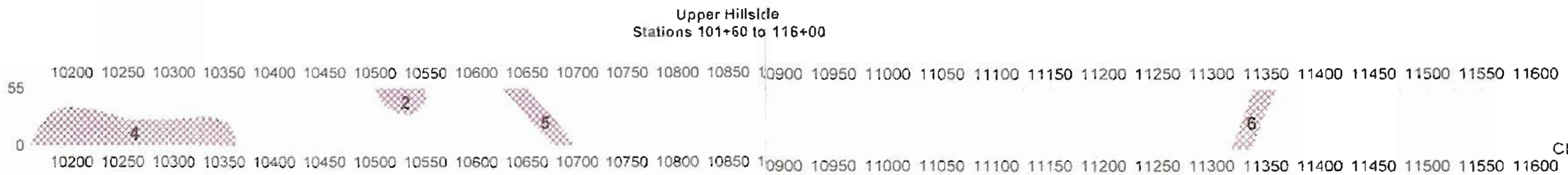
mapping variations in thickness and changes in the electrical properties. Overburden anomalies range in character from low resistivity bull's-eyes (less than 50 ohm-m) to lenses of high resistivity (greater than 200 ohm-m), with a nominal background level ranging from 80 to 120 ohm-m. The low-resistivity zones are interpreted to be primarily clayey intervals, though the presence of an electrically conductive pore fluid cannot be ruled out. High-resistivity anomalies within the overburden are interpreted as either floating blocks of intensely weathered rock or coarser-grained (less clayey) intervals. Two levels are interpreted within the bedrock: the top of the epikarst, or weathered, zone, and the top of competent (unweathered) bedrock. The top of the epikarst layer is interpreted to occur at the 2400 ohm-m interval. The bedrock surface is interpreted to occur at that contour interval where the resistivity values rise consistently above 5000 ohm-m.

In the absence of karst conditions, one would expect a horizontal, low resistivity surface layer of generally constant thickness, corresponding to soil, underlain by a higher resistivity bedrock layer. However, in this karst area the ERT transects show anomalous resistivity patterns indicative of the irregular nature of the subsurface geology (follow on Figure 1). The ERT transects from the lower pasture area (62+10 to 64+80) show a northeast-southwest trending electrical anomaly, which appears as a localized drop in the interpreted bedrock surface that becomes broader to the west of the centerline ("1" on Figure 1). This may indicate the presence of a clay filled depression in the limestone.

The ERT transects from the lower hillside area (94+50 to 100+60) show two northwest-southeast trending electrical anomalies in the epikarstic zone, interpreted as cutters (see Table 1) one of which one seems to correspond with an existing surface feature (labeled "2" on Figure 1). In addition, two independent features can be seen on the transect east of the centerline, but they are interpreted to be part of a broader linear channel that narrows to the northwest ("3" on Figure 1). These features may indicate a preferred joint orientation that has individual clay filled solution features in the







LEGEND

As a general note all transects, except Lower Pasture, are oriented so that the bottom of the page is the exisitng Rt. 101. Lower Pasture is oriented so that exisiting Rt. 101 is to the top of the center line.

1. A northeast-southwest trending electrical anomaly that appears as a localized drop in the interpreted bedrock surface that becomes broader to the west of the centerline.

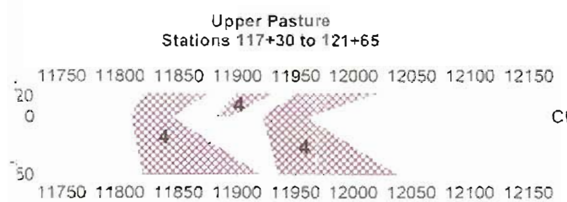
2 These are bowl shaped depressions or troughs in the bedrock surface: a cutter

3 Two independent features are located 95 feet east of the centerline. These anomalies are characterized as separate features in the interpreted epikarst surface that are part of a broader linear channel that narrows to the northwest.

4 Clayey material, possibly underlying a sandy soil with no bedrock detected to a depth of at least 50 feet.

5. Narrow, deep (50' +) shaft or clay-filled fracture which appears to correlate with an open karstic shaft to the west of the line. This has a great probability of posing significant risk to the road.

6 A shallow, clay-filled solution feature beneath the sandstone caprock.



0 100 200

1"=100'

Edmonson-Warren County, Kentucky

Route 101 Expansion: Areas of Suspected Karst Activity

Project No. 654600 Date:January 30, 2004

Prepared by: P.E. LaMoreaux and Associates

FIGURE 1

limestone (cutters). The top of competent rock in this area varies from a low of 80 feet below ground surface (approximately 530 feet elevation) to a high at the ground surface (approximately 650 feet elevation). The low bedrock areas correspond to the features located in the epikarst zone. The trend of possible voids and solution features suggests that they may follow similar fracture systems that control the development of area caves.

The ERT transects from the upper hillside area (101+60 to 116+00) only show karstic features between 101+60 and 107+10 due to the change in bedrock from a limestone to sandstone, which can be interpreted from the resistivity data. In the area between 101+60 and 107+10 three distinct electrical anomalies are present in the epikarstic zone. The first anomaly appears to be a broad depression on the centerline ("4" on Figure 1), the second is a solutionally enlarged fracture that trends NE-SW across the centerline ("2" on Figure 1). The third appears to be a narrow, deep (50' +) shaft or clay-filled fracture which corresponds with the existing cave to the west of the centerline ("5" on Figure 1). Depth to bedrock varies from a low of 80 feet below ground surface (approximately 575 feet elevation) to a high on the surface (approximately 760 feet elevation). The low bedrock areas correspond to the features located in the epikarst zone. Between 107+10 to 116+00 the bedrock lithology has changed from Girkin Limestone to the Big Clifty sandstone member, therefore an epikarst zone is no longer present although there is still a solution feature found in the bedrock. It is interpreted to be a shallow, clay-filled solution feature beneath the sandstone caprock ("6" on Figure 1).

The ERT transects from the upper pasture area on the sandstone caprock (117+50 to 121+00) have a different character than those on the limestone. Moreover, because the sandstone caprock is underlain by limestone, it is affected by both karstic undermining and gravitational erosion related to the edge of the escarpment. There appear to be two broad karst anomalies that span all three transects ("4" on Figure 1), as well as one anomaly that originates on the center line and trends to the west. The southernmost anomaly corresponds with a known sinkhole that has been filled by the owner, and appears to be greater than 50 feet in depth based on the resistivity. Bedrock was only detected on the southern end of the western transect, where it underlies the surface at shallow depth. For the majority (118+20 to 121+00) of this transect, and all of the others, there are no resistivities indicative of bedrock detected. The surface layer has moderate resistivity and appears to correspond to a sandy soil. Because of the complex nature of the geologic setting here, and the lack of any ground truth borings, the interpretation of the data is more tentative.

The lower pasture gravity data shows a series of broad low gravity zones which are most likely due to a deeper feature related to a regional lineament containing extensive fractures, weathered zones, and cavity systems. There are three distinct low gravity anomalies in the lower pasture grid. The main feature is a northwest-southeast trending gravity low to the west of the centerline; followed by a low gravity feature at the southwestern edge of the site which has a value of –276.55 mGals and may extend further to the south; and a third, smaller, low gravity anomaly, which corresponds to the filled sinkhole. The data from both grids shows the final gravity anomaly distribution corresponding to the underground density distribution. The data clearly illustrates that there are some low gravity anomalies more than 300□Gal lower than in other areas. These low gravity anomalies could be regarded as low density anomalies, and in the lower pasture grid where it could be interpreted as following the trend of a large depression in the field as well as the sinkhole out of the study area but generally on the same trend.

The upper grid has a similar gravity pattern, although distinctly different quantitative values associated with the variation of density. The modeled data depicts a series of alternating high and low gravity zones in a generally north-south orientation, thought to be a regional lineament similar to those in the lower pasture. The figure clearly shows that there are three low gravity anomalies up to 250μGal lower than the normal background, which correspond to blue and green zones, as well as two anomalies 200 μGal higher than the normal background (red zones).

Although both geophysical methods used at the site can provide valuable information regarding the subsurface, it is the combination of both techniques, which provides the most useful interpretations. Each method provided valuable information by which a model of the subsurface can be drawn, although they do not always agree. In a reconnaissance field study, more data can be obtained using ERT allowing for a more conclusive independent interpretation. In many applications of microgravity the location of a cave was already known, and its effect on the gravity measurements could simply be extrapolated to map the unknown continuation of the passage. However, in an area where it is not known whether a cave is present or not, the interpretation of a gravity anomaly is not as definite as the interpretation of the resistivity profile. If only one method can be used, due to economic and time limitations, PELA recommends electrical resistivity tomography, unless the path of a known and documented cave is being traced.

1.0 INTRODUCTION and SCOPE-OF-WORK

On December 15th, 2002 the Kentucky Transportation Center at the University of Kentucky (KTC-UK), under contract to the Kentucky Transportation Cabinet, and P.E. LaMoreaux and Associates, Inc. (PELA) entered into an agreement to conduct geophysical testing and analysis on a proposed new highway alignment in south central Kentucky. The objectives of the geophysical studies were to:

- Use an integrated geophysical approach to identify the absence or presence of karst conditions underlying the proposed new highway alignment.

- Use a combination of two geophysical techniques to provide a 3-D understanding of the complex geology often associated with karst terranes, and a top-of-rock estimate.

- Evaluate the need for future ground modification.

In order to accomplish the project objectives, P.E. LaMoreaux & Associates, Inc. (PELA) initiated this investigation with a general overview and then followed that with a detailed site investigation using the two surface geophysical techniques: electrical resistivity tomography (ERT), and microgravity. The general overview included a review of existing site-specific reports, published regional geologic and hydrologic literature for the area, and field observations of local geology and surface karst features.

An integrated survey using microgravity and electrical resistivity tomography (ERT) was conducted to locate existing subsurface karst features and to help guide ground modification along the road through known sinkholes, and over solution widened fractures and possible caverns. In most studies, surface geophysical methods are used in combination. PELA acquired nine ERT profiles and completed two 300 square foot microgravity grids to cover the areas of highest interest, including areas with visible sinkholes at the time of the survey.

The original plans had called for a more extensive coverage of microgravity data. However, because the contract called for a microgravity grid and map data, rather than a series of microgravity profiles, the extensive effort necessary to collect and process grid data was more costly than the contract budget would permit. Therefore, upon consultation between PELA and KTC-UK, it was agreed to confine the microgravity grids to two areas, one in the lower pasture on the sinkhole plain, and one on top of the Chester Escarpment, on the sandstone caprock (see Site Geology, below). Both grids are centered around an existing surface depression which is undoubtedly a sinkhole.

P.E. LaMoreaux and Assoc., Inc. (PELA) carried out a two-phase geophysical investigation, which defined geologic conditions and identified karst features in the subsurface. Phase I identified karstic anomalies and potentially sinkhole-prone areas by measuring 3 parallel traverses of two-dimensional electrical resistivity tomography and combining the data to provide a three-dimensional interpretation, which is more sensitive and efficient than three-dimensional resistivity technology at present (Maule et.al 2000). The original plan was to cover the entire area of study with three lines of ERT data, but the presence of a metallic guard rail close to the planned location of one of the profiles, made it impossible to collect one of the three lines in that area. Phase II was the detailed microgravity investigation of the two sinkhole areas mentioned above, one on the limestone, and one on the sandstone caprock.

1.1 SITE DESCRIPTION

Relocation of an approximately two mile section of KY Route 101 is planned near the Edmonson-Warren County boundary in southern Kentucky, a known karst area north of Bowling Green, KY (Figure 2). Within the total project length, there are two areas of interest totaling approximately 3,000 feet. The first is 100 feet in length (Station 63+00 to 64+00). The second area is from Station 95+00 to Station 121+50 (2,650 feet in length).

1.2 REGIONAL GEOLOGY, HYDROGEOLOGY AND KARST CONDITIONS

A review of existing literature was made to establish expected conditions on-site. The source of geologic and hydrologic information was primarily Kentucky Geologic Survey bulletins and reports. Karst data were provided by a variety of sources that included cave maps, spring surveys, and general karst reports. These reports provided information on the stratigraphy, hydrologic setting, sinkhole distribution, depth of known cave systems in the area, distribution of springs, etc. This type of information provided the geologic foundation upon which to understand site-specific conditions.

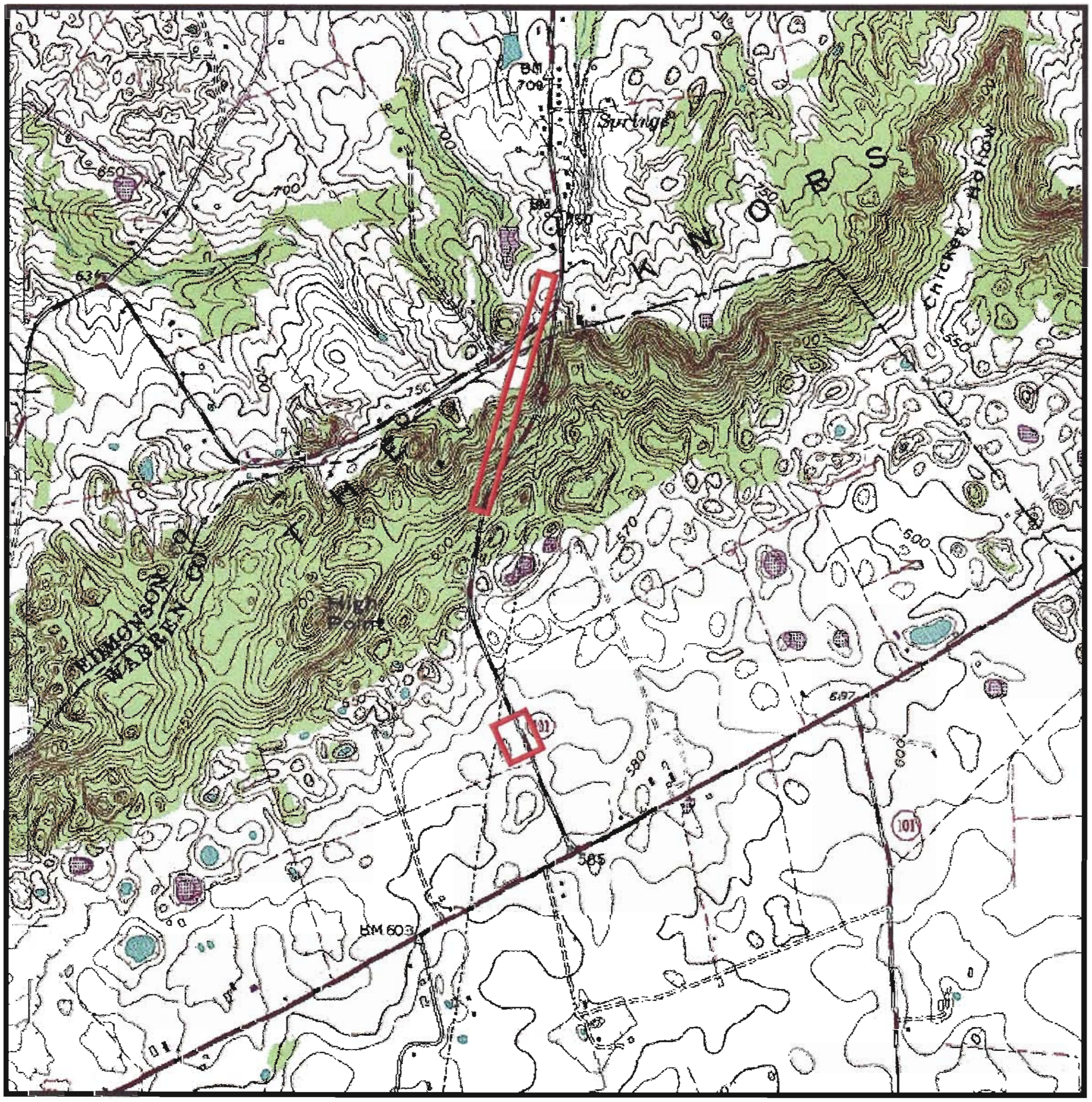


Figure 2. Site topographic map with locations of study areas in red. Modified from the Smiths Grove quadrangle, Kentucky USGS, 1966.

1.2.1 Geology

This site is located in the Western Pennyroyal physiographic region, a crescent shaped area extending from the Ohio River north of Elizabethtown southward, then westward through Bowling Green and Hopkinsville, then northward again back to the Ohio River (Currens, 2002). Many of the state's longest caves, and the terrane most densely pitted with sinkholes, are in this region. The geology of the study area consists of horizontally bedded sedimentary rocks of the Meramecian and Chesterian series of Upper Mississippian age.

Many of the cave and karst features associated with the Mammoth Cave system in Edmonson County are developed in the Ste. Genevieve Formation and the lower part of the overlying Girkin Formation.

Travelling northwards along KY 101 through the study area, one essentially proceeds upward through the stratigraphic column. At the southern limit of KY 101, the bedrock is predominantly Mississippian age Ste. Genevieve Limestone. Continuing northwards towards the county line there are outcrops of the lower part of the Girkin Formation, followed by the overlying Golconda Formation (Figure 3) (USGS, 1966). These Formations comprise the parent material of the Hammack-Baxter, and Baxter-Nicolson soil associations that make up the study area soils.

The Ste. Genevieve Limestone underlies the portion of the Pennyroyal Plateau nearest to the Chester Escarpment. The Ste. Genevieve Limestone is 35-40 m thick and overlies the St. Louis Limestone. The Ste. Genevieve Limestone is a very light-gray partially oolitic limestone and dolomite with numerous chert beds and nodules. The Mississippian Girkin Formation is a shallow-water, carbonate-dominated unit in west-central Kentucky, lithologically similar to the Ste. Genevieve Limestone below. Carbonates in the Girkin are in most places fragmental to oolitic calcarenites; dolomitic zones are thin, silty and associated with siliciclastic horizons. Siliciclastic intervals are thin and cyclic, represented mostly by shales and shaley carbonates. Coarser siliciclastics are rare and local.

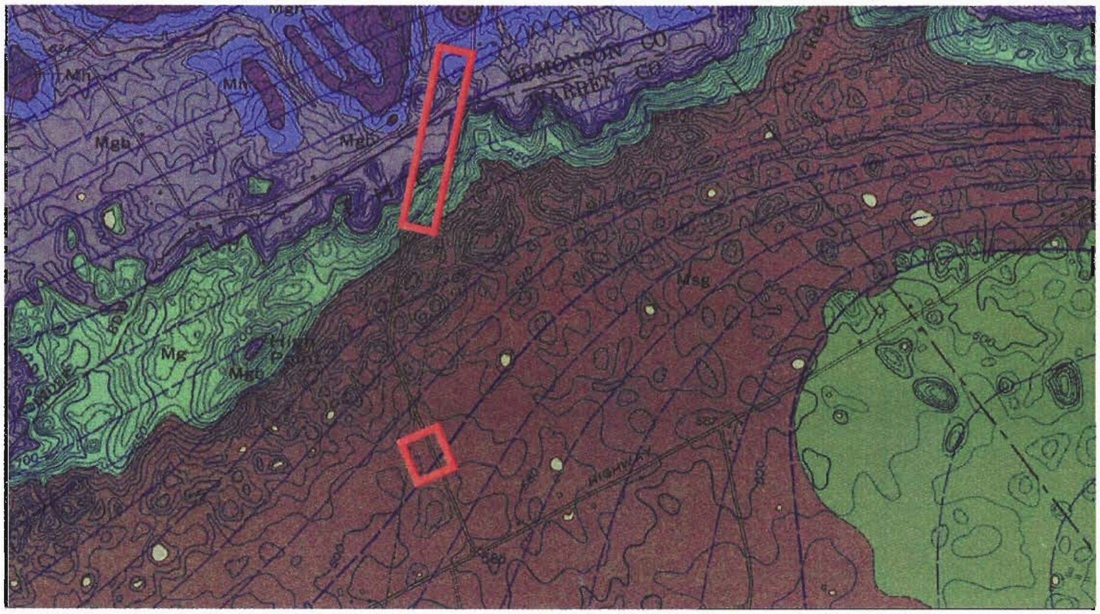


Figure 3. Portion of the Smiths Grove geologic map, current site boundaries outlined in red. Brown area is the Mississippian Ste. Genevieve (Msg), the green area is the Mississippian Girkin Formation (Mg), while the purple area is the Mississippian Big Clifty sandstone member of the Golconda Formation (Mgb). Modified from the USGS, 1966.

In most places siliciclastics generally grade upward into carbonates. The Golconda Formation overlies the Girkin Formation. It has two members—the Big Clifty Sandstone, which is 50 to 120 feet thick and is composed of fine grained sandstone interbedded with siltstone and shale, and the Haney Limestone, which is 10 to 50 feet thick and is composed of medium grained, chert-bearing limestone. The Big Clifty Sandstone acts as a protective caprock that retards the erosion of the Chester Uplands.

The study area spans three physiographic provinces (Figure 4). To the north is the Chester Upland, underlain primarily by Mississippian clastic rocks. To the south is the Pennyroyal plateau, underlain by lower Mississippian limestones and shales. The steep slope forming the edge of the Chester Uplands and overlooking the Pennyroyal Plateau is called the Chester Escarpment. The Chester Escarpment is developed on the edge of the Big Clifty Sandstone caprock, and is strongly influenced by regional and local structure (Deike, 1989). The Escarpment is easily noted on site as the area where sandstone becomes the bedrock and is visible in road outcrops occurring at approximately 110+50. The southern portion of the route below 90+00 is considered to

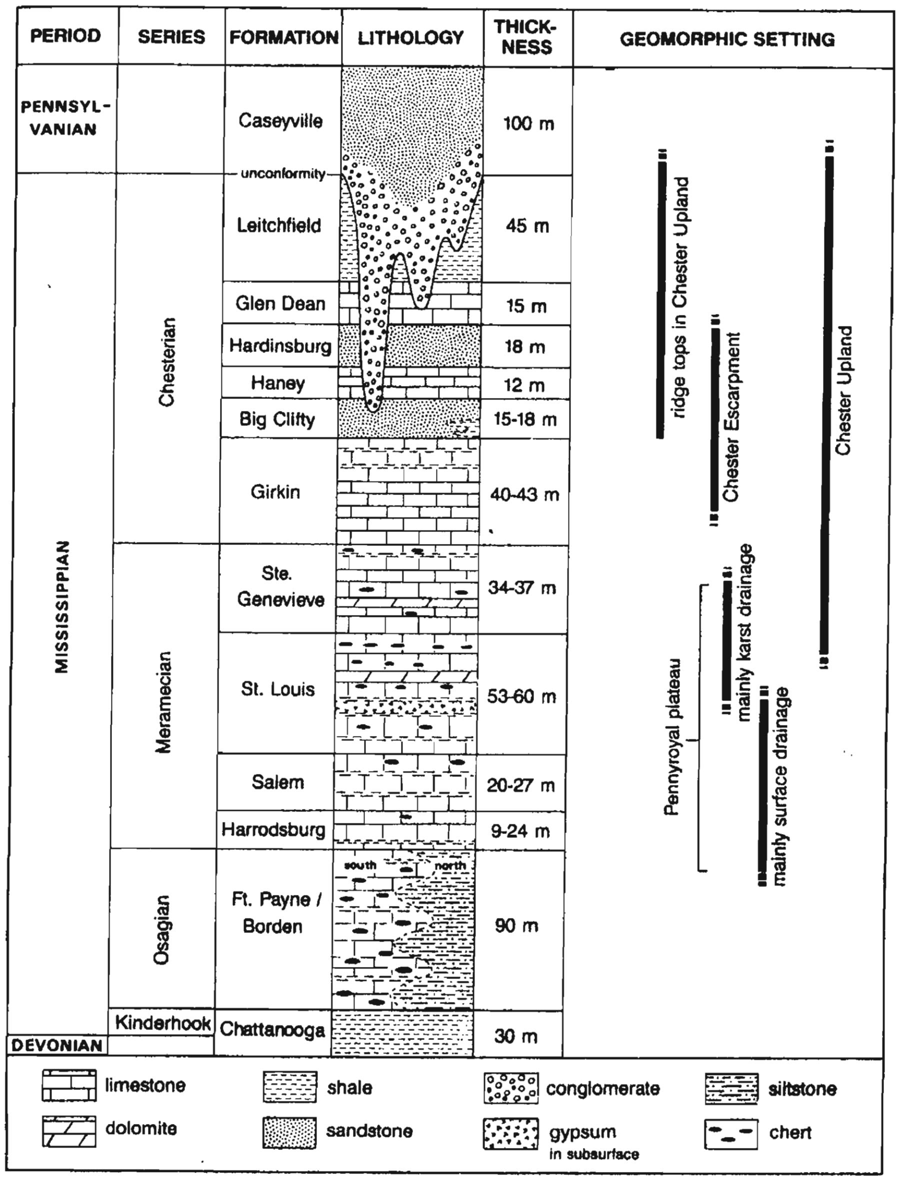


Figure 4. Stratigraphic section for the Mississippian and lower Pennsylvanian rocks of south-central Kentucky and the land surface they form. Current study area is highlighted in yellow. (After Hess et al., 1989)

be the Pennyroyal Plateau. In this area devoid of surface streams, the karst aquifer receives internal runoff through thousands of sinkholes. Most of this water enters the upper St. Louis or lower Ste. Genevieve limestones. Everything above 111+00 is generally the Chester Upland.

1.2.2 Site Hydrogeology

The most characteristic feature of karst terrane is the concentration of water flow in underground solution conduits, which generally form a subterranean, dendritic drainage pattern. In this classic karst terrane, subsurface drainage flows from numerous sinkhole inputs to a few major springs. The beginnings of these karst basins occur to the south where surface drainage (streams) flows onto the Sinkhole Plain. Where this surface drainage first encounters the soluble limestone bedrock, the flow sinks underground. From these input points, small conduits merge into larger cavernous passages that feed the major trunks leading to each of the springs. Each spring has a separate underground drainage basin. Most of the springs are located along the Green River. To the north of the river the area is underlain by clastic rocks, so karstic drainage is not present.

1.2.3 Basic Chemistry of Limestone Dissolution and Formation of the Epikarstic Zone

Dissolution of bedrock (usually limestone or dolomite) in karst areas results in a terrane[1] characterized by *bedrock pinnacles*, *closed topographic depressions*, *solution cavities*, *caves*, and *sinkholes.* In karst terranes, infiltrating precipitation dissolves the carbonate bedrock, causing the top of rock to erode downward leaving behind a soil mantle of insoluble clay and silica residue from the rock. Karst terrane in the Appalachian Valley and Ridge Province and the Interior Plateaus, of which Central Kentucky

[1] The entire landscape formed in soluble rock areas is known as a karst terrane. The term *terrane* is used rather than *terrain* to include subsurface features as well as surface features.

is a part, is characterized by a cover of clayey sediment overlying limestone or dolomite[2].

As rainwater falls and percolates through the soil it absorbs carbon dioxide (CO_2) from the atmosphere and even more from the soil, which has high CO_2 levels generated by decaying organic matter. Thus, the recharge water becomes a weak solution of carbonic acid, which dissolves limestone ($CaCO_3$). When this acidified water seeps down through the soil and reaches the limestone, it continues moving downward under the force of gravity through any interconnected pores, fractures, or bedding planes in the rock. As the weak carbonic acid flows downward, it dissolves and widens the pores or cracks ("joints") through which it flows. Most Paleozoic limestones, like those in Kentucky, have very little pore space, so almost all water flow is through fractures and joints.

Most near-surface rocks are marked by a dense, criss-crossing network of joints. These ubiquitous cracks are widened by solution, but the majority do not penetrate to any significant depth, breaching no more than a few layers of rock--only a few tens of feet. When joints have been widened by solution, they can transmit water readily. However, because of the limited vertical extent of most joints, the water cannot continue to move downward. Solutionally widened fractures or joints are called *karren*. Solution widened channels can range in size from minor seams to large cavernous openings at depth. Along the irregular rock surface, undissolved pinnacles of rock alternate with deep, usually clay-filled, solution-widened fractures commonly termed *cutters*. Within the residual soil mantle there may be as yet undissolved pieces of the bedrock called *floaters*.

Joints and fractures vary in character. Master joints are those more prominent, but less common, cracks which penetrate continuously through many layers of rock.

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[2]Limestone and dolomite are similar carbonate rocks—compounds of calcium, magnesium, and carbonate (CO_3)—which often occur in interbedded sequences. To simplify, only the term limestone will be used, but the discussions of karst formation refer to both limestone and dolomite similarly.

Such master joints provide the pathways for water to move downward to greater depths. The vertical path created where two master joints intersect is a particularly favorable avenue for the downward movement of water. This linear zone dissolves more rapidly than the surrounding areas because it carries more water. As it grows larger, it can transmit water in ever greater quantities, pirating drainage from the surrounding rock mass. This self-accelerating process results in a few greatly enlarged tubes or pipes penetrating down through the limestone with little rock dissolved in between, except in the upper portion of the limestone.

Because the water is most acidic when it first comes in contact with the limestone, the solution process is most rapid at the limestone surface and decreases as the water seeps downward into the limestone and the acidity is neutralized. Thus, the upper zone of the limestone is intensely weathered and dissolved along joints and bedding planes (the horizontal surfaces between rock layers), forming a three-dimensional network of interconnected planar features. This intensely weathered, highly permeable zone is normally confined to the upper few tens of feet of the limestone and is called the *epikarstic zone* (Williams, 1986) (Figure 5). Because the flow of water in the epikarst zone concentrates radially toward the drainage shafts, the areas surrounding the shafts are most intensely dissolved and preferentially lowered, forming a depression in the limestone: a solution sinkhole. Solution sinkholes are only visible if the limestone is exposed at the ground surface, with little or no soil cover.

1.2.4 The Formation of Subsidence Sinkholes

Sinkholes form where drainage down a sufficiently wide solution opening (a *shaft* or *throat*) washes the soil mantle down into dissolved cavities in the underlying rock (either a single cave or a system of smaller solution channels) - a process commonly referred to as *soil piping.* In areas where the residual soil mantle is clay-rich and cohesive, a soil void may develop above the bedrock shaft or drain and it will collapse upward over time, initially with no surficial topographic expression. This incipient sinkhole is present only as an air-, water-, or mud-filled void in the soil which may erode upward over time until the ground surface collapses (a cover collapse sinkhole, Figure 6A). However, this erosion process may also occur gradually, by slow, continuous erosion or plastic flow, accompanied by imperceptible ground subsidence (a cover subsidence sinkhole, Figure 6B).

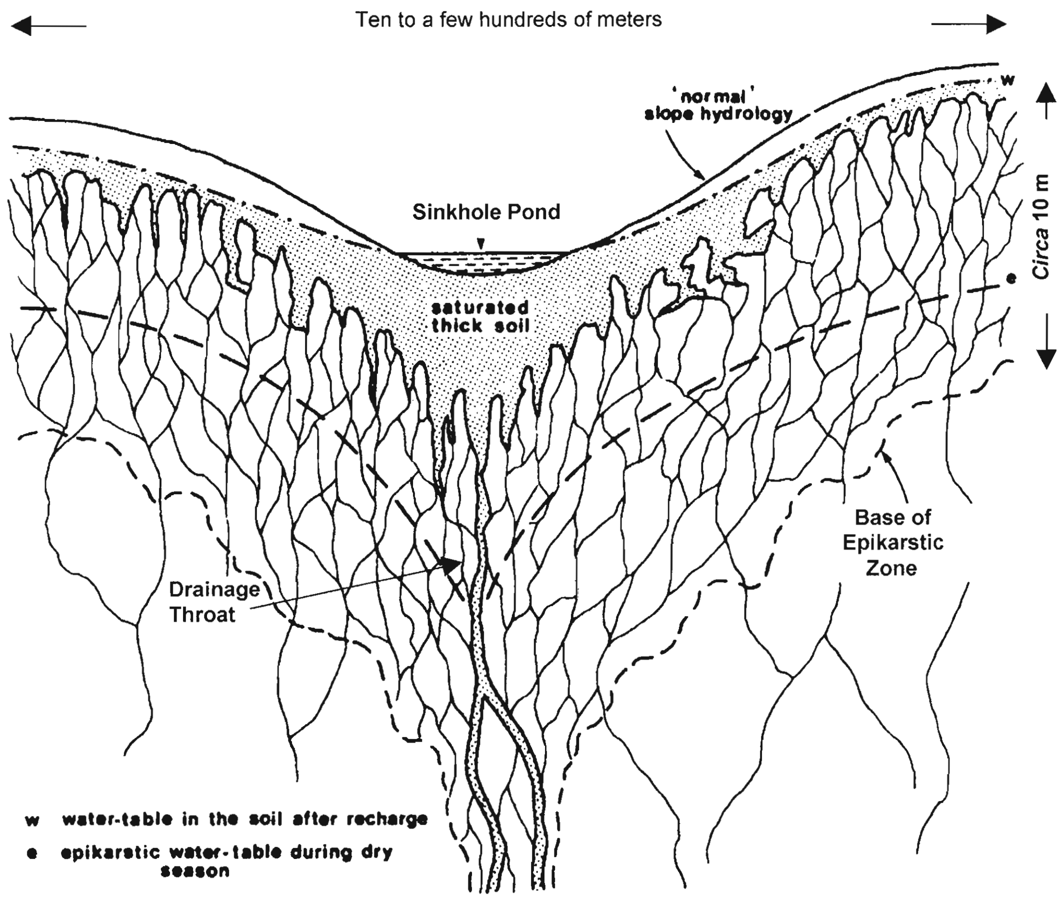


Figure 5. Diagram showing development of epikarstic zone in limestone covered by a thick, residual clay soil. (Modified from Williams, 1986)

The final triggering mechanism of the ground surface "collapse" may be natural or anthropogenic--an increased static and/or dynamic load to the weakened system. When an unusual natural event (heavy rainfall or drought) or cultural activity (such as concentrated surface water runoff, excessive pumping of groundwater, or drilling or construction activity) impacts a site with existing well-developed karst conditions, erosion of soil may be accelerated, resulting in a subsidence and/or a collapse feature at the surface.

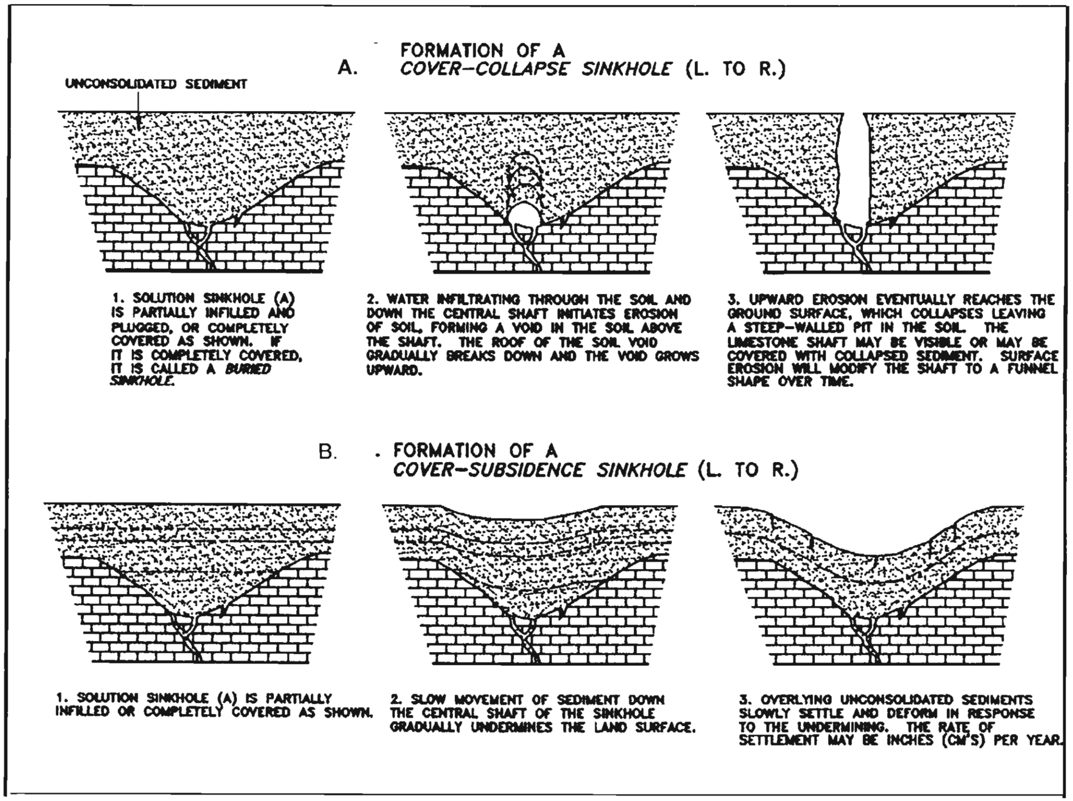


Figure 6. Development of Subsidence Sinkholes by sudden collapse (A) or by gradual subsidence (B).

In some instances, continued erosion of the surface sediment may result in a broad depression in which the limestone shaft is exposed in the bottom. The shaft may be open, leading into a cave, or it may be sealed with debris. If it is sealed, this is generally a metastable condition and at some time the seal will be breached and the process of erosion and subsidence will continue.

It is also possible for sinkholes to develop when the rock roof of a cave in the limestone suddenly collapses. Such an event is rare, but it can occur. Where cavernous openings are present beneath an area planned for human infrastructure, it is critical to delineate these areas so that the development can be planned to avoid any potential collapse.

Because of their propensity for ground subsidence and occasional catastrophic sinkhole collapse, karst areas are of marked geotechnical concern. In addition, due to the tremendous lateral variations in subsurface conditions, correlation of information between even closely spaced borings is highly speculative in karst terranes.

There are surface karst features located within the right of way of the proposed new highway alignment or very close to it. Several of these are mature sinkholes where the limestone is exposed in the center; the throat is filled with mud and there are no indications of instability of the sinkhole. One feature, to the west of the right-of-way near 106+30, is an open shaft apparently leading to a cave. The extent of that cave is not known and was not within the scope of this contract.

2.0 INTRODUCTION To The THEORY of the GEOPHYSICAL INVESTIGATION

The science of geophysics applies the principles of physics to the study of the Earth. Geophysical investigation techniques used in engineering involve the measurement of the physical properties of the shallow subsurface and the interpretation of the underlying geologic structure based on the values of, and variations in, those properties. The purpose and benefits of geophysics are illustrated nowhere better than in karst terranes.

A geophysical investigation, although subject to ambiguities or uncertainties of interpretation, provides a relatively rapid and cost-effective means of deriving areally distributed information on the subsurface geology. Geophysical techniques are capable of detecting and delineating local features of potential interest that could not be discovered by any realistic drilling program.

The geophysical techniques commonly applied to detection of karst features are:

- Electromagnetics (EM) and Electrical Resistivity - detect variations in subsurface electrical properties related to anomalously thick or wet soils (electrical conductivity highs), voids in the electrically conductive clay soil overburden (electrical conductivity lows), clay-filled seams or cavities within bedrock (electrical conductivity highs), or air-filled caves in rock (extreme lows in electrical conductivity).
- Natural Potential (NP) - detects minute, naturally occurring electrical currents commonly associated with concentrated infiltration, or other movement, of subsurface water (often called streaming potentials).
- Microgravity - detects minute variations in the Earth's gravity, which in karst terranes are often due to subsurface voids or solution cavities where "missing" subsurface mass results in measurably lower gravity.
- Ground Penetrating Radar (GPR) - provides rapid results and is effective in many settings, except in thick clay. Radar waves are radiated into the ground as an antenna is towed across the ground surface while simultaneously recording the reflections from subsurface features. The resulting two-dimensional cross-sections can be interpreted to predict where sinkholes may develop, to map the top of bedrock, or to locate manmade features such as underground storage tanks or graves, among other tasks. GPR has been used extensively for geotechnical investigations of karst in Florida, in areas where the surficial sediments are sandy. Clayey sediments have a high electrical conductivity and attenuate the radar signal after only one or two meters of penetration.
- Seismic Methods - can provide profiles of the top-of-rock which may display conical depressions of the type associated with subsidence sinkholes, or deep troughs or cutters which may represent sinkhole-prone lineaments. Some seismic methods may also be able to detect low velocity zones or areas of soft sediment

In all geophysical studies the interpretation is only as good as the data, and therefore, it is necessary to acquire applicable and sufficient data. Applicable data were obtained by using two different measurement techniques, which respond to various subsurface characteristics (physical and electrical). Sufficient data was achieved by obtaining closely spaced measurements along each survey line, with survey lines spaced to optimize the lateral reliability. The combination of techniques used on this site allowed a modicum of redundancy in the measurements obtained. If different measurement techniques result in a similar interpretation, the level of confidence in the data and its interpretation is enhanced.

2.1 THE ELECTRICAL RESISTIVITY TOMOGRAPHY (ERT) METHOD

The electrical resistivity method measures the bulk resistance of earth materials to the passage of electricity, which is a relatively simple process. This measurement correlates most strongly with the electrical properties of the pore water, the amount of pore water, and the presence of clay materials in the matrix of the rock. The resistivity method records both lateral and vertical changes in subsurface resistivity. Natural variations in subsurface resistivity may be caused by changes in soil or rock types, changes in the thickness of soil and rock layers, structural features like fractures or cavities, and many other factors. Compact soils or rock units will lack water content and have a resistive nature. Regions where the soil or rock is weathered and filled with water will tend to decrease the measured resistivity.

The resistivity method requires that an electric current be introduced into the ground through a pair of electrodes. The resulting voltage produced at the surface of the ground is measured across another pair of electrodes. When a current is applied to a body of homogeneous geologic material, a potential field is created. This potential field exists only in the subsurface, and not in the air, since air is an infinite resistor. The potential field has a source at one electrode and a sink at the other. The measured resistance is the ratio of the measured voltage to the current flowing through the ground. The *apparent* resistivity is computed as the measured resistance multiplied by a geometric factor that is determined by the array and spacing of the electrodes. The units of resistivity are ohm-meters or ohm-feet (1 ohm-meter = 3.28 ohm-feet).

Resistivity electrodes are usually arranged in a straight line using one of several arrays. The successful application of this technique for delineating karst features depends on an understanding of karst terranes and the selection of the appropriate electrode array (Zhou, Beck & Adams, 2002).

The commonly used arrays are the Wenner array, Schlumberger array, and Dipole-dipole array (Reynolds, 1997) (Figure 7). These different electrode configurations have particular advantages, disadvantages and sensitivities, to either vertical or horizontal change in the subsurface materials. Because of the three-dimensional nature of karst features such as sinkholes, cavities, and depressions in the bedrock surface, it is important to have an array that is sensitive to *both* vertical and horizontal changes. The dipole-dipole array produces the most detailed data distribution and is therefore PELA's preferred method.

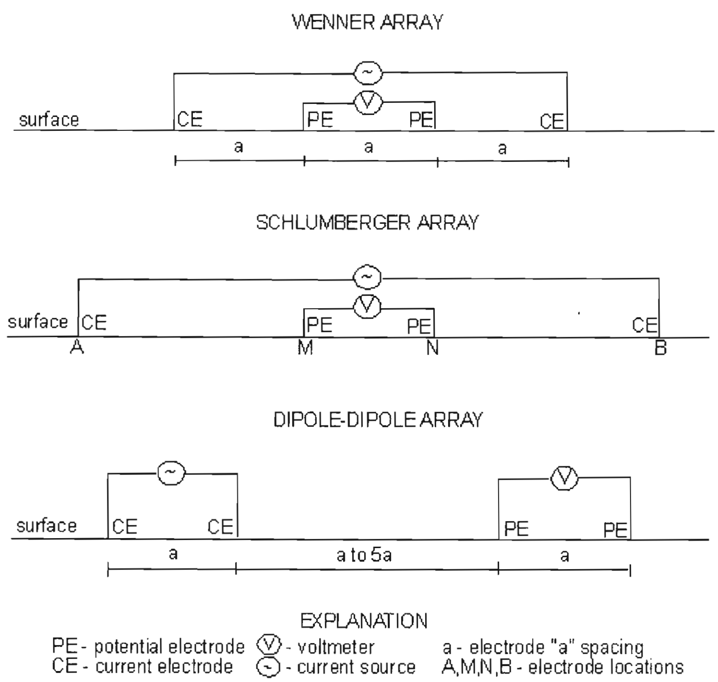


Figure 7. Graphic illustration of a variety of typically used electrode arrays. Modified from Reynolds, 1997.

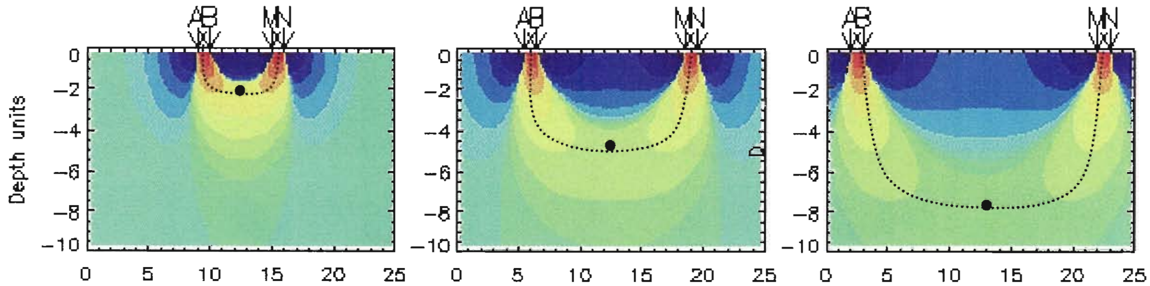


Figure 8. Signal contribution plot for the dipole-dipole configuration. Dark blue areas effect the signal very little. Areas ranging from red to green contribute most of the measured signal. The black dot represents the pseudo-depth at which the measurement is plotted. Increased depth penetration is obtained by increasing the inter-dipole spacing.

A common factor in these configurations is a set of current input electrodes usually labeled A and B and a set of voltage measurement (potential) electrodes usually labeled M and N. The dipole-dipole method places the A and B electrodes to one side with a fixed spacing between them. The M and N electrode pair, with an equal spacing to that of A and B, are placed co-linearly a distance equal to an integer multiple of the spacing away from A and B. Figure 8 above shows the basic dipole-dipole electrode configuration. By increasing the separation between the dipoles, more of the injected current flows to greater depths, as indicated in Figure 8. Because the total resistance in the electrical path increases, as electrode spacing is increased, more current must be generated to force current to flow through these longer paths. Thus, the maximum distance by which the dipoles can be separated is in part dictated by the size of the generator used to produce the current. Because current flows primarily near the Earth's surface for small dipole spacings, values of apparent resistivity for these measurements will be dominated by the resistivity characteristics of the near surface. If the dipoles are spread farther apart and the apparent resistivity remeasured, these measurements will incorporate information from deeper strata. Although the measurement includes the characteristics of all the strata through which the electric field flows, mathematical analysis of the data can separate the characteristics of the various depths.

2.2 THE MICROGRAVITY METHOD

Microgravity measurements are sensitive to the subsurface mass beneath the measuring point, and they are most sensitive to the shallowest materials. Therefore, microgravity can discriminate between locations underlain by dense rock at shallow depths, and those where there is a void or cavity in the rock. However, a greater thickness of less dense sediments, such as the soil overlying the bedrock, will also be detected as a gravity low. Microgravity measures one data point at each station which sums all the subsurface variations that may be occurring. Therefore, it is difficult to obtain a unique interpretation of the data.

Microgravity data in engineering and environmental applications must be collected in a grid or along a profile with stations spaced less than 5 meters apart. The measured microgravity at any given location will generally be influenced by the density of the material beneath the location, the elevation of the ground, the topography around the measuring point, and the latitude. In order to relate gravity data to subsurface density, the other factors must be accounted for. Measured microgravity data is processed to remove the other predictable components of the gravitational field of the earth. The processed data are known as Bouguer residual gravity anomalies, measured in μGal.

The Earth's gravity is an acceleration generally between 9.78 and 9.83 meters per second per second. These units are too large for more detailed measurements, so the gal (1 cm/s^2), milligal (1 mm/s^2) and microgal ($\mu m/s^2$) are used. Regional gravity surveys use the milligal (mgal) as the unit of measurement while local, microgravity surveys are conducted in microgals (μgal). The Earth's gravity is about 983,000,000 microgals; microgravity surveys generally map anomalies of between 5 and 200 microgals. By very precise measurement of gravity and by careful correction for variations in the larger component due to the whole earth, a gravity survey can detect natural or man-made voids, variations in the depth to bedrock, and geologic structures of engineering interest.

Gravity measurements are based upon Newton's Law of gravitation which state that two masses M_1 and M_2, are attracted to each other by a force (F_g), which varies on the square of the distance (r) between them:

$$F_g = G\left(\frac{M_1 M_2}{r^2}\right)$$

The constant (G) is the universal gravitational constant:

$$G = 6.670 \times 10^{-8} \frac{dynes * cm^2}{g^2} = 6.670 \times 10^{-11} \frac{N * m^2}{kg^2}$$

From this, the acceleration of gravity (a) is:

$$a = G\left(\frac{M}{r^2}\right)$$

For engineering and environmental applications, the scale of the problem is generally small (targets are often between 1-10 m in size). Therefore, conventional gravity measurements, such as those made in petroleum exploration, are inadequate. Station spacings are typically in the range of 1-10 m. Even a new name, microgravity, was invented to describe the work because it requires a resolution of a microgal (µGal = 0.001 mGals or one part per billion of the Earth's gravity). Microgravity requires preserving all of the precision possible in the measurements and analysis so that small objects can be detected.

The distribution of Bouguer corrected gravity can identify locations on the earth's surface that have relatively higher or lower gravity caused by lateral variations in subsurface density. Microgravity has been used extensively to locate bedrock caves from the ground surface. The lower density of the air, water, or mud within a cave compared to the surrounding solid carbonate rock results in a low-gravity anomaly over the cave.

In limestone areas, depth to bedrock is often very irregular with limestone pinnacles that protrude upward and cutters that extend downward. Cutters are V-shaped, soil-filled crevices formed by solution of the limestone by water as it percolates down to the karst aquifer. Soil voids may form as the regolith (overburden) is eroded downward into solutionally-enlarged voids in the bedrock. For these reasons, a low-gravity anomaly may indicate a bedrock cave, a void in the overburden, or a location where the depth to bedrock is significantly greater, among other possible explanations. Gravity data alone cannot differentiate between a shallow and deep cause of the anomaly, although careful modeling can help to refine the interpretation.

As explained above, gravity variations on the Earth's surface are due to many factors. Gravimeters do not give direct measurements of gravity. Rather, a meter reading is taken which is then multiplied by an instrumental calibration factor to produce a value of observed gravity (g_{obs}). In order to isolate the effects of small differences in subsurface density, it is necessary to correct gravity measurements to a common datum, such as sea level (the geoid). Most applied corrections include: elevation effects (free air correction), extra mass effects (Bouguer infinite slab; full terrain correction), latitude correction (using the international gravity formula), and tide and drift correction (by reoccupying a base station or with a computer program to predict the tides).

The **free-air correction** makes allowances for the reduction in the magnitude of gravity with height above the geoid, irrespective of the mass of the rock below. The free-air correction is the difference between gravity measured at sea level and at the station elevation with no rock in between. A value of 0.3086 mGal/m is accepted for most engineering applications and is positive (added to observed gravity value) above sea level and negative below.

$$g_{FA} = 0.3086h \text{ mGal}$$

where h is the height in meters above sea level (geoid)

The **Bouguer correction** accounts for the attraction of the rock material between sea level and the elevation of the station. Whereas the free-air correction compensates for the reduction in that part of gravity due only to the increased distance from the center of the Earth, the Bouguer correction is used to account for the rock mass between the measuring point and sea level (geoid). It is based on the assumption that the surface of the Earth is everywhere horizontal (parallel to the geoid) and at this elevation above sea level. This correction is subtracted since the material between sea level and the station level is being removed.

$$g_B = -0.04193\square h \text{ mGal}$$

where ρ is the density of the slab in gm/cm^3 and h is the elevation difference in meters between the observation point and sea level (geoid)

The **latitude correction** is necessary because Earth is not a perfect sphere but is flattened at the poles due to centrifugal forces (an ellipsoid). Thus, the pull of gravity is greater at the poles because they are closer to the center of Earth than elsewhere on Earth's surface. This correction is done using the international gravity formula (IGF), which describes the variation in gravity at sea level.

The **terrain correction** accounts for the gravitational attraction of all nearby material higher than the gravity station and also removes the effect of missing material in any low areas near the station, so as to reconstruct the infinite slab hypothesized in making the Bouguer correction. The elevations for all stations need to be established to an accuracy of at least ±0.3 cm. A firmly fixed stake or mark should be used to allow the gravity meter operator to reoccupy the exact station where the elevation was measured. High station densities are often required. It is not unusual for station intervals of 1-3 m to be required to map anomalous masses whose maximum dimension is 10 m. Because the number of stations in a grid goes up as the square of the number of stations on one side, perpendicular profiles are often used (rather than a grid) if the trend of the longest dimension of the target body can be established before the survey begins.

After elevation and position surveying, actual measurement of gravity is often accomplished by one person in areas where solo work is allowed. Because of short-term variations in gravimeter readings caused by less than perfect elasticity of the moving parts of the suspension, by uncompensated environmental effects, and by the human operator, it is necessary to improve the precision of the station readings by repetition.

3.0 ELECTRICAL RESISTIVITY MEASUREMENT and INTERPRETATION

The ERT field survey was conducted between January 21 and February 2, 2003. Table 1 lists the coordinates of all the transects. By the collection of multiple resistivity data points at various locations in a linear array, that are representative of various depths, a two-dimensional (2D) geo-electric interpretation of the site can be made. The objective was to identify changes in subsurface electrical resistivities that can be used to infer changes in soil and rock conditions beneath the site. In particular, the objectives included assessing top-of-rock elevation, and identifying any lateral changes in soil and rock conditions that could indicate the presence of karst features, such as highly weathered zones and possible solution-widened fractures or large cavities within the bedrock.

3.1 EQUIPMENT

Resistivity measurements were collected with an AGI Sting R1 Earth Resistivity Meter in conjunction with the Swift automatic multi-electrode switching system (Figure 9). The resistivity equipment is composed of three primary components: 1) the Sting R1 resistivity meter with data storage capability; 2) the Swift automatic multi-electrode switching system, which is an accessory for the Sting; and 3) the Sting/Swift cables which contain fixed cylindrical stainless steel switches that attach to stainless steel electrodes that are inserted (hammered) into the ground. A total of 56 electrodes, broken into eight segments of 7 electrodes, were used during data acquisition.

Figure 9. Field setup of the Sting/Swift multi-electrode system. Numbers refer to discussion in text.

3.2 FIELD PROCEDURE

The basic array utilized the entire 56 electrodes; spaced 10 feet apart for a total transect length of 550 feet on the surface. The computerized program within the Sting/Swift system selects various combinations of two current electrodes and two measurement electrodes, arranged in the dipole-dipole array, to collect a suite of resistivity measurements continuously along the transect, and also at various dipole separations to obtain data representative of various depths. For lines longer than 550 feet (56 electrodes), a *roll-along* technique was used to generate a continuous geoelectrical profile. When the instrument has completed that portion of the measurements using the first fourteen electrodes, those electrodes are removed and reconnected to the far end of the line, increasing the length to 690 feet; this can be repeated for the second fourteen electrodes, *ad infinitum*. The depth of penetration remains as it was for the original 56 electrode array, but a transect of any length is theoretically possible. Various transect lengths were used depending on local site conditions (Table 1).

The small electrode spacing (10 feet) provides the level of detail necessary to locate narrow fractures, and a depth of investigation of approximately 80 feet, which was selected to be sensitive to potential local caves. Although the system can be programmed to use any electrode array, the data were collected in the dipole-dipole array which provides increased resolution over other electrode configurations. After setting up each 56 electrode array and performing the contact resistance test to insure that all electrodes made adequate contact with the ground, apparent resistivity data were automatically recorded using the Sting/Swift system. Data were downloaded from the Sting resistivity meter at the end of each day.

3.3 ELECTRICAL RESISTIVITY DATA PROCESSING

The resistivity field data comprise resistance measurements between various electrodes and related array geometry information. An *apparent* resistivity value, which depends only on the resistance measurements and the array geometry, is calculated by the instrument. Apparent resistivity values combine the characteristics of all the various strata through which the electric current flows, therefore a true depth cannot be determined for the measurement. A depth is *assigned* as was shown in Figure 8. For this reason, the two-dimensional display of apparent resistivity data is called a pseudosection. However, all the apparent resistivity data are then combined and inverted (processed) to yield a cross-section showing the variation of true resistivity with actual depth.

The data were inverted with RES2DINV software, a commercially available program (Loke, 2002). Prior to data inversion, the raw data were first edited by removing any negative apparent resistivity values and data points with standard deviations greater than 2%. These data points were considered noisy and unreliable. Other programming steps include setting up appropriate horizontal and vertical filters, selecting the inversion method, adding topographic data and then interpreting the data. RES2DINV is an iterative imaging program that estimates a two-dimensional distribution of *true* resistivity values that produced the apparent resistivity values which were measured. For each iteration, a finite difference algorithm is used to produce a cross-section of calculated apparent resistivity that would be produced by the modeled true resistivity distribution. The program then compares this *modeled* apparent resistivity distribution with the *measured* apparent resistivity section and modifies the model until an acceptable match between the measured and calculated pseudosections is achieved. The difference between the measured and calculated pseudosections is quantified as the Root-Mean-Square (RMS) error. A low RMS value indicates a close match between the modeled geological profile and the data measured on site.

Final data processing involves the generation of color-coded contour sections of the data using a two-dimensional plotting program. ERT resistivity models are presented in cross-section or 3-D model blocks, with centerline distance shown along the horizontal axis, depths, or elevation along the vertical axis. The geoelectrical model represents the electrical stratigraphy of the subsurface. The modeled resistivity cross-sections for the site are shown in Appendix A.

3.4 ELECTRICAL RESISTIVITY DATA INTERPRETATION

The resistivity models have an average maximum depth of approximately 80 feet. A single measurement of apparent resistivity at a given electrode spacing represents a weighted average of the resistivity and geometric effects over a relatively large volume of material, with the shallow portions contributing most heavily. If the surficial layer has a very high resistivity, a limited amount of current will flow into the ground, resulting in low signal-to-noise ratios for deeper measurements.

Each electrical profile can be thought of as a 2-dimensional slice of the three-dimensional subsurface variation in electrical characteristics of the site. Each profile depicts both the lateral and vertical extents of various subsurface features. By using multiple, parallel transects, the data can be directly processed in two-dimensions and then combined to produce three-dimensional block models of the subsurface.

The spatial resolution of the resistivity models is dependent upon the array type and electrode spacing used. The thinnest horizontal model blocks in the resistivity inversion have widths equal to half the electrode spacing. Depending on the resistivity contrast, it is possible to *detect* features smaller than this spacing, but not possible to *resolve* them into separate features.

The vertical resolution is primarily dependent on the depth of the feature of interest, the resistivity contrast and the array type. A conservative rule-of-thumb is that vertical resolution equals 30% of the depth of the feature. That is, at ten feet deep the technique can resolve a separate layer at least three feet thick. It is possible to *detect* layers that are thinner than 30% of the depth, but unlikely to *resolve* them into separate layers. As a general guideline, an isolated, spherical object with a diameter “d” will be detectable to a depth of “2d”, assuming a sufficient resistivity contrast exists with the surrounding geology (personal communication with Loke, 2004).

The thickness and width of the model blocks increase with depth. The model block thickness ranges from 5 feet thick in the shallowest layer to approximately 15 feet thick in the deepest layer. The widths of the blocks range from 5 feet in the shallowest layer to over 80 feet in the deepest layer. Therefore, because of the larger sampling volumes at depth there is reduced resolution.

It is well known that surface topography can have a significant effect on the resistivity measurements (Tsourles *et al.* 1999). For accurate interpretation, the effect of the topography must be accounted for. One common method is the "topographic corrections" method where the apparent resistivity values for a homogeneous earth model with the observed topography is calculated. The ratio of the true resistivity to the calculated apparent resistivity values for the homogenous model is then multiplied with the measured apparent resistivity values (Fox *et al.* 1980). In theory, this method is exact if the subsurface below the survey line is also homogeneous. Since the actual subsurface geology is always inhomogeneous, the calculated correction factors are at best approximate.

Resistivity profiles typically showed an irregular surface at the contact between low and high resistivity materials (the clay overburden and the limestone bedrock, respectively). Subsurface anomalies of high and low resistivity were also observed within each layer. The 2D-ERT data depicts features within the overburden and the bedrock, mapping variations in thickness and changes in the electrical properties. Overburden anomalies range in character from very-low resistivity *bullseyes* (less than 50 ohm-m) to lenses of high resistivity (greater than 800 ohm-m), with a nominal background level ranging from 100 to 500 ohm-m. The low-resistivity zones are generally interpreted to be clayey intervals, though the presence of an electrically conductive pore fluid cannot be ruled out. High-resistivity anomalies within the overburden are interpreted as either residual blocks of weathered rock or coarser-grained (less clayey) intervals. The top of bedrock was indicated on the profiles at the transition between the low resistivity clay soils and the high resistivity limestone. The resistivity of the clay soils was typically less than 500 ohm-m. The resistivity of the bedrock was typically greater than 2000 ohm-m. The interpreted epikarstic zone is between 500 and 2000 ohm-m. The resistivity profiles indicate that the top of bedrock is very irregular at the site.

3.5 ERT RESULTS

Resistivity profiles were created through the inversion process discussed previously. The profiles illustrate trends in resistivity that may be interpreted to represent a distribution of subsurface materials or lithologies. The identified geoelectric boundaries separating layers of different resistivities may or may not coincide exactly and continuously with boundaries separating layers of different lithologic composition. These differences may result from the gradational presentation of the electrical stratigraphy. Therefore, the electrical stratigraphy can vary from the geologic stratigraphy, and caution should be exercised when reviewing and interpreting the resistivity profiles.

Two general assumptions were made when interpreting this ERT data:

1. The contact between the limestone and overburden is laterally continuous, and
2. The contact is sharp.

The interpreted graphs are shown in Appendix A. Comments on the transect by transect interpretations are given in Table 1. In the absence of karst conditions, one would expect a horizontal, low resistivity surface layer of generally constant thickness, corresponding to soil, underlain by a higher resistivity bedrock layer. However, in this karst area the ERT transects show anomalous resistivity patterns indicative of the irregular nature of the subsurface geology.

The resistivity models have an average maximum depth of approximately 80 feet. The 2D-ERT data outlines irregular features within the overburden and the bedrock, mapping variations in thickness and changes in the electrical properties. Overburden anomalies range in character from low resistivity bull's-eyes (less than 50 ohm-m) to lenses of high resistivity (greater than 200 ohm-m), with a nominal background level ranging from 80 to 120 ohm-m. The low-resistivity zones are interpreted to be primarily clayey intervals, though the presence of an electrically conductive pore fluid cannot be ruled out. High-resistivity anomalies within the overburden are interpreted as either floating blocks of intensely weathered rock or coarser-grained (less clayey) intervals. Two levels are interpreted within the bedrock: the top of the epikarst, or weathered, zone, and the top of competent (unweathered) bedrock. The top of the epikarst layer is interpreted to occur at the 2400 ohm-m interval. The bedrock surface is interpreted to occur at that contour interval where the resistivity values rise consistently above 5000 ohm-m.

Table 1. Line by line description of karst features along the planned expansion of KY route 101. Features noted are those of specific concern to stability of the road. They are described based only on the data from one line.

Line No.	Start Point	End Point	Feature Start Point	Feature End Point	Length of Feature	Comments and Interpretation
1	62+10	64+80	63+00	63+25	25 feet	A bowl shaped depression or trough in the bedrock surface: a cutter.
1	62+10	64+80	63+80	64+15	35 feet	A bowl shaped depression or trough in the bedrock surface: a cutter.
2	62+10	64+80	63+35	63+65	30 feet	Wide, deeply-weathered zone to a depth of at least 80 feet. No material with resistivity in the rock range.
3	62+10	64+80	62+75	63+80	105 feet	A broad depression in the bedrock surface.
3	62+10	64+80	63+95	64+25	30 feet	A bowl shaped depression or trough in the bedrock surface: a cutter.
4	95+00	104+65	95+25	95+75	50 feet	A bowl shaped depression or trough in the bedrock surface: a cutter.
4	95+00	104+65	97+60	98+15	55 feet	A solution-widened fracture in the bedrock, infilled with clayey overburden.
4	95+00	104+65	98+90	99+50	60 feet	A bowl shaped depression or trough in the bedrock surface: a cutter.
4	95+00	104+65	100+50	101+50	100 feet	A broad, bowl shaped depression or trough in the bedrock surface.
4	95+00	104+65	101+70	102+20	50 feet	A bowl shaped depression or trough in the bedrock surface: a cutter
5	94+40	101+40	95+30	96+70	140 feet	Low resistivity material (range of clay) at depth, beneath continuous high resistivity (rock range) material. A depression in the limestone surface centered between 96+30 and 96+70. Interpreted as a clay-filled cave.
5	101+50	115+40	101+50	102+70	120 feet	Wide, clay-filled zone to a depth of at least 80 feet. No material with resistivity in the rock range.
5	101+50	115+40	106+80	107+15	35 feet	Narrow, deep (50' +) shaft or clay-filled fracture which appears to correlate with an open karstic shaft to the west of the line. This has a great probability of posing significant risk to the road.
5	101+50	115+40	112+50	113+70	120 feet	Thin, near-surface layer of high resistivity (rock range) underlain by an elliptical zone of low resistivity material. This area correlates with a surface depression and may be indicative of future subsidence. It may be a shallow, clay-filled solution feature beneath sandstone caprock.
6	94+30	101+20	96+20	96+50	30 feet	Minor depression or trough in limestone surface: minor cutter.
6	94+30	101+20	99+10	99+50	40 feet	Isolated zone of high resistivity material at surface. Interpreted as rock floater near or at surface underlain by clay, or possibly a rock pinnacle.

6	102+50	116+40	105+00	105+65	65 feet	A bowl shaped depression or trough in the bedrock surface: a cutter.
6	102+50	116+40	106+25	106+55	30 feet	Narrow, deep (50' +) shaft or clay-filled fracture which appears to correlate with an open karstic shaft to the west of the line. This has a great probability of posing significant risk to the road.
6	102+50	116+40	107+05	107+70	65 feet	Low resistivity material (range of clay) at depth, beneath continuous high resistivity (rock range) material. Interpreted as possibly a clay-filled solution feature.
7	117+30	121+30				Appears that throughout the length of this transect competent bedrock is more than 50 feet below ground surface.
7	117+30	121+30	118+10	118+45	35 feet	Extremely low resistivity potentially indicative of a saturated zone or very clayey interval, may also represent a conductive body in the fill.
7	117+30	121+30	118+80	118+95	15 feet	Extremely low resistivity potentially indicative of a saturated zone or very clayey interval, may also represent a conductive body in the fill.
7	117+30	121+30	119+25	119+60	35 feet	Extremely low resistivity area underlying an area that may have bedrock near the surface.
8	117+65	121+65				Appears that beyond 118+15 of this transect competent bedrock is more than 50 feet below ground surface.
8	117+65	121+65	118+20	119+20	100 feet	Very low resistivity anomaly that is broad nearer to the surface and then as it deepens becomes more like a shaft. This area is within a depression in the surface that was reported to be a filled in sinkhole by the owner Texie Colley.
8	117+65	121+65	119+35	120+35	100 feet	Very similar to above except there is no surface expression.
9	117+40	121+40				Appears that throughout the length of this transect competent bedrock is more than 50 feet below ground surface.
9	117+40	121+40	118+20	118+75	55 feet	Very low resistivity pocket.
9	117+40	121+40	119+00	119+30	30 feet	Extremely low resistivity area underlying an area that may have bedrock near the surface.
9	117+40	121+40	119+50	120+20	70 feet	Extremely low resistivity area underlying an area that may have bedrock near the surface.

A bowl or cup shaped anomaly is one in which dissolution of the limestone surface has produced a depression which was filled with a less resistive clayey soil. These areas are not thought to represent a great risk for sudden catastrophic collapse but may represent areas of persistent gradual subsidence.

The shaft anomalies are best described as a shaft of unconsolidated sediment filling a fracture in the bedrock. These areas are a substantial hazard as they lack any support in the middle of the feature and as such are possibly unstable and subject to collapse.

In the absence of karst conditions, one would expect a horizontal, low resistivity surface layer of generally constant thickness, corresponding to soil, underlain by a higher resistivity bedrock layer. However, in this karst area the ERT transects show anomalous resistivity patterns indicative of the irregular nature of the subsurface geology (follow on Figure 1). The ERT transects from the lower pasture area (62+10 to 64+80) show a northeast-southwest trending electrical anomaly, which appears as a localized drop in the interpreted bedrock surface that becomes broader to the west of the centerline ("1" on Figure 1). This may indicate the presence of a clay filled depression in the limestone.

The ERT transects from the lower hillside area (94+50 to 100+60) show two northwest-southeast trending electrical anomalies in the epikarstic zone, interpreted as cutters (see Table 1) one of which one seems to correspond with an existing surface feature (labeled "2" on Figure 1). In addition, two independent features can be seen on the transect east of the centerline, but they are interpreted to be part of a broader linear channel that narrows to the northwest ("3" on Figure 1). These features may indicate a preferred joint orientation that has individual clay filled solution features in the limestone (cutters). The top of competent rock in this area varies from a low of 80 feet below ground surface (approximately 530 feet elevation) to a high at the ground surface (approximately 650 feet elevation). The low bedrock areas correspond to the features located in the epikarst zone. The trend of possible voids and solution features suggests that they may follow similar fracture systems that control the development of area caves.

The ERT transects from the upper hillside area (101+60 to 116+00) only show karstic features between 101+60 and 107+10 due to the change in bedrock from a limestone to sandstone, which can be interpreted from the resistivity data. In the area between 101+60 and 107+10 three distinct electrical anomalies are present in the epikarstic zone. The first anomaly appears to be a broad depression on the centerline ("4" on Figure 1), the second is a solutionally enlarged fracture that trends NE-SW across the centerline ("2" on Figure 1). The third appears to be a narrow, deep (50' +) shaft or clay-filled fracture which corresponds with the existing cave to the west of the center-line ("5" on Figure 1). Depth to bedrock varies from a low of 80 feet below ground surface (approximately 575 feet elevation) to a high on the surface (approximately 760 feet elevation). The low bedrock areas correspond to the features located in the epikarst zone. Between 107+10 to 116+00 the bedrock lithology has changed from Girkin Limestone to the Big Clifty sandstone member, therefore an epikarst zone is no longer present although there is still a solution feature found in the bedrock. It is interpreted to be a shallow, clay-filled solution feature beneath the sandstone caprock ("6" on Figure 1).

The ERT transects from the upper pasture area on the sandstone caprock (117+50 to 121+00) have a different character than those on the limestone. Moreover, because the sandstone caprock is underlain by limestone, it is affected by both karstic undermining and gravitational erosion related to the edge of the escarpment. There appear to be two broad karst anomalies that span all three transects ("4" on Figure 1), as well as one anomaly that originates on the center line and trends to the west. The southernmost anomaly corresponds with a known sinkhole that has been filled by the owner, and appears to be greater than 50 feet in depth based on the resistivity. Bedrock was only detected on the southern end of the western transect, where it underlies the surface at shallow depth. For the majority (118+20 to 121+00) of this transect, and all of the others, there are no resistivities indicative of bedrock detected. The surface layer has moderate resistivity and appears to correspond to a sandy soil. Because of the complex nature of the geologic setting here, and the lack of any ground truth borings, the interpretation of the data is more tentative.

3.6 LIMITATIONS

In general it may not be possible to model a unique solution for a particular anomaly. The anomalies identified are based on the assumption that the overburden soil and the limestone have distinct electrical resistivity properties. The interpretations are subjective due to the following restrictions:

1. Limitations inherent in electrical methods: The measured apparent resistivity values are volume-averaged. This is inherent to resistivity methods and tends to obscure small-scale irregularities in the geologic interfaces. The data are more generalized at greater depths;
2. Non-uniqueness of the modeling results: It is possible for different geological models to produce similar profiles of calculated apparent resistivity, just as in other geophysical modeling programs.
3. Complex geology in karst terranes: Due to the complex and irregular structure of residual components at the weathered soil/limestone interface, the profile may be interpreted incorrectly. Isolated, near-surface areas of high resistivity could be caused by air-filled cavities, concentrations of residual sandstone, or limestone "floaters" in the overburden. An apparent depression in the limestone surface on the profile may be caused by a clay-filled cutter, a narrow clay-filled fracture, or possibly a water-filled cavity. An apparent pinnacle in the modeled limestone surface could actually be caused by the presence of a small air-filled cavity in the soil.

Because of these limitations, the interpretation of any apparently significant anomaly must be confirmed by *in-situ* boring data before costly actions are taken based on the geophysics alone.

Metal guardrails extend from station 104+75 to station 116+00 near the Edmonson-Warren County line. These cultural factors are significant sources of interference for the resistivity measurements. During a measurement cycle, the applied current can flow through these metallic conductors, resulting in readings that do not accurately characterize natural geologic conditions. In principle, the ERT transects should be as far away from these features as possible. Based on our experience, the data quality would be affected if interference sources parallel to the transect are closer than the depth of the investigation. Consequently, the complete transect length could not be covered by the ERT investigation in some areas near the guard rails, although every possible effort was made.

4.0 MICROGRAVITY MEASUREMENT AND INTERPRETATION

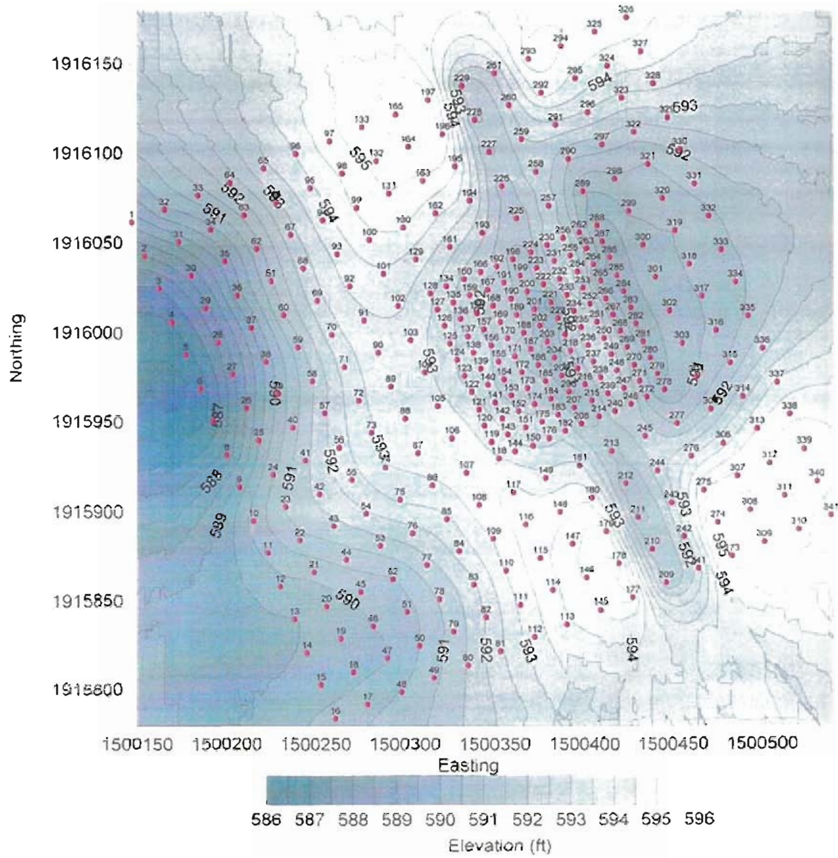
The microgravity field survey was conducted between February 3rd and February 21st, 2003. Figure 10 shows the data points and their spatial distribution. The objective of the microgravity survey work performed along the proposed new highway alignment was to map karst features in the limestone, because solution cavities and channels are potential areas were sinkhole subsidence may occur.

A microgravity survey (also referred to as a gravity survey) provides a measure of change in the subsurface density. Microgravity has been used extensively to investigate subsurface karst features in Kentucky and elsewhere. The microgravity survey is an exploration method that investigates density anomalies such as cavities with 1m resolution. This is done by measuring the distribution of gravity at μGal sensitivity, whereas the sensitivity is mGal in conventional methods.

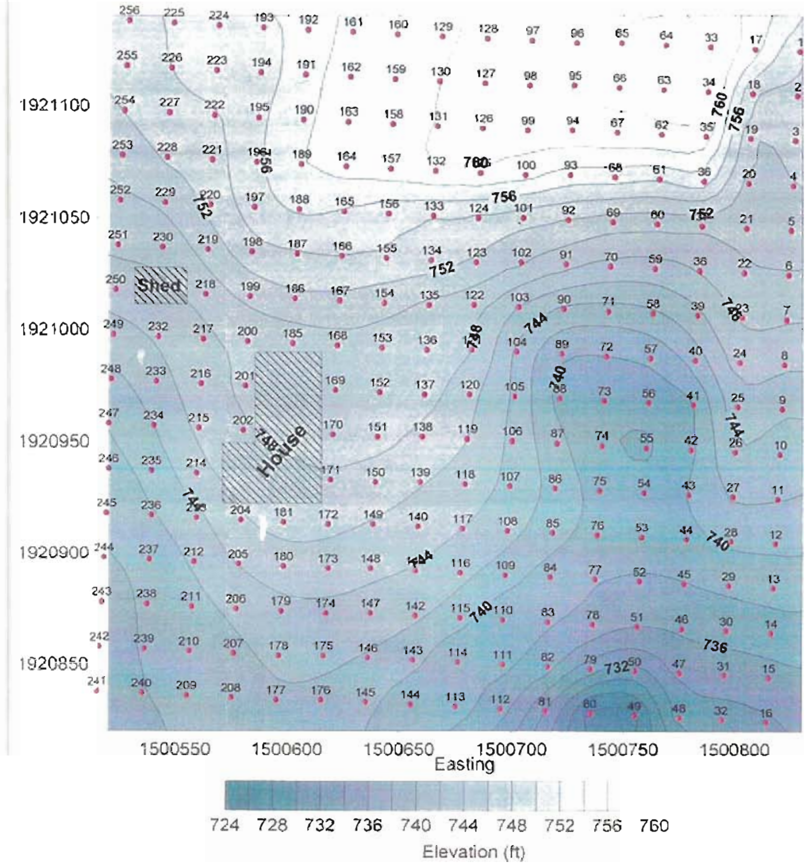
4.1 EQUIPMENT

The survey was acquired using a Scintrex CG-3M Autograv Microgravity Meter. The gravimeter was kept powered and level throughout the fieldwork.

Topography and Microgravity Stations
Lower Pasture Grid



Topography and Microgravity Stations
Upper Grid



PELA

FIGURE 10

Edmonson-Warren County, Kentucky

Route 101 Expansion: Topography and Microgravity Stations

Project No. 654600 Date: March 31, 2003

Prepared by: P.E. LaMoreaux and Associates

4.2 FIELD PROCEDURE

Because the density of data required for a three-dimensional gravity survey is so great, it was not possible to cover the entire area of interest within the budget of the project. After consultation with the client, two grids were completed. One was located in the fields in the lower portion of the site area where an existing sinkhole has been patched by DOT and a large sinkhole is present nearby in the field. A 300 by 300 foot grid was established on 20 foot station spacing, with a secondary 100 by 100 foot grid with 10 foot spacing in the center over the known sinkhole. This resulted in approximately 370 points being collected over the area. The second grid was located at the northern end of the area of interest, closer to the Edmonson-Warren County line on the property of Ms. Texie Colley, over a filled sinkhole which penetrated through the sandstone caprock. A 300 by 330 foot grid was used, with 20 foot station spacing, giving a good compromise between resolution and site coverage. This resulted in approximately 260 points being collected over the area. The meter was setup over the nail marking each station. The meter height was recorded at each station and referenced from the head of the nail to a point on the gravity meter. The station name and meter height were recorded in the field notebook. The data were also electronically stored in the meter and downloaded to a computer after each field day. Data were not acquired at some of the stations due to a snow storm that buried the nail heads. A complex looping procedure with one loop of the survey being bounded by two occupations of the base station was used during this survey because of its large aerial extent, which required the use of multiple base stations. Base readings were taken at the start and end of each day and at roughly hourly intervals throughout the day in order to establish a drift curve for that particular day. Repeat readings were taken at each station in rapid succession to ensure repeatability of the measurements. Individual readings were taken over the period of one minute.

rain model might produce ±10 μgal of error. This estimate does not include terrain density variations. Even if known, such variations are difficult to apply as corrections.

Massive limestone	2.4 - 2.7 g/cm^3
Air Void	0.0 g/cm^3
Debris filled void:	1.8 g/cm^3
Water filled void:	1.0 g/cm^3

Table 2. Modeled densities of relevant materials.

Once the basic latitude, free-air, Bouguer and terrain corrections are made, an important step in the analysis remains: regional-residual separation. In most surveys, and in particular those engineering applications in which very small anomalies are of greatest interest, there are gravity anomaly trends of many sizes. The larger anomalies are generally regional variations, and the smaller magnitude local anomalies of interest will be superimposed on them. A simple method of separating local, residual anomalies from regional variations is to visually smooth the gravity contour lines or profiles and subtract this smoothed representation from the reduced data. The remainder will be a residual anomaly representation.

Both gravity surveys were processed to produce residual Bouguer gravity maps where the effect of drift, elevation and the influence of topography are removed. A density of 2.5 g/cm^3 was used for the limestone density for the calculation of the Bouguer correction. Complete Bouguer gravity anomalies were computed for a variety of densities between 1.8 and 2.67 g/cm^3. Due to the low relief of the survey area, and the relatively uniform geology beneath the survey points, the choice of a density is nearly arbitrary; different densities offset the entire survey, but do not change the peak-to-trough amplitude of residual anomalies, or the anomaly shape. This was checked by comparing the magnitude of variation across the survey using different densities.

A planar surface was fit to the data as a regional trend. It was then removed from the data to provide Bouguer residual values. The planar surface was defined as:

Regional Plane Removed = 816.463-0.000225235(X)-0.0000822614(Y) mGals; where X and Y are the grid Easting and Northing coordinates in feet respectively.

4.4 GRAVITY RESULTS

The interpretation of a gravity survey is limited by the fact that there is not a unique solution and by the assumption of subsurface homogeneity (that the physical properties of every element of subsurface volume have the same value regardless of its location). A distribution of small masses at a shallow depth can produce the same effect as a large mass at greater depth. Additional data on the density contrast or the specific geometry is required to resolve the non-unique solutions. This external control may be in the form of geologic plausibility, drill-hole information, or measured densities. In this investigation, we have defined microgravity anomalies as those areas having lower than average microgravity values within the site.

Figure 11 shows both the final corrected gravity distribution and the corresponding anomaly distribution for the lower pasture area. The figure clearly shows that there are three low gravity anomalies more than 200μGal lower than the average background, which correspond to the blue and green zones on the figure. The main feature in the lower pasture grid is a northwest-southeast trending gravity low to the west of the centerline (A on Figure 11), that broadens to the north and appears to include two parallel features, which both have localized minima at approximately 41.5772 degrees of latitude. There is another area of low gravity at the southwestern edge of the site (B), which has a value of –276.55 mGals and may extend further to the south; it may be an extension of the larger trend at A. There is a third, smaller, low gravity anomaly (C) near the center of resistivity Transect 1, which corresponds to the filled sinkhole.

Figure 12 shows both the final corrected gravity distribution and the corresponding anomaly distribution for the upper grid area. The upper grid has a similar gravity pattern, although vastly different quantitative values associated with the variation of density. The modeled data depicts a series of alternating high and low gravity zones in a generally north-south orientation, thought to be a regional lineament similar to those in the lower pasture. The figure clearly shows that there are some low gravity anomalies up to 250μGal lower than the normal background, which correspond to blue and green zones, as well as some anomalies 200 μGal higher than the normal background (red zones).

These low gravity anomalies could be regarded as low-density anomalies, or mass deficiencies. It is reasonable to hypothesize that low gravity anomalies and continuous low gravity trends in this terrain may correspond to highly weathered joints and lineaments, large cavity networks or a combination thereof. It is also important to note that the sinkhole adjacent to the Collie residence in the upper grid, which has been filled with construction debris, fill, and miscellaneous items, may not represent a significant density contrast to the surrounding limestone.

5.0 INTEGRATION OF DATA

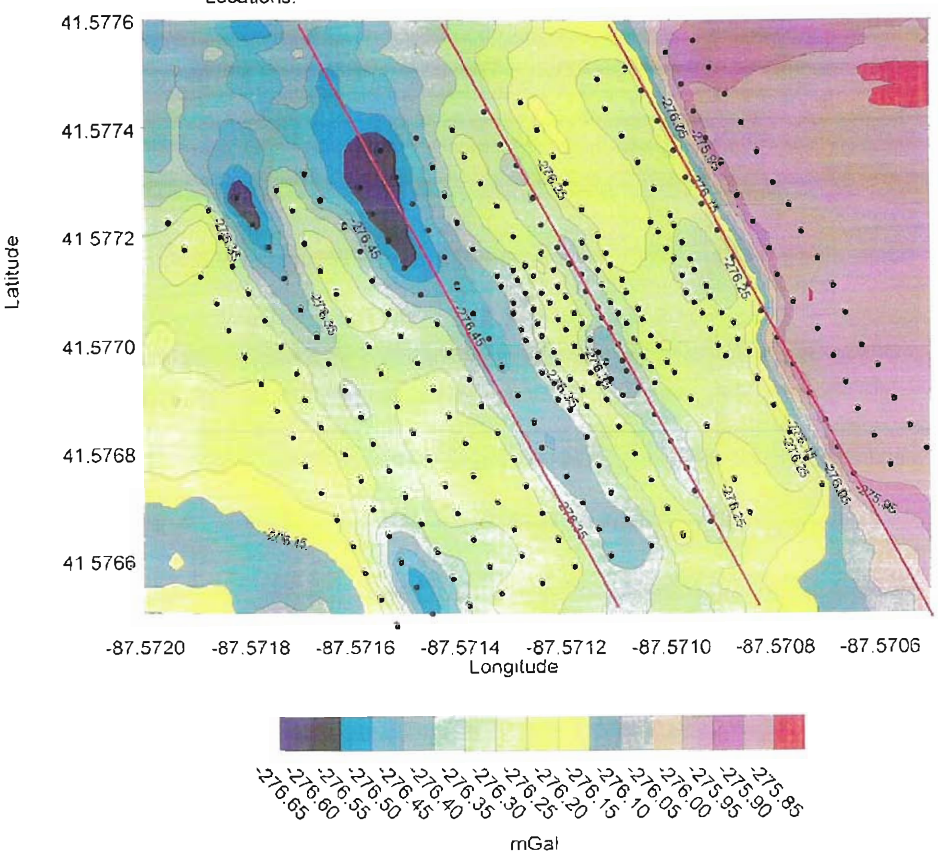
Since no single method of measurement will uniquely define subsurface conditions, the combination of measurements and integrated sources of data offers a significantly improved capability to assess subsurface conditions and reduce the uncertainty of the conceptual model. After the data sets were individually processed and analyzed, the results were integrated into a comprehensive conceptual model of site geologic conditions. Each set of data is first interpreted on its own. Then, the interpretation is refined by combining individual data sets. The first step in this process was to integrate individual lines of resistivity into wire mesh surface plots to depict the pseudo 3-D interrelationships of features on site. The figures in Appendix B show surface plots of the top of competent rock and also the top of the epikarst layer as interpreted from resistivity contours[3]. With this added step, the interpretation becomes clearer as some features on the different lines can be seen to align themselves in an orientation or a shape. In addition, it is now easier to assign a geologic description to the feature as it may be a bedrock feature versus an epikarst feature or may show a fracture alignment as compared to being an isolated depression or shaft. A good example of features that are aligned is between 106+00 and 107+20 on Transects 5 and 6. Where on the independent resistivity profiles these were individual shafts, when combined and plotted on a surface plot, a trend can be seen, and these can be interpreted as a solution widened joint or other similar fracture controlled karst feature.

When measurements by different methods support similar interpretations, the interpretations will have a higher level of confidence. One instance where the integration of the microgravity data and the ERT data provided corroboration was between 63+00 and 63+50 on the centerline. The anomaly is located in an area where a previously repaired sinkhole was located. On the resistivity transect this anomaly had a rounded depression of low resistivity infill within the surrounding high resistivity area. On the

[3] Please note that because this is a surface plot, subsurface features such as clay-filled solution cavities, cannot be shown. Therefore, for a complete interpretation of the resistivity data, the individual transect cross-sections and Table 1 should be consulted.

Bouger Corrected Mrogravity-Lower Grid

Bouger Corrected Gravity assumed Density of 2.5 g/cc
Red lines are ERT Transect Locations, Black dots are Microgravity Station Locations.



Interpreted Bouger Corrected Microgravity Data with background removed. Reds are interpreted high microgravity anomalies, while blues and greens are low gravity anomalies.

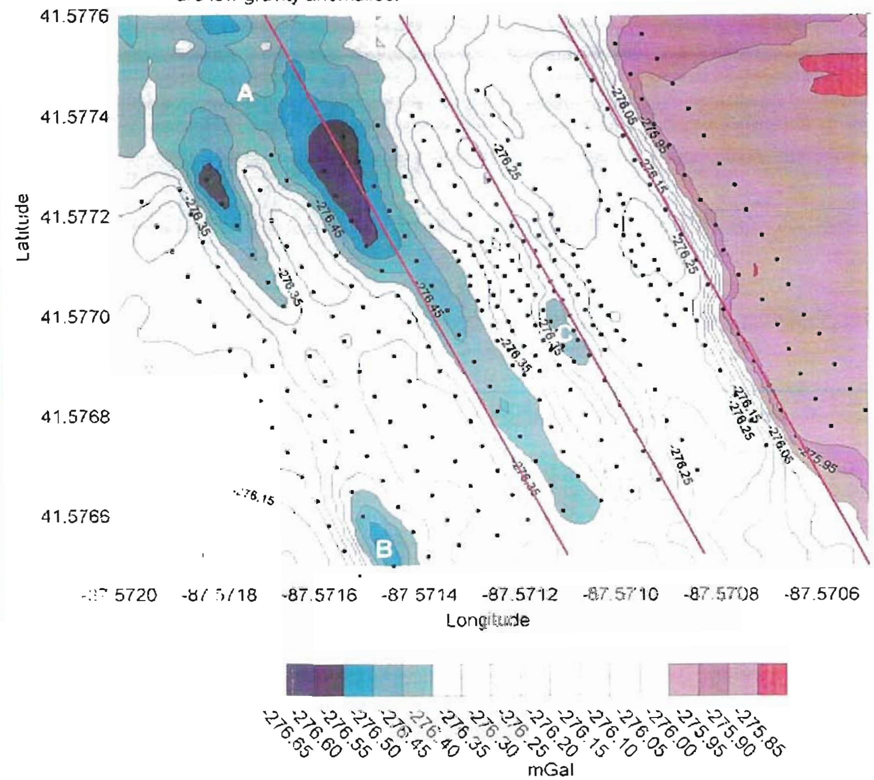


FIGURE 11

Edmonson-Warren County, Kentucky

Route 101 Expansion: Stations 62+10 to 64+80

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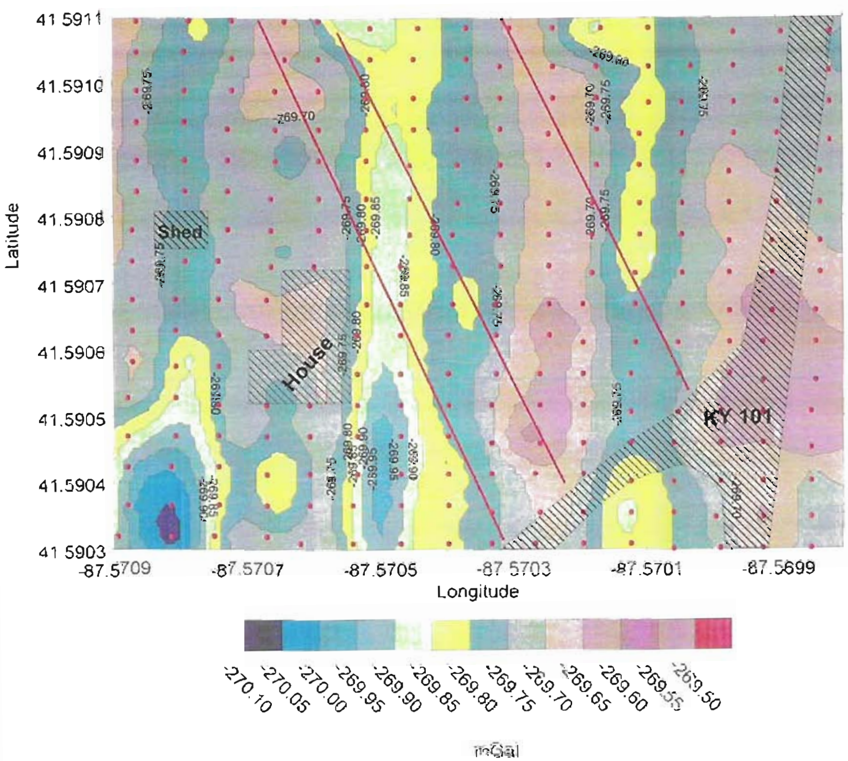
Prepared by: P.E. LaMoreaux and Associates

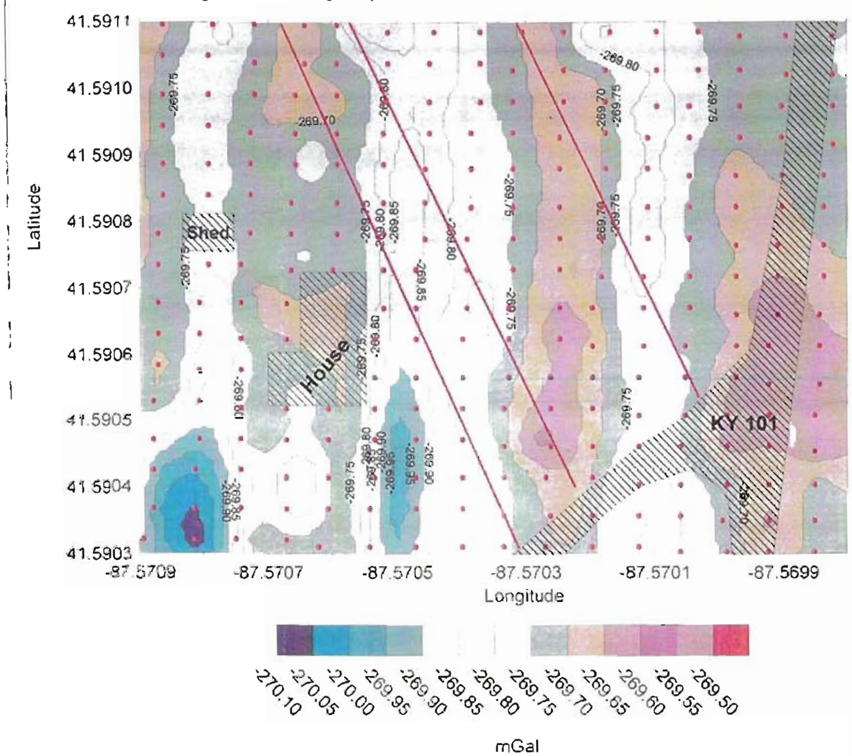
*Distance between microgravity stations is 20 feet to the outside of the inner grid. Inner grid spacing is 10 feet apart.

Bouger Corrected Microgravity-Upper Grid

Bouger Corrected Gravity assumed Density of 2.5 g/cc
Red lines are ERT Transect Locations, Red dots are Microgravity Station Locations.



Interpreted Bouger Corrected Microgravity Data with Background Removed
Reds and oranges are interpreted high microgravity anomalies, while blues and greens are low gravity anomalies



*Distance between microgravity station is 20 feet.

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FIGURE 12

Edmonson-Warren County, Kentucky

Route 101 Expansion: Upper Grid

Project No. 654600 Date: October 30, 2003

Prepared by: P.E. LaMoreaux and Associates

interpreted microgravity plots the area was lower than background values and as such could represent a weathered zone on the top of rock or a depression in the top of rock. Due to the magnitude of the mass deficiency and the low resistivity values, it is not interpreted to be an air filled void space.

However, it must be noted that the different methods respond to different characteristics which may not both be present in one feature. For instance, clay and limestone have a very high resistivity contrast. However, dense clay and limestone have only a moderate gravity contrast. Therefore, clay-filled features may be detected on the resistivity transects and may not be significant on the gravity data. On the other hand, air-filled cavities have an abnormally high resistivity and also an abnormally low gravity. Therefore, such features should be detected by both techniques. It would appear from the literature and from this research, that microgravity data is most useful for mapping large, air-filled caves where they are already known, or suspected, to exist.

6.0 ENGINEERING HAZARDS RELATED TO SINKHOLES AND THEIR POTENTIAL IMPACT ON THE PROPOSED ROAD ALIGNMENT

Karst features are prevalent throughout Warren and Edmonson Counties, Kentucky. Although karst features present challenges for development, they do not preclude development. Various types of sinkholes present various engineering hazards, some more serious and difficult to deal with than others.

Figure 1 is a general interpretation of the major resistivity anomalies in the site area. However, it is generalized and should not be used for specific engineering remediation. For specific, detailed interpretation of site conditions, it is necessary to use the individual resistivity transects (Appendix A). As explained in the section on interpretation, even the specific resistivity transects should not be regarded as an "x-ray" of the ground, but as useful guidance which will help identify the majority of the problem areas on the site.

6.1 Engineering Hazards Caused by Solution Sinkholes and Their Potential Impact on the proposed road alignment

Solution sinkholes are not generally a foundation problem. The solution process is imperceptibly slow, and change is negligible in a human's time frame. Solution sinkholes, however, are drainage conduits into the subsurface, and this function engenders two serious hazards. First, any contamination produced in the vicinity may drain into the sinkhole and then contaminate the ground water. Because of the open conduit flow that is prevalent in karst aquifers, contamination may move great distances very rapidly with little opportunity for natural processes to degrade the contamination. Second, because solution sinkholes are generally drained by cavernous conduits having a limited carrying capacity, heavy precipitation events may exceed this carrying capacity and produce flooding. Further, unexpected changes may occur within the conduits, such as rockfalls, suddenly reducing the carrying capacity and causing more severe flooding. In mantled karst terranes such as this it is rare to see purely solutional sinkholes. Most sinkholes are poly-genetic, where all the sinkhole-forming processes have played a role in their development. Unfortunately, that means that all of the potential hazards may apply to such poly-genetic sinkholes.

6.2 Engineering Hazards Caused by Bedrock Collapse Sinkholes and Their Potential Impact on the proposed road alignment

Bedrock collapse sinkholes (cave collapse) will have only negligible impact on the proposed rerouting. As previously mentioned, White (1988), Waltham (1989), Beck and Sayed (1991), and Sowers (1996) all agree that such collapses are extremely rare, almost non-existent, on a human time scale. None of the geophysical data indicates any air-filled caves close to the ground surface.

6.3 Engineering Hazards Caused by Cover Subsidence Sinkholes and Their Potential Impact on the proposed road alignment

Cover subsidence sinkholes are generally broad and shallow and they develop slowly; they usually cause damage simply by undermining and cracking rigid foundations. Evidence documenting the occurrence of such sinkholes is derived almost exclusively from the damage that is caused. Probably because of the very minor surface expression of these features, there are no statistics available on their lateral extent. Because of the very low magnitude of subsidence at the center—a few inches up to a foot—the lateral extent of **significant** settlement is probably well under one hundred feet. However, after several years of continued development, some remedial action may be necessary. This would be obvious long before the process was hazardous to the integrity of the roadway.

6.4 Engineering Hazards Caused by Cover Collapse Sinkholes and Their Potential Impact on the proposed road alignment

Cover collapse sinkholes form suddenly and produce a steep-sided depression. The lateral dimensions vary from less than ten feet to tens or hundreds of feet in diameter. The depth is often tens of feet. Should one develop beneath the roadway, the roadway would collapse into the resulting depression causing a potentially fatal hazard for motorists. The vast majority of the sinkholes that form are small. The potential width of a cover collapse sinkhole is related to the cohesiveness of the sediment and the stable slope angle, as well as the thickness of the sediment. In clayey sands or dense clays the sides of the sinkhole may be vertical. In loose sands the side slopes approach a 2:1 ratio and the diameter of the sinkhole is limited to approximately four times the thickness of the sand. An example of a potential site for this type of sinkhole is interpreted to occur between 97+50 and 98+25 on resistivity Transect 4.

6.5 Engineering Hazards Caused by Other Karst Features and Their Potential Impact on the proposed road alignment

Deep, clay-filled cutters may be subject to slow settlement due to differential compaction, or due to slow karstic erosion. Examples of this type of feature are interpreted to occur at 107+00 on Transect 5, 106+40 on Transect 6.

7.0 CONCLUSIONS

The standard method of geotechnical site investigation is to drill a pattern of boreholes to delineate the spatial extent of various features, in this case karst features. However, unless the spacing is less than the feature dimensions it is possible to miss it completely. Moreover, the density of borings necessary to insure detection of karst features is prohibitively expensive. A cavity may be filled with air, water, or collapse material resulting in a contrast in physical properties that may be detected using appropriate geophysical methods. Applied geophysics can contribute to the solution of most geotechnical engineering and environmental problems. The interpretation of geophysical contrasts is based on geologic assumptions. Uncertainty is inherent in the geophysical interpretation process. Preparation of geophysical models usually assumes the following:

(a) Earth materials have distinct subsurface boundaries.

(b) A material is homogeneous (having the same properties throughout).

(c) The unit is isotropic (properties are independent of direction).

These assumptions are, in many cases, in discrepancy with the reality of geologic occurrences. Units may grade from one material type to another with no distinct surface between two materials. Non-uniqueness applies to all geophysical methods, and is most conveniently resolved by understanding geologic reality in the interpretation. One powerful technique is microgravity, which locates areas of contrasting subsurface density from surface measurements of the earth's gravity. Another equally powerful technique is electrical resistivity tomography, which can locate voids and other solution features within naturally resistive bedrock, by measuring changes in electrical resistivity from surface measurements. Probably the most important task of any site investigation is characterizing the natural geologic conditions. Understanding the geologic conditions can make the difference between success and failure for site investigations. Mapping natural geologic conditions includes a wide variety of objectives such as:

- determining thickness of unconsolidated materials, top of rock or structural features;
- mapping lateral variations in sand/clay deposits; and
- locating geologic anomalies (e.g., sinkholes, bedrock channels, fractures, and faults

Establishing new roadways or expanding existing ones, often involves traversing previously undeveloped properties with few records or documentation. This investigation illustrates the effectiveness of ERT testing for the detection and mapping of the top of an irregular bedrock, and local geologic anomalies. Both surface geophysical methods provide a high degree of spatial sampling to ensure that buried features and environmental concerns are adequately characterized before construction.

The benefits of such measurements include: non-destructive sampling, in-situ measurements of a wide range of physical properties, sampling larger areas or volumes and providing continuous measurements in some cases. These benefits result in a greater sample density, which can more readily identify uniform conditions as well as locate anomalous conditions. Once anomalies conditions are identified, those areas requiring further tests, borings or repairs can be accurately and quickly located.

Although both geophysical methods used at the site can provide valuable information regarding the subsurface, it is the combination of both techniques, which provides the most useful interpretations. Each method provided valuable information by which a model of the subsurface can be drawn, although they do not always agree. In a reconnaissance field study, more data can be obtained using ERT allowing for a more conclusive independent interpretation. In many applications of microgravity the location of the cave was already known, and its effect on the gravity measurements could simply be extrapolated to map the unknown continuation of the cave. However, in an area where it is not known whether a cave is present or not, the interpretation of a gravity anomaly is not as definite as the interpretation of the resistivity profile. If only one method can be used, due to economic and time limitations, PELA recommends electrical resistivity tomography, unless the path of a known and documented cave is being traced.

Crawford and others, 1999, concluded that, out of the geophysical techniques they had tried, the best results were obtained by using microgravity traverses to locate bedrock caves, voids in the overburden and to investigate sinkhole collapses. PELA disagrees with this statement because in a reconnaissance field study more data can be obtained using ERT and it can provide a more conclusive interpretation. A comparison of modeled gravity values obtained from resistivity results with actual microgravity data does not provide sufficient information to locate voids at a site with a highly variable bedrock surface. In Dr. Crawford's study the location of the cave was already well known, and its effect on the gravity measurements could simply be extrapolated to map the unknown continuation of the cave. However, in an area where it is not known whether a cave is present or not, the interpretation of the gravity anomaly is not as definite as the interpretation of the resistivity profile. This is extremely apparent when the upper grid microgravity data is compared to both the resistivity results and the known history of the site. The gravity data is governed primarily by large-scale features and failed to delineate the dimensions of the known sinkhole on the property. While the ERT clearly delineated a low resistivity anomaly in the area of the known sinkhole, indicating that the debris infilling the sinkhole is highly conductive, which upon communication with the landowner is know to be true. The magnitude of small scale differences between the actual microgravity results and the modeled results in areas of unknown voids are similar is magnitude to the differences that area caused by subsurface voids. In addition to anomaly evaluation, the source and size of the irreducible field errors must be considered. Under the proper conditions of large enough anomalies, good surface conditions, and some knowledge of densities, microgravity can be an effective tool for engineering investigations. If only one method can be used, due to economic and time limitations, PELA recommends electrical resistivity tomography, unless the path of a known and documented cave is being traced.

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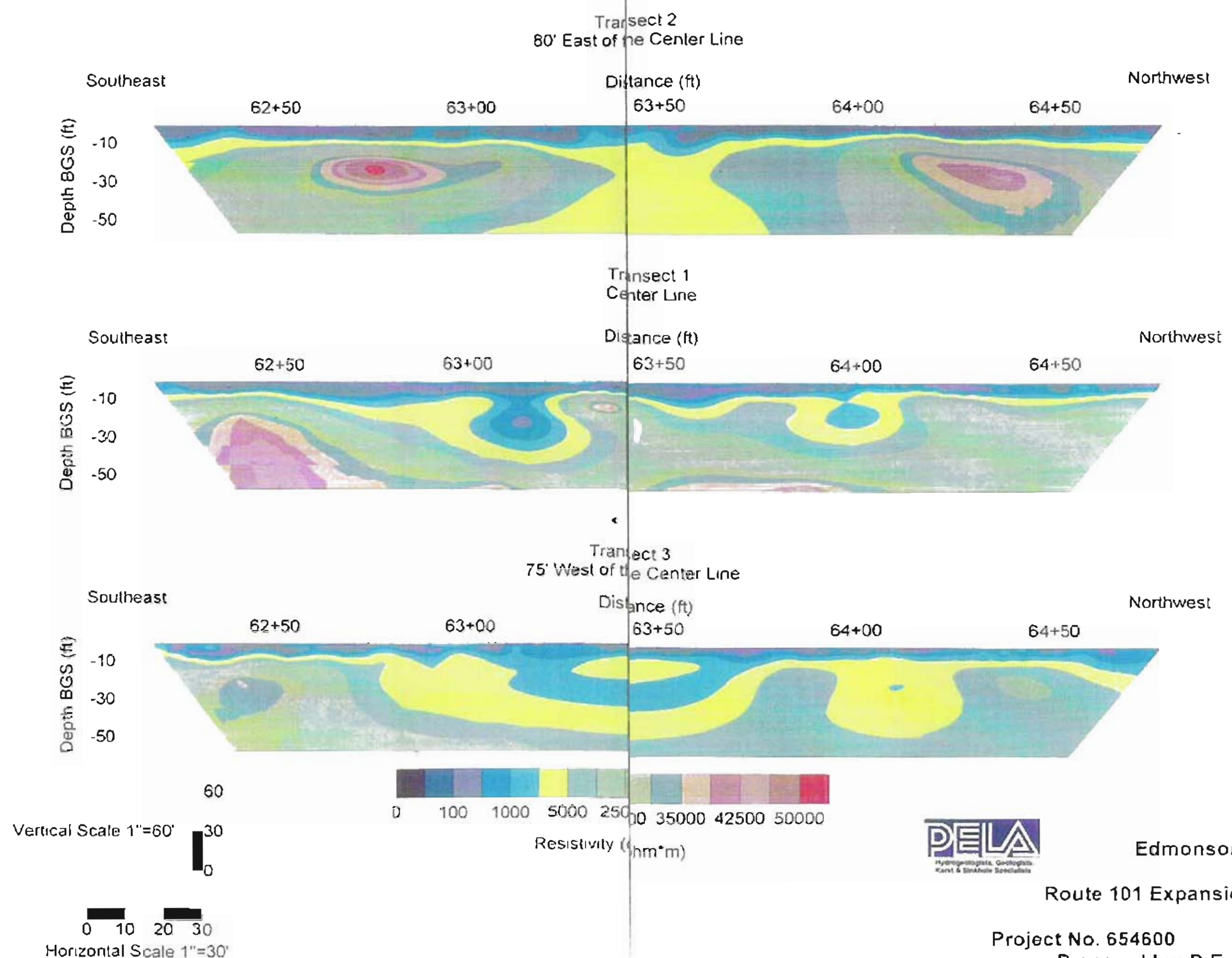
APPENDIX A: Electrical Resistivity Profiles

P.E. LaMoreaux & Associates

Electrical Resistivity Profile Transects 1, 2, 3
Stations 62+10 to 64+80



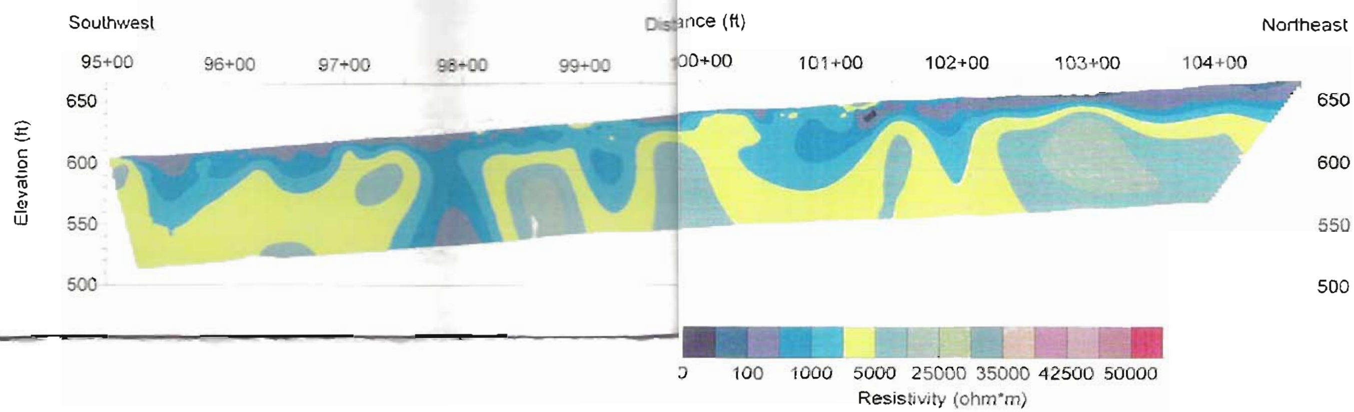
Edmonson-Warren County, Kentucky

Route 101 Expansion: Stations 62+10 to 64+80

Project No. 654600 Date: March 31, 2003

Prepared by: P.E. LaMoreaux and Associates

Electrical Resistivity Profile Transect 4
95' East of the Center Line



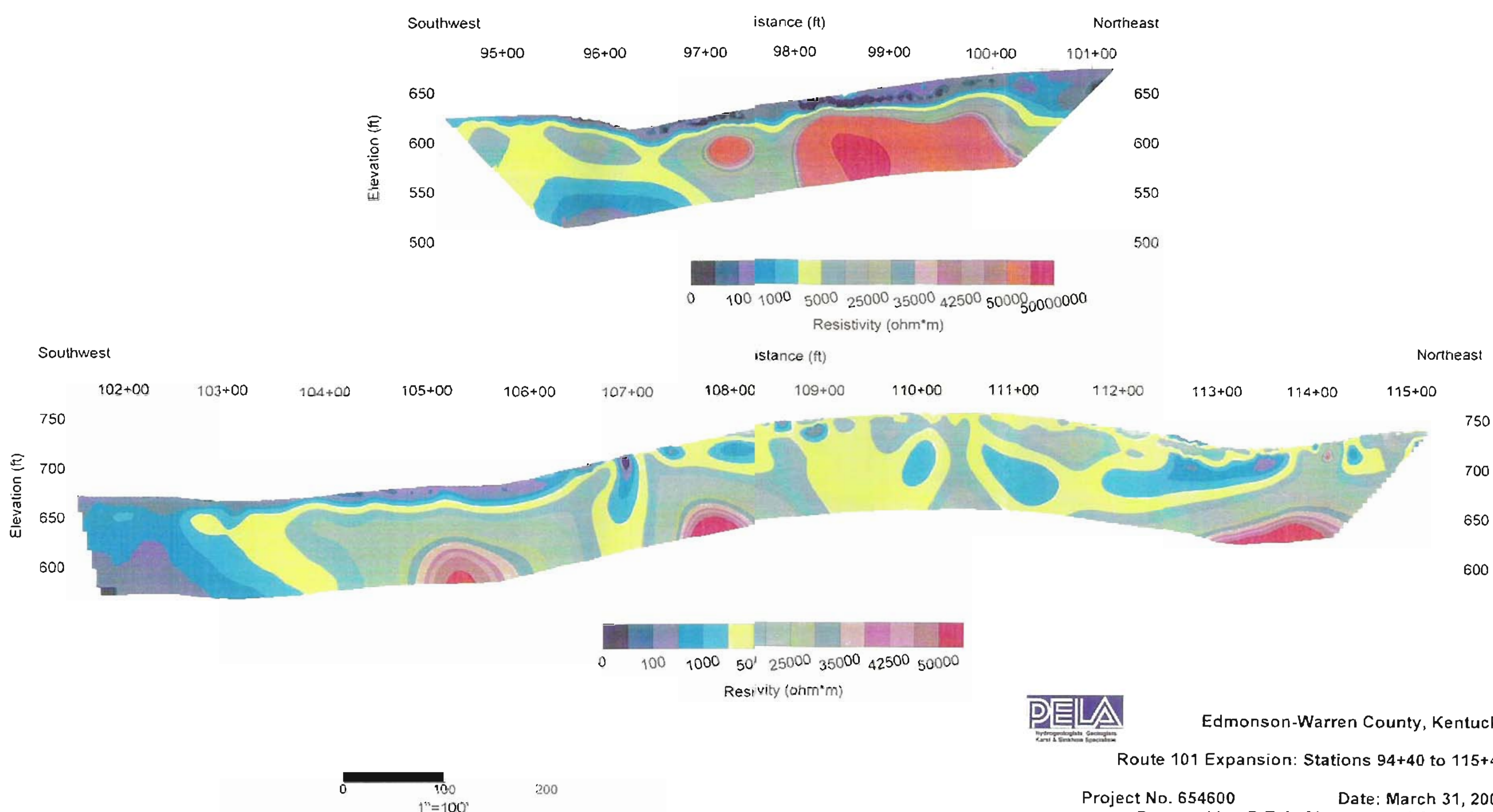
Edmonson-Warren County, Kentucky

Route 101 Expansion: Stations 95+00 to 104+65

Project No. 654600 Date: March 31, 2003

Prepared by: P.E. LaMoreaux and Associates

Electrical Resist/ity Profile Transect 5
Ce:ter Line



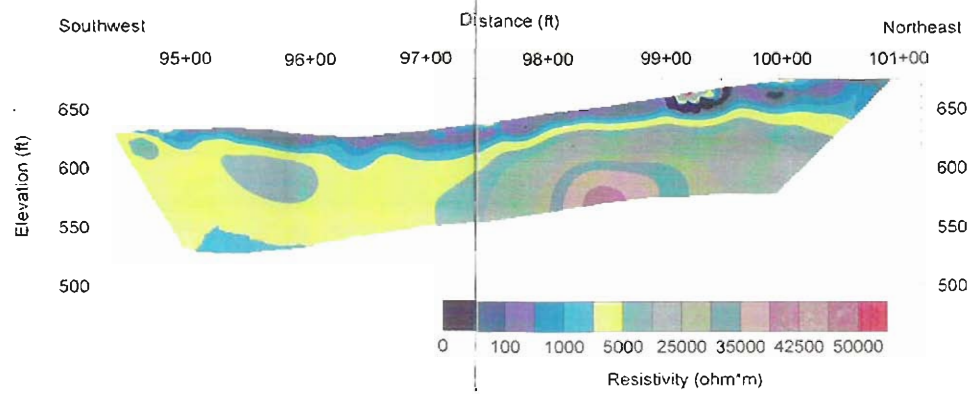
Edmonson-Warren County, Kentucky

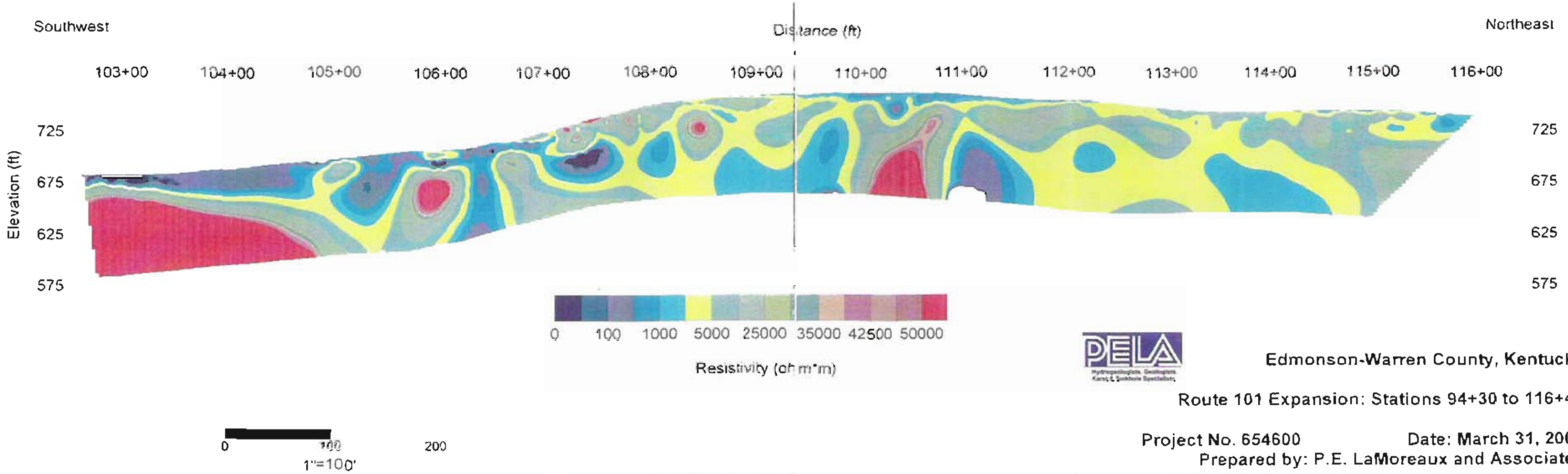
Route 101 Expansion: Stations 94+40 to 115+40

Project No. 654600 Date: March 31, 2003

Prepared by: P.E. LaMoreaux and Associates

Electrical Resistivity Profile Transect 6
Stations 94+30 to 101+20 20' West of the Center Line
andStations 102+50 to 116+40 55' West of the Center Line





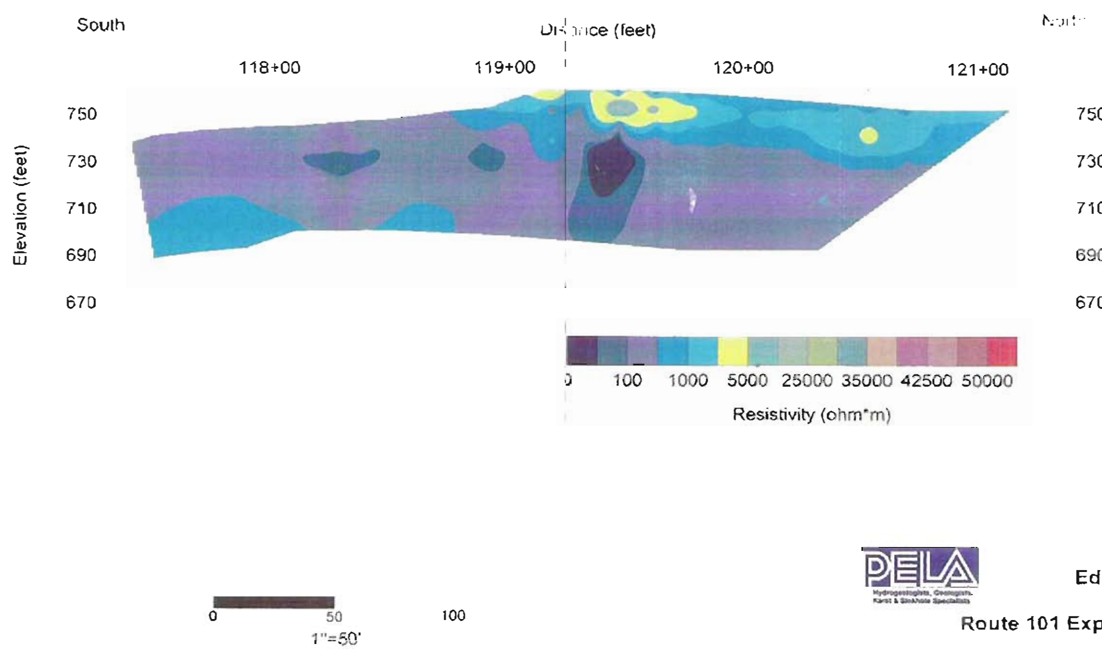
Edmonson-Warren County, Kentucky

Route 101 Expansion: Stations 94+30 to 116+40

Project No. 654600 Date: March 31, 2003

Prepared by: P.E. LaMoreaux and Associates

Electrical Resistivity Profile Transect 7
Center Line



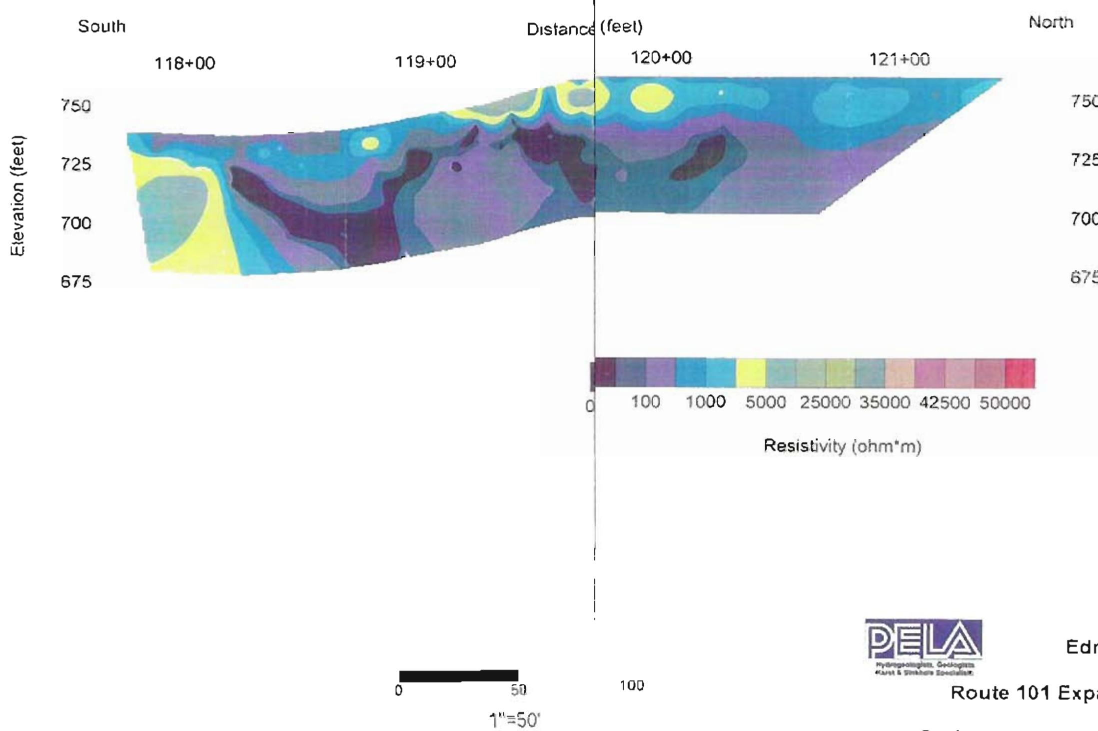
Edmonson-Warren County, Kentucky

Route 101 Expansion: Stations 117+30 to 121+30

Project No. 654600 Date: March 31, 2003

Prepared by: P.E. Lamoreaux and Associates

Electrical Resistivity Profile Transect 8
50' East of the Center Line



Edmonson-Warren County, Kentucky

Route 101 Expansion: Stations 117+65 to 121+65

Project No. 654600 Date: March 31, 2003

Prepared by: P.E. LaMoreaux and Associates

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APPENDIX B: Top of Epikarst and Top of Rock Plots Interpreted From Combined Resistivity Transects

P.E. LaMoreaux & Associates

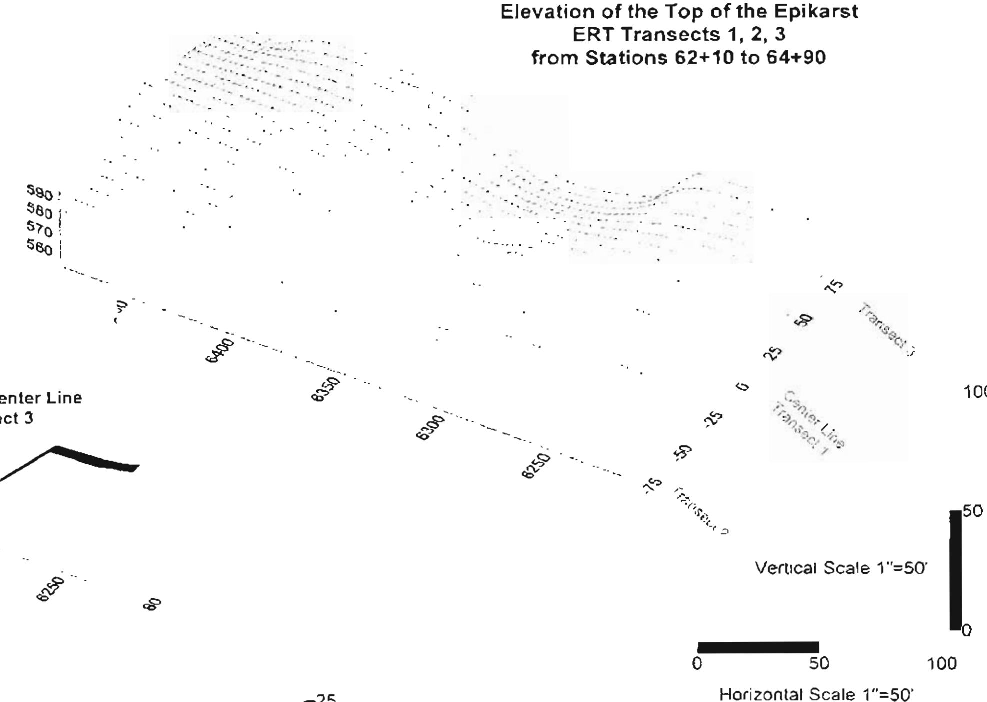
Edmonson-Warren County, Kentucky

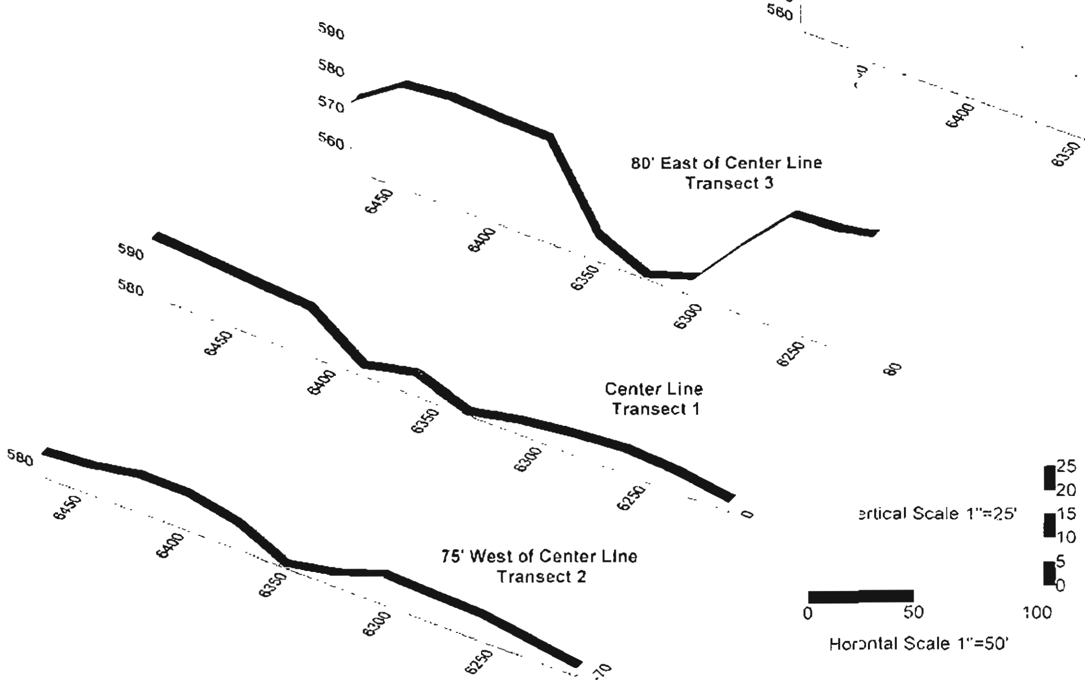
Route 101 Expansion: Stations 62+10 to 64+90

Project No. 654600 Date: March 31, 2003

Prepared by: P.E. Lamoreaux and Associates

Elevation of the Top of the Epikarst
ERT Transects 1, 2, 3
from Stations 62+10 to 64+90





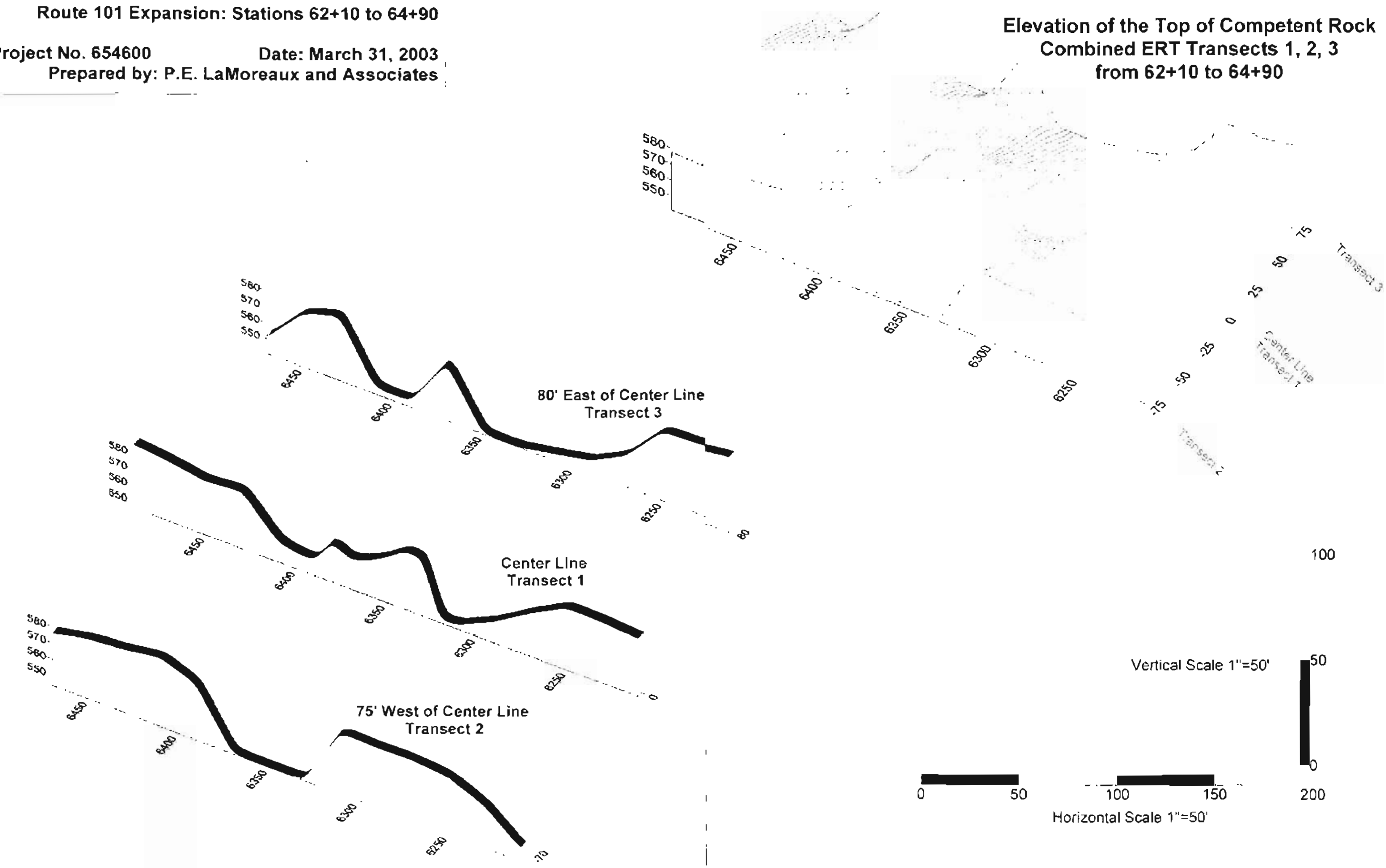
Edmonson-Warren County, Kentucky

Route 101 Expansion: Stations 62+10 to 64+90

Project No. 654600 Date: March 31, 2003

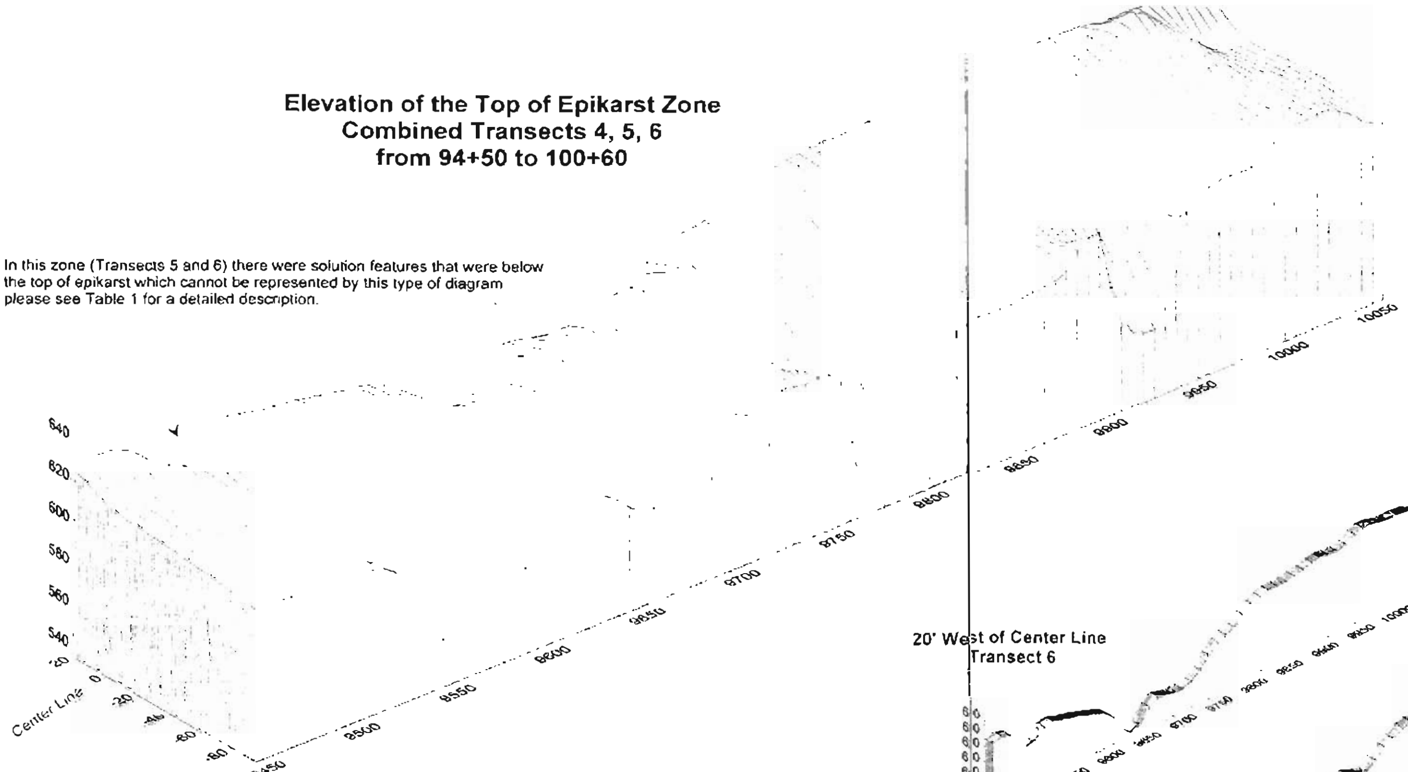
Prepared by: P.E. LaMoreaux and Associates

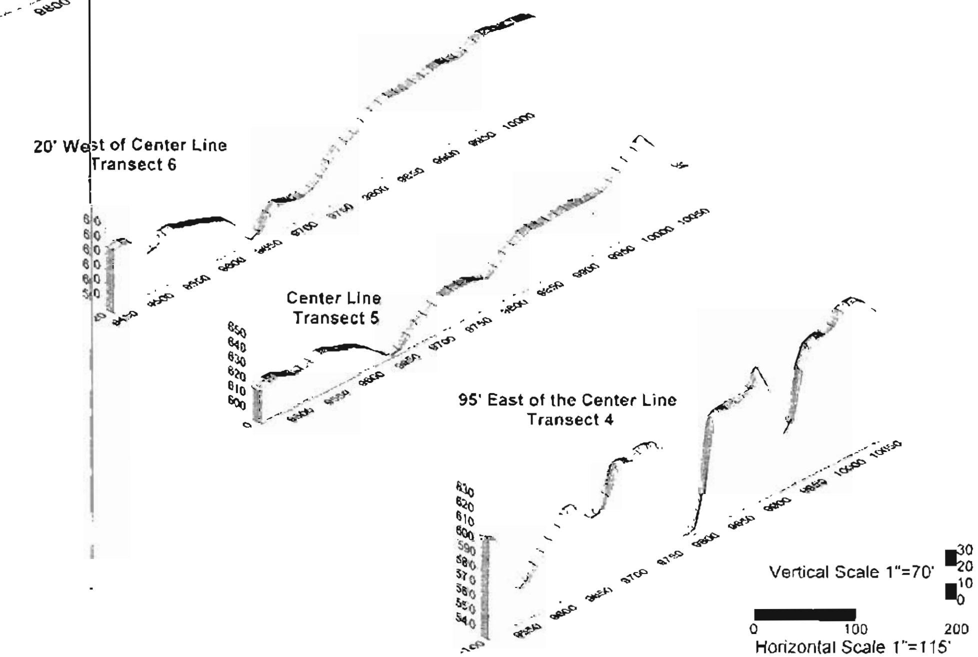
Elevation of the Top of Competent Rock
Combined ERT Transects 1, 2, 3
from 62+10 to 64+90



Elevation of the Top of Epikarst Zone
Combined Transects 4, 5, 6
from 94+50 to 100+60

In this zone (Transects 5 and 6) there were solution features that were below the top of epikarst which cannot be represented by this type of diagram please see Table 1 for a detailed description.





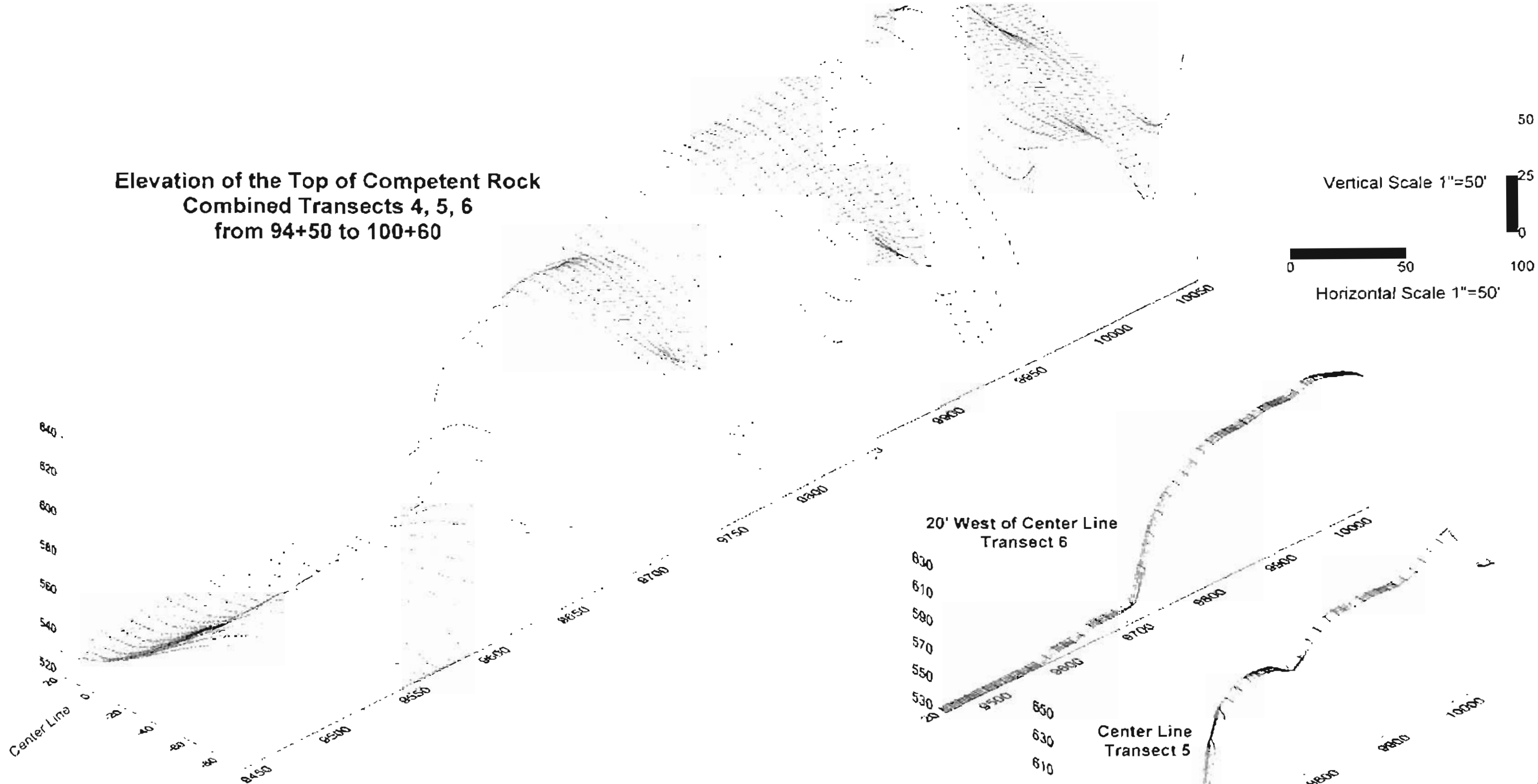
Edmonson-Warren County, Kentucky

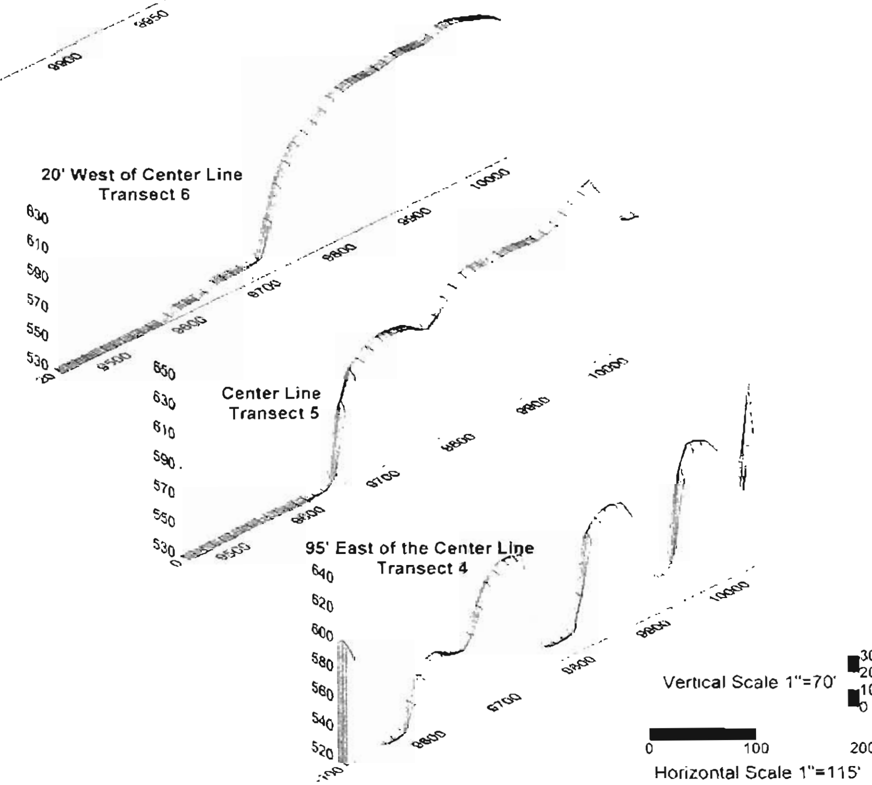
Route 101 Expansion: Stations 94+50 to 100+60

Project No. 654600 Date: March 31, 2003

Prepared by: P.E. LaMoreaux and Associates

Elevation of the Top of Competent Rock
Combined Transects 4, 5, 6
from 94+50 to 100+60





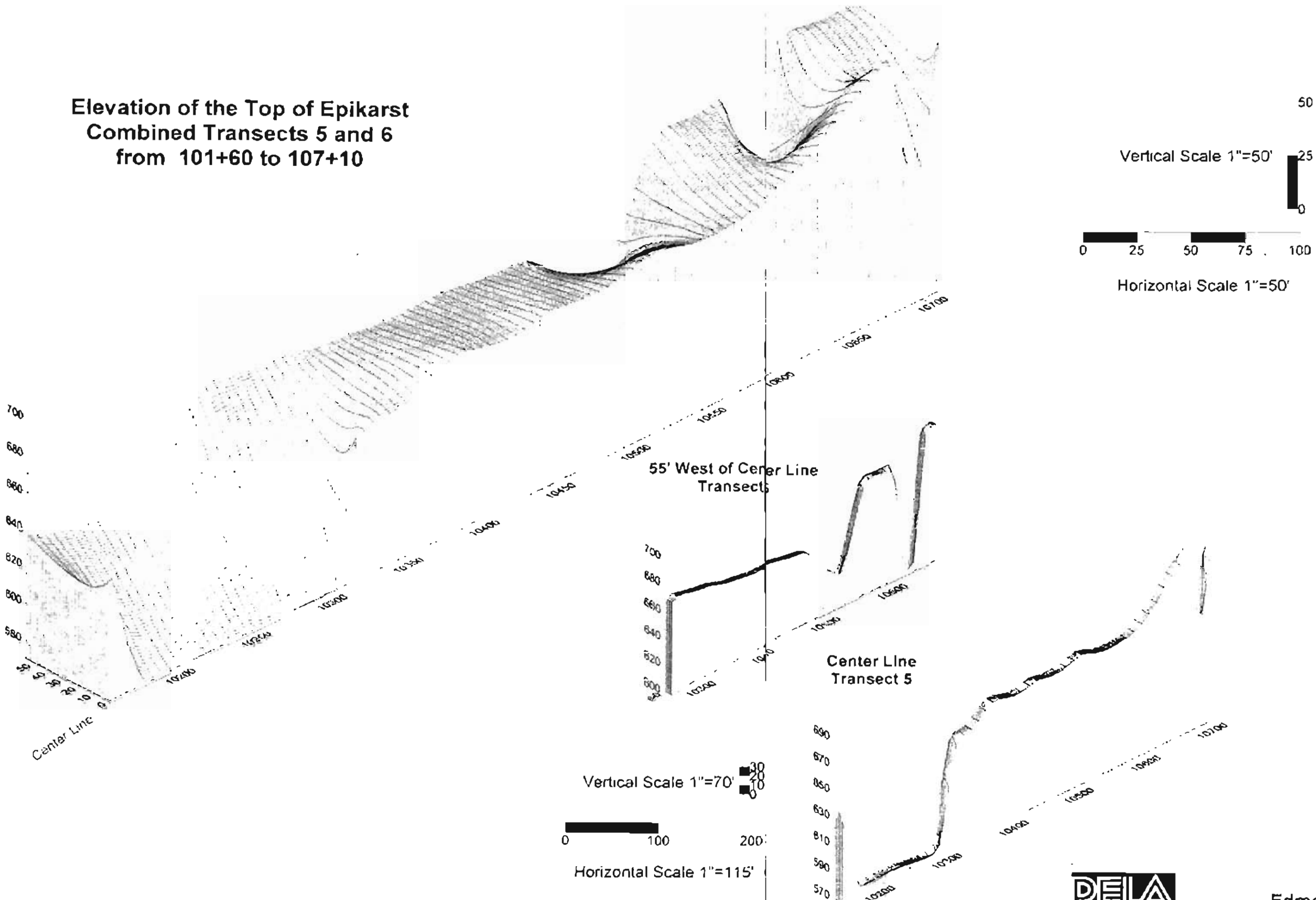
Edmonson-Warren County, Kentucky

Route 101 Expansion: Stations 94+50 to 100+60

Project No. 654600 Date: March 31, 2003

Prepared by: P.E. Lamoreaux and Associates

Elevation of the Top of Epikarst
Combined Transects 5 and 6
from 101+60 to 107+10



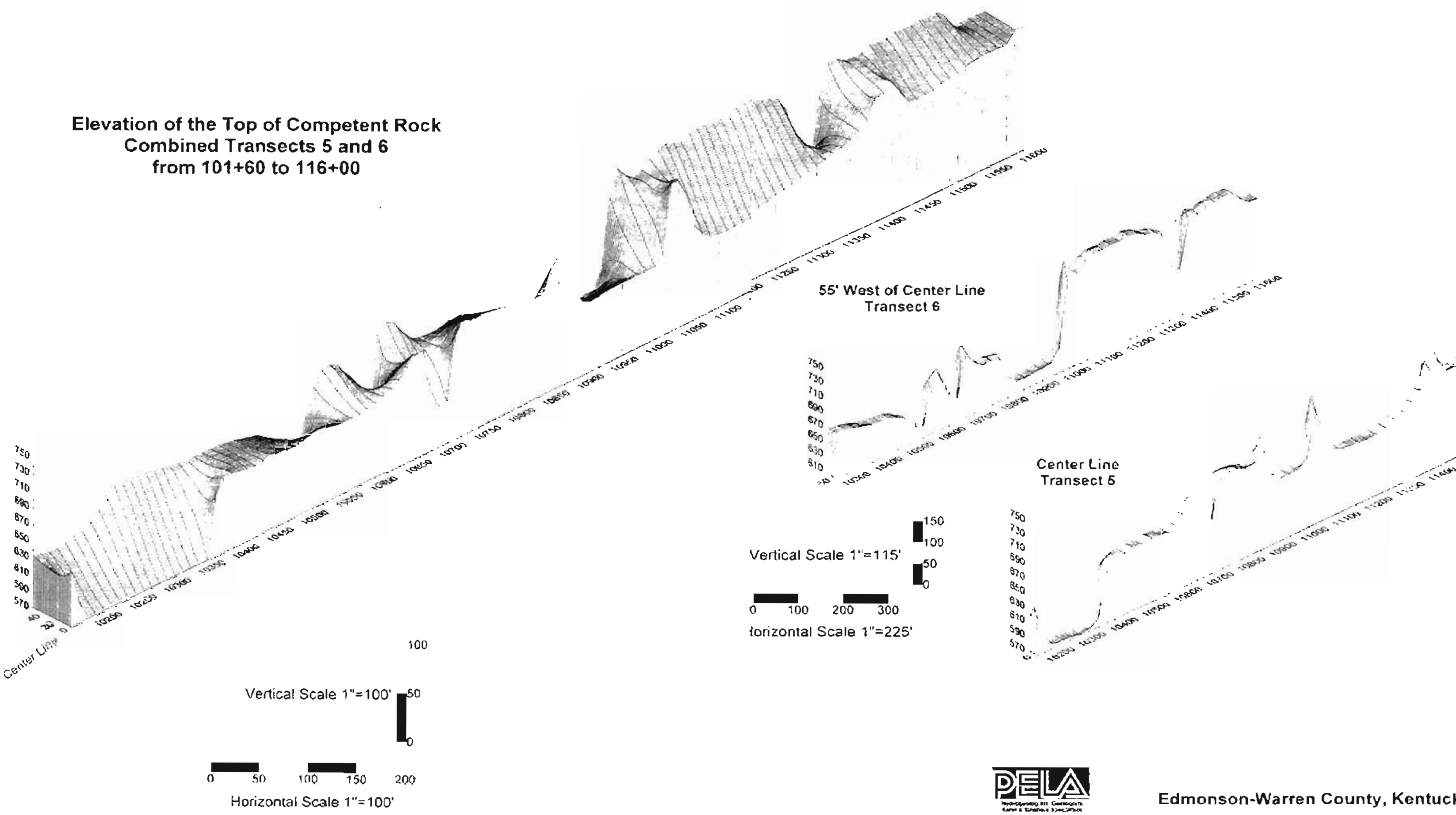
Edmonson-Warren County, Kentucky

Route 101 Expansion: Stations 101+60 to 107+10

Project No. 654600 Date: March 31, 2003

Prepared by: P.E. LaMoreaux and Associates

Elevation of the Top of Competent Rock
Combined Transects 5 and 6
from 101+60 to 116+00



Edmonson-Warren County, Kentucky

Route 101 Expansion: Stations 101+60 to 116+00

Project No. 654600 Date: March 31, 2003

Prepared by: P.E. LaMoreaux and Associates

APPENDIX B

US 31-W Report

MICROGRAVITY SUBSURFACE INVESTIGATION OF A COLLAPSE NEAR US HIGHWAY 31-W BYPASS, HARDIN COUNTY, KENTUCKY

October 2003

Prepared for:

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MICROGRAVITY SUBSURFACE INVESTIGATION OF A COLLAPSE NEAR US HIGHWAY 31-W BYPASS, HARDIN COUNTY, KENTUCKY

Center for Cave and Karst Studies

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MICROGRAVITY SUBSURFACE INVESTIGATION OF A COLLAPSE NEAR US HIGHWAY 31-W BYPASS, HARDIN COUNTY, KENTUCKY

Center for Cave and Karst Studies

1. INTRODUCTION

The Center for Cave and Karst Studies was contracted by the Kentucky Transportation Center, Frankfort, Kentucky to perform a microgravity subsurface investigation of a sinkhole collapse near the 31-W Bypass in the vicinity of Elizabethtown, Kentucky.

1.1 Location

The investigated sinkhole collapse is located off the west side of a section of the southbound lane of 31-W Bypass extending around Elizabethtown, Kentucky (Figure 1.1). The sinkhole collapse is located approximately 85 feet to the west off the emergency shoulder of the roadway. Figure 1.2 is a view of the sinkhole from its East and West sides.

1.2 Geology

The primary geologic units in the Elizabethtown area are Mississippian Age limestones and dolomites. The most prominent rock units in the area are the St. Louis Limestone and the overlying Ste. Genevieve Limestone. The St. Louis Limestone ranges from 200 to 300 feet in thickness and is characterized by thin- to thick-bedded limestone and dolomite with some thin shale beds (Kepferle, 1966). The St. Louis Limestone is the major bedrock unit in the Elizabethtown area. Figure 1.3 is a photograph of the St. Louis Limestone exposed by the sinkhole collapse.

The Ste. Genevieve Limestone outcrops south and west of Elizabethtown. It consists of limestone and dolomite with beds of oolitic limestone and some shale. Its thickness is approximately 80 feet thick in this area (Kepferle, 1966). The Lost River Chert Bed occurs near the top of the Horse Cave Member. The bottom of the Horse Cave Member of the Ste. Genevieve is the contact with the underlying St. Louis Limestone. The Lost River Chert Bed consists of a10-foot zone of erosionally- resistant silicified limestone that contains coarse fossil fragments and abundant chert. Where the Lost River Chert is present, the chert serves to protect the underlying Horse Cave Member from chemical solution. Where the protective Lost River Chert Bed is not present, sinkholes can form in the underlying St. Louis Limestone. In the investigated area weathered pieces of the Lost River Chert litter the ground. This could indicate an area where the Lost River Chert Bed has been removed by erosion leaving the lower Horse Cave Member venerable to relatively small regolith arch collapse sinkholes. About 40 feet below the Lost River Chert Bed, at the top of the St. Louis Limestone, is another limestone unit with abundant balls and beds of chert referred to as the Corydon Chert Member. It is about 60 feet thick and cave streams are often perched upon it. Where one or both of these cherty layers is present, the landscape usually is characterized by large rather flat, bowl-shaped sinkholes. Where they are missing the landscape usually consists of deep more funnel-shaped sinkholes.

1.3 Microgravity

The method used in the investigation involved the use of a Scintrex CG-3M Autograv Microgravity Meter. The purpose of the study was to use Bouguer gravity techniques in order to detect and delineate possible voids in the regolith and/or bedrock and thus delimit the risk of further enlargement of the sinkhole collapse. The data is presented documenting both the Bouguer gravity in microgals and the elevation in feet at each measurement location.

1.4 Area Investigated

During the second examination of the area, the sinkhole was investigated and found to contain a opening in the underlying bedrock, on the south side of the collapse, through which soil is sliding (Figure 1.4). As a result, three parallel traverses where established to the south side of the collapse (Figure 1.5). All three traverses began southeast of the collapse, extending to the southwest. Traverse 1 extended 100 ft; Traverses 2 and 3 were 140 ft in length. The pond to the west of the collapse prevented Traverse 1 from extending any further than 100 feet. Traverse 1 was sent up adjacent to the south side of the collapse, over an area of the collapse that contained a subsurface extention that could only be seen from within the sinkhole. By knowing the existence of this less dense area, the machine's ability could be established. Traverse 2 was 20 feet from Traverse 1, while Traverse 3 was placed 40 feet from Traverse 2. Each Traverse contained stations at a 10-foot spacing interval. The area was mostly covered by soil and vegetation, with the area nearest to the roadway having a more shallow depth to bedrock and shattered vegetation. The asphalt-paved 31-W Bypass southbound lane extended from north to south on the east side of the investigated site.

2. MICROGRAVITY RESEARCH PROCEDURES

2.1 Introduction

Gravity surveys are used to detect variation in the density of subsurface materials. Variations in the earth's gravitational field higher than normal indicate underlying material of higher density while areas of low gravity indicate areas of lower density. In order to detect voids or cavities, very high precision is required. Accurate gravity readings to 10 microGals (1 Gal = 1 cm/s^2) are necessary. This is equal to 1 part in 100,000,000 of the earth's normal gravity. A SCINTREX CG-3M Autograv Microgravity Meter which has a 0.5-microGal sensitivity was used for this investigation. For a more detailed discussion of microgravity as a method for detection of subsurface features and Center for Cave and Karst Studies experience with this method, please refer to Appendix (I) and Appendix (II).

2.2 Microgravity Research Procedures

The SCINTREX CG-3M Autograv underwent a 48-hour stabilization period prior to field use. Field calibration was performed on the instrument and consisted of a long-term drift correction and temperature compensation adjustment.

The following corrections are calculated for each gravity measurement:

- Instrument Drift (short term),
- Earth Tides,
- Reference Ellipsoid (latitude),

- Free-Air Effect (elevation), and
- Bouguer Slab Density

A base station was established at the survey site and gravity was repeatedly measured at this base station every two hours in order to derive instrument drift. A base station derived instrument drift curve was interpolated to the time of each survey station reading and each station reading was then corrected for instrument drift by the Geosoft OASIS Montaj reduction program.

Earth tide corrections are based on latitude and longitude of the survey station and the gravitational effect of the sun and moon at any given point in time. This correction was made for each gravity reading using latitude and longitude derived from a GPS measurement made at the site and determined by recording date and time for each instrument reading (converted to UTC for calculations). The reference ellipsoid correction refers to the fact that the earth is an imperfect sphere with gravitational variation as a function of latitude.

Differences in elevation between each survey station and the base station were compensated for using free-air correction calculation. The free-air effect compensates for the decrease in gravity with elevation due to increasing distance from the center of the earth. Ground elevation for each microgravity station was surveyed to the nearest hundred of a foot and instrument height was measured to the nearest 1/10 of an inch.

Theoretical gravity is modified to obtain simple Bouguer gravity by applying the Bouguer slab effect correction. This correction refers to the attraction of the slab of material, which is caused by variation in density, between the station elevation and sea-level. Topographic relief across the survey site did not require terrain corrections to be applied to the data set.
In most karst areas, the following average density values are assumed:

Air = 0 g/cm^3 Water = 1.0 g/cm^3

Regolith or cave sediments = 1.5-2.2 g/cm^3 Limestone = 2.5-2.67 g/cm^3

Therefore, density contrasts of 0.5 to 2.7 g/cm^3 are anticipated for any subsurface cavity, depending on whether the cavity is filled with sediment, water or air and whether the cavity is surrounded by regolith or bedrock. Air-filled cavities in bedrock with a density contrast of approximately 2.5 g/cm^3 are the easiest to detect while water-filled voids in regolith with a density contrast of approximately 0.5 g/cm^3 are the most difficult. Shallow, large, air-filled voids are the easiest to detect with deep, small, water-filled voids in regolith the most difficult.

2.3 Detection of Subsurface Features in Karst Terrain

Bouguer gravity can identify locations on the earth's surface that have relatively higher or lower gravity caused by lateral variations in subsurface density. Crawford (1995) has used microgravity extensively to locate bedrock caves from the ground surface (Appendix I). The lower densities of the air, water or mud within a cave compared to the surrounding carbonate rock results in a low- gravity anomaly. Crawford has also used microgravity to locate voids in the regolith (unconsolidated material above bedrock) which are potential sinkhole collapses. Since regolith is less dense that limestone bedrock, Bouguer gravity can also identify variations in depth to bedrock.

2.4 Microgravity Used for Sinkhole Collapse Investigations

Crawford has used microgravity to investigate subsurface conditions in the vicinity of sinkhole collapses. Microgravity provides useful information concerning a) depth to bedrock, b) extent and shape of the void below the surface, c) location of the crevice, or crevices, through which regolith and water are sinking and d) additional regolith voids in the vicinity. Appendix I further details the use of microgravity for sinkhole collapse investigations.

2.5 Survey Layout

Survey lines were marked with an orange paint mark or a labeled wooden stake every 10 feet apart to mark each station. A universal base station was established at a location within the study area in order to measure changes in drift during the time measurements were being made.

2.6 Field Methods

The SCINTREX CG-3M Autograv microgravity meter used for this survey provided the following on-board data corrections:

1. Continuous Tilt Correction—for instrument level.
2. Seismic Filter—for interference caused by vibration.
3. Auto-Reject—for statistical rejection of anomalous readings.

At each measuring station the instrument was manually leveled to within +/- 5 arcseconds. Instrument height was measured to the nearest 1/10 inch for each station. Measurement read-time on the SCINTREX CG-3M Autograv was programmed for 60 seconds (one reading per second for resultant average). The time of measurement (HH/MM) was accurately recorded for each measurement. Data was recorded digitally by the microgravity meter and field notes maintained by the survey team.

2.7 Data Reduction

Corrections to measured field gravity were applied based on latitude and longitude, time of measurement, elevation of measurement, and instrument height data recorded by the field personnel for each survey station. Data reduction was facilitated by a computer program called Geosoft Oasis Montaj. Data reduction includes the following corrections:

1. Instrument Drift
2. Reference Ellipsoid (a function of latitude)
3. Earth Tide
4. Elevation (free-air effect)
5. Bouguer slab effect (density)

After all corrections have been calculated, the reduced data consists of a Simple Bouguer Gravity value for each measured point. Increasingly negative values for Bouguer gravity indicate greater deficits in mass below each measurement point. Graphic plotting of data produces a trend line that illustrates the relative fluctuations in gravity within the survey area.

2.8 Criteria for Interpreting Reduced Data

Reduced survey data consist of Simple Bouguer Gravity. Fluctuations in measured gravity can be attributed to changes in depth to bedrock, variations in density of competent subsurface materials, regolith voids and bedrock voids. Existing information on depth to bedrock were used to facilitate interpretation. The following criteria were used to guide interpretation of the reduced microgravity data:

- Anomalies are interpreted based on disconformity between local trends in measurements. This includes data sets with essentially "flat" graphic trends as well as trends which increase or decrease with horizontal distance. A gradually increasing or decreasing trend across a data set is often representative of depth to bedrock trends or regional gravity trends. Anomalies within a data set are identified as variations within such trends.
- Anomalies are interpreted based on magnitude. While neither the magnitude of the actual subsurface feature nor the depth to the feature can be concluded from survey data, greater magnitudes of disconformity within the data set indicate more probable detections of actual subsurface features, such as sediment-filled, water-filled or air-filled voids in the limestone bedrock or regolith.

- Symmetry of an anomaly within the data set indicates a more probable detection of actual subsurface features. Data sets exhibiting a gradual decrease from local average in Bouguer microgravity followed by a gradual increase to local average (i.e. a "bowl" shape) are considered more positive indicators of a low-gravity anomaly with less likelihood of instrument error. Single point anomalies are generally considered unreliable indicators of actual anomalies.

3. RESULTS

3.1 General

The profile trends depicted have not been smoothed or fitted and are based on careful selection of the most accurate 60 second reading at each station based on the following.

1. Readings which exhibit the lowest standard deviation were plotted where repeated 60 second measurements were made at a single station.
2. Where repeated 60 second measurements were made at a single station, selection was based on which tilt value was within +/- 5 arcseconds.
3. Where repeated 60 second measurements yielded similar standard deviation, a conservative selection was made of the reading which conformed to the general trend exhibited by the traverse, i.e. a "best fit".

3.2 Microgravity Results

The microgravity survey data taken in the field are presented in Appendix I. The data, once corrected by the OASIS Mataj program are included in Appendix II. The microgravity profiles derived from the corrected data along with elevation for each of the traverses can be seen as Figures 3.1 through 3.3. Figure 3.4 contains the contoured microgravity data.

All three traverses show an overall decrease in gravity as they extend to the east. This is likely due to the increase in the depth to bedrock as the traverse continues. Where bedrock is closer to the surface the density is greater then in areas where more regolith exists between the microgravity meter and bedrock.

Traverse 1 indicates an anomaly approximately 50 µgals in size at a distance of less than two feet from the edge of the surface expression of the collapse. However, the collapse did extend underneath stations 125 through 150.

Traverse 2 also indicated an anomaly approximately 30 µgals in size underneath station 250. This is likely a subsurface continuance of the microgravity expression of the collapse.

Traverse 3 does not indicate any unusual gravity fluctuations.

From the contoured data there appears to be an extension of a lower density area that extends from the collapse towards the south. Therefore, it appears that this is an indication of the subsurface opening in the bedrock.

4. CONLUSION

The sinkhole collapse is a result of a regolith arch collapse. It has been formed by the downward movement of regolith into a crevice in the underlying bedrock (Figure 1.4). The measurements of microgravity every 10 feet along 3 traverses parallel to the sinkhole collapse did not reveal a large low gravity anomaly pattern. However, the small anomalies that were detected along Traverses 1 and 2 appeared to decrease in size further from the collapse. Therefore, except for these anomalies, the microgravity subsurface investigation did not reveal any large voids that might indicate the potential danger of a sinkhole collapse under the adjacent I-65 Bypass. Unfortunately, it is possible that regolith arches can grow rapidly during large rains and should be remediated. The most effective way of repairing a sinkhole collapse is to excavate the collapse to bedrock. The sinkhole should be filled with large rocks at bedrock and graded upward to finer materials (Figure 4.1). This method allows water to move up or down through the fill without moving the material and thus creating new regolith arches and potential collapses. If during the excavation process the crevice(s) at the base of the sinkhole is located, it is best not to seal it. Groundwater may only be diverted to another location where it may induce another sinkhole collapse. Graded filling will allow for drainage within the repaired area without increasing risk of collapse elsewhere.

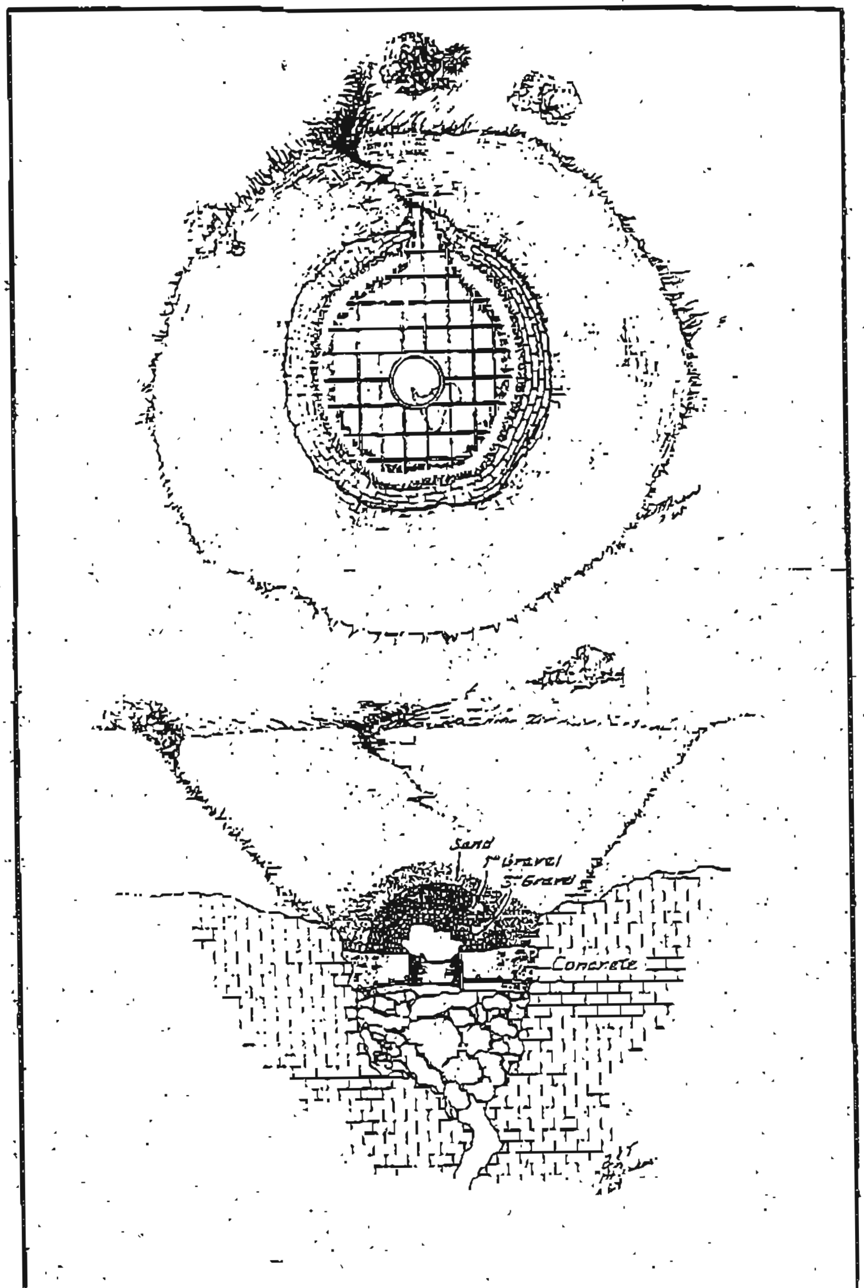

Figure 4.1: Artist's rendition of an inverted graded rock filter used to fill a regolith arch collapse. Note the reinforced concrete cap used to stabilize the broken fill in the sinkhole.

Diagram by S. Parker, in Bergstrom, (1970).

5. REFERENCES

1. Crawford, N.C.; Lewis, M.A., Winter, S.A. and J.A. Webster (1999). Microgravity Techniques for Subsurface Investigation of Sinkhole Collapses and for Detection of Groundwater Flow Paths Through Karst Aquifers, in Beck, Pettit and Herring (edr.) Hydrogeology and Engineering Geology of Sinkholes and Karst, Balkema, Rotterdam, ISBN 90 58090469

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3. Kepferle, Roy C. (1966). Geologic Map of the Elizabethtown Quadrangle, Hardin and Larue Counties, Kentucky. USGS.

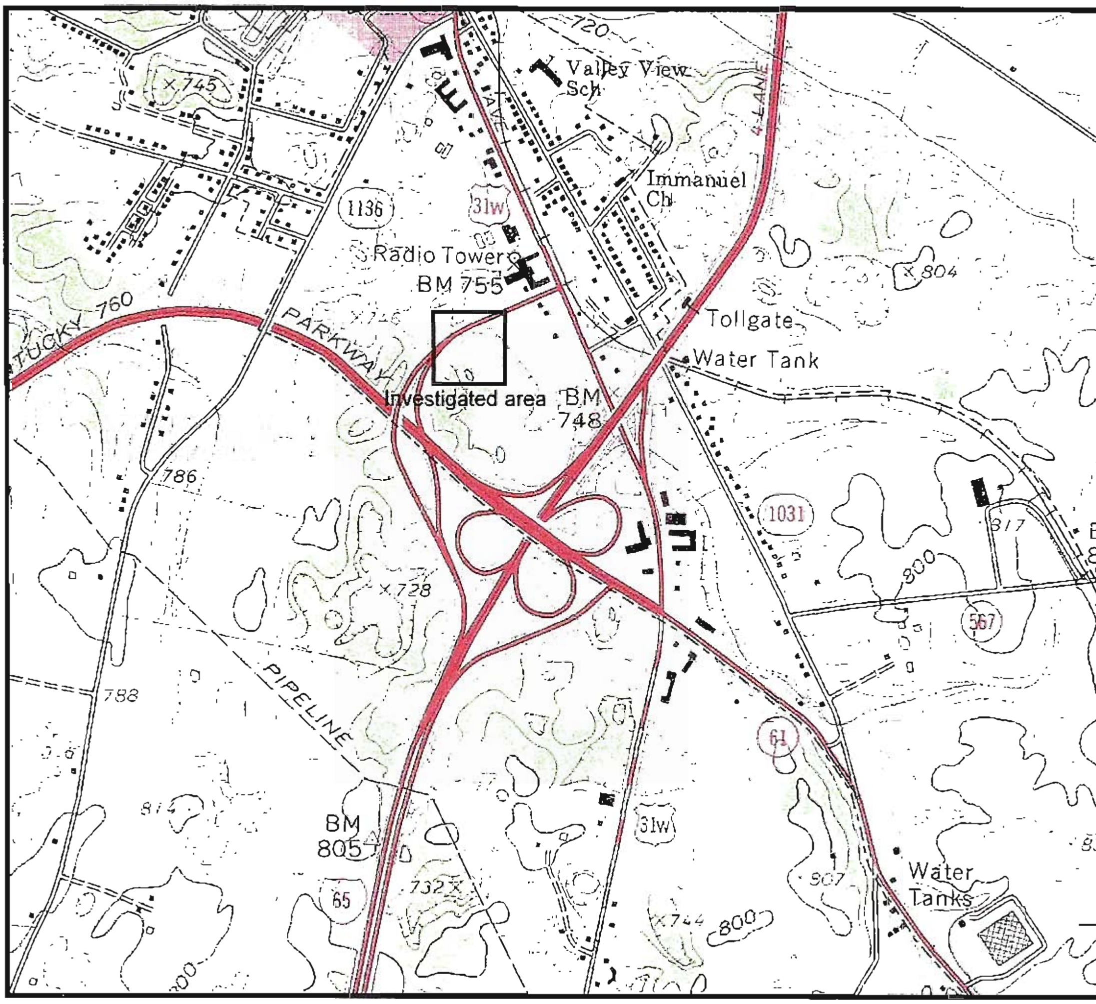

Figure 1.1: Portion of the Elizabethtown 7.5 minute Quadrangle Topographic Map showing the location of the investigated area.

Figure 1.2: Picture showing the east and west sides of the collapse, respectively.

Figure 1.3: Picture showing the opening in the bedrock through which soil is piping downward.

Figure 1.4: Picture showing the interior of the collapse.

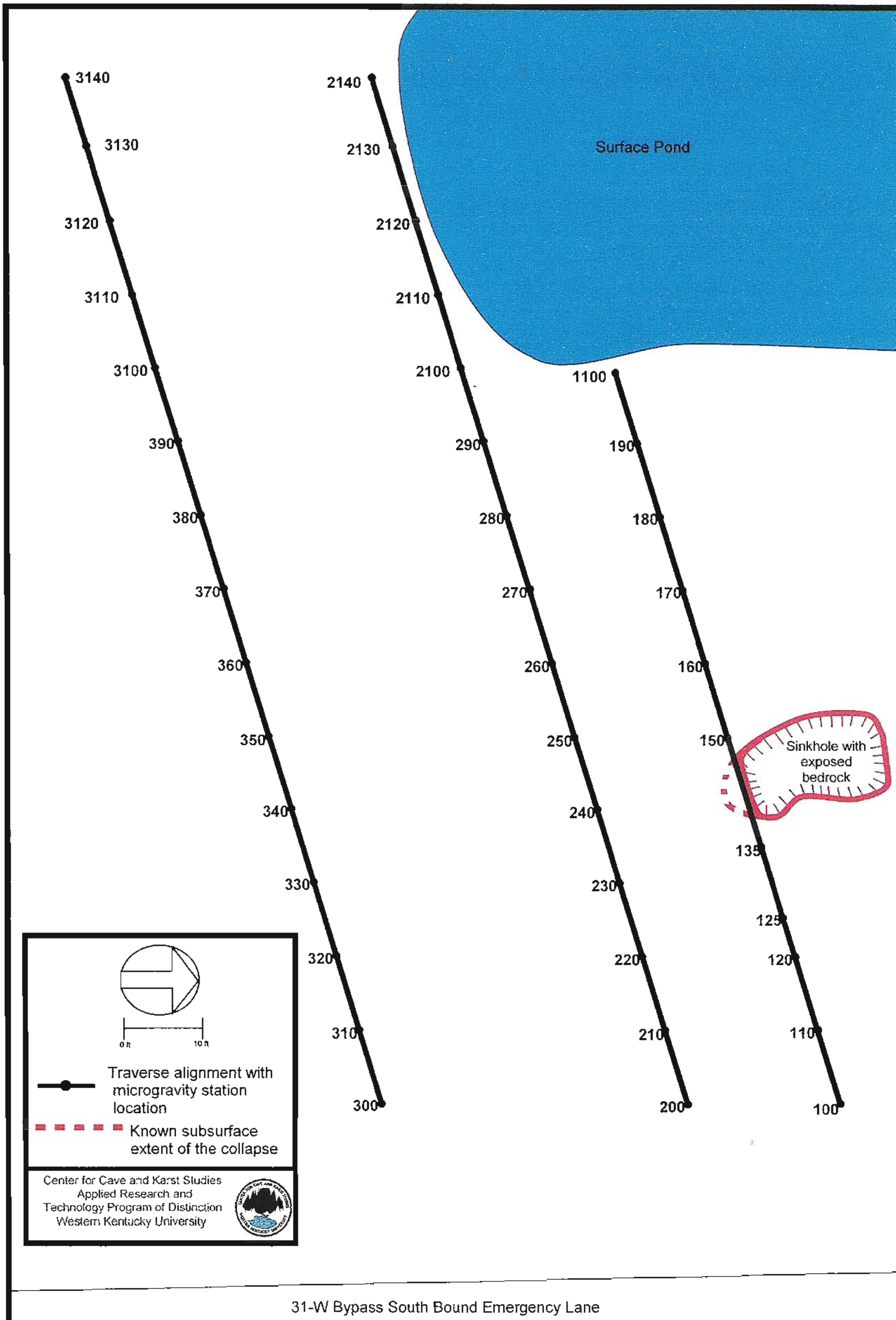

Figure 1.5: Map showing layout of traverses.

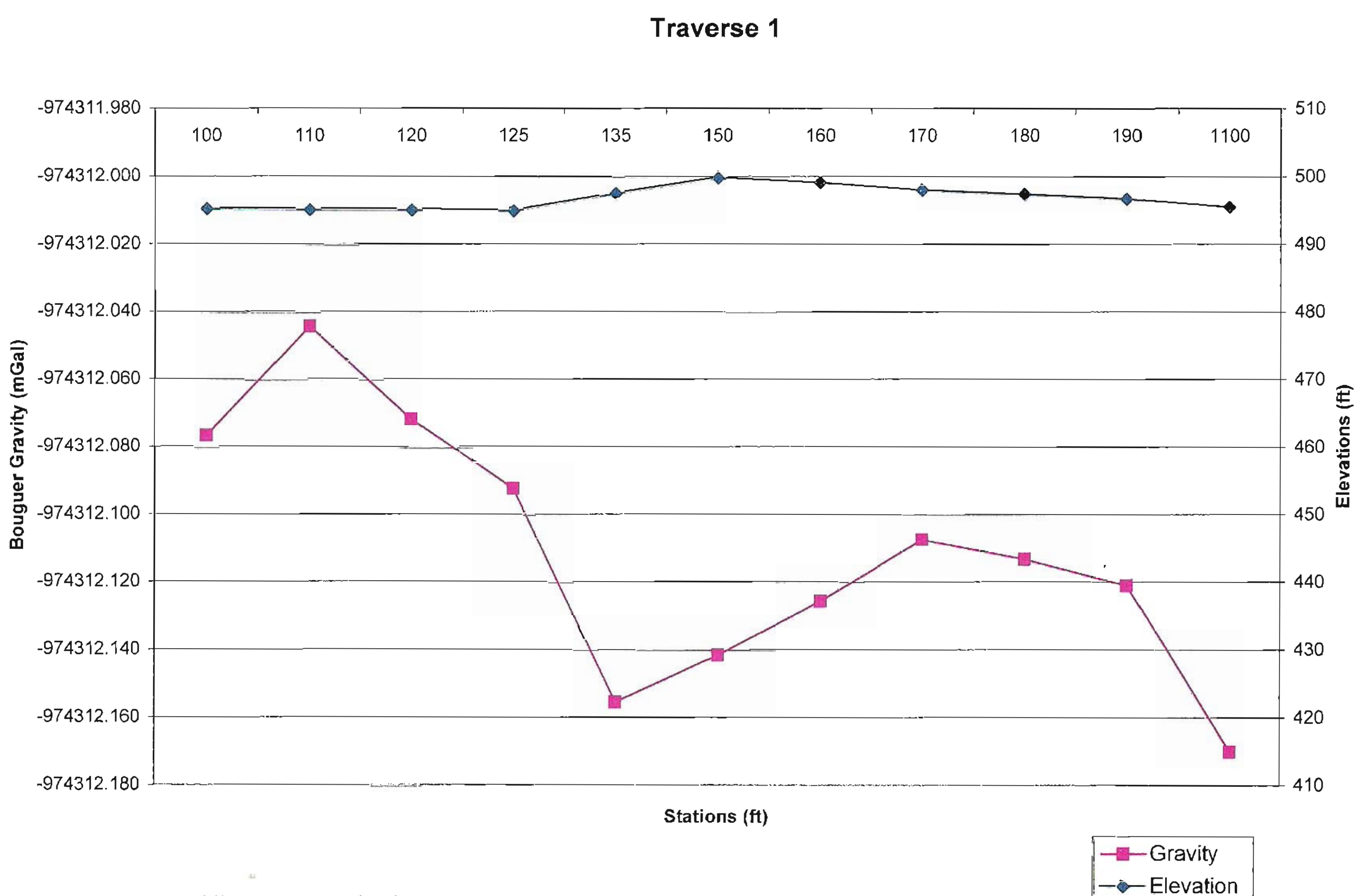

Figure 3.1: Microgravity profile for Traverse 1.

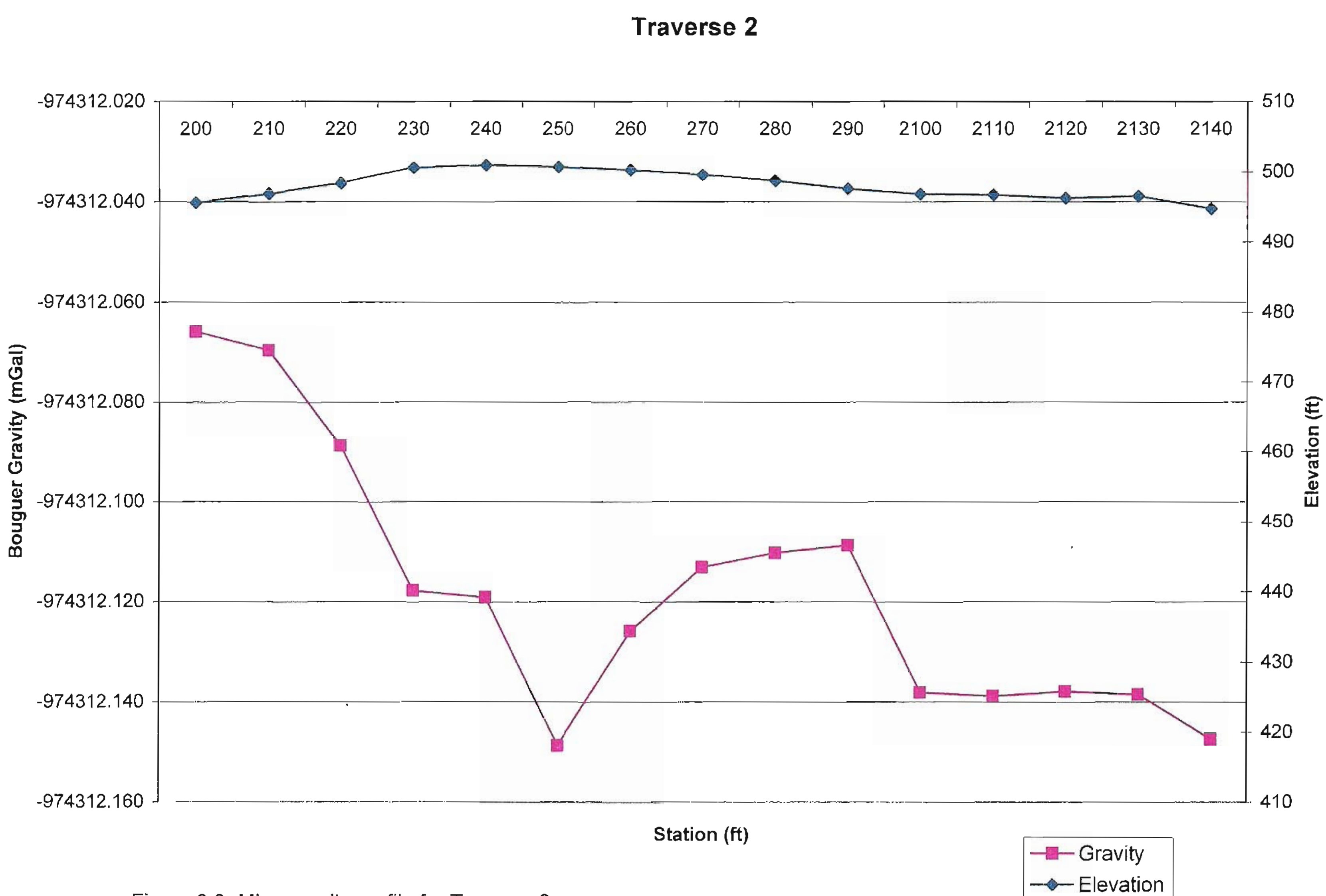

Figure 3.2: Micrograity profile for Traverse 2.

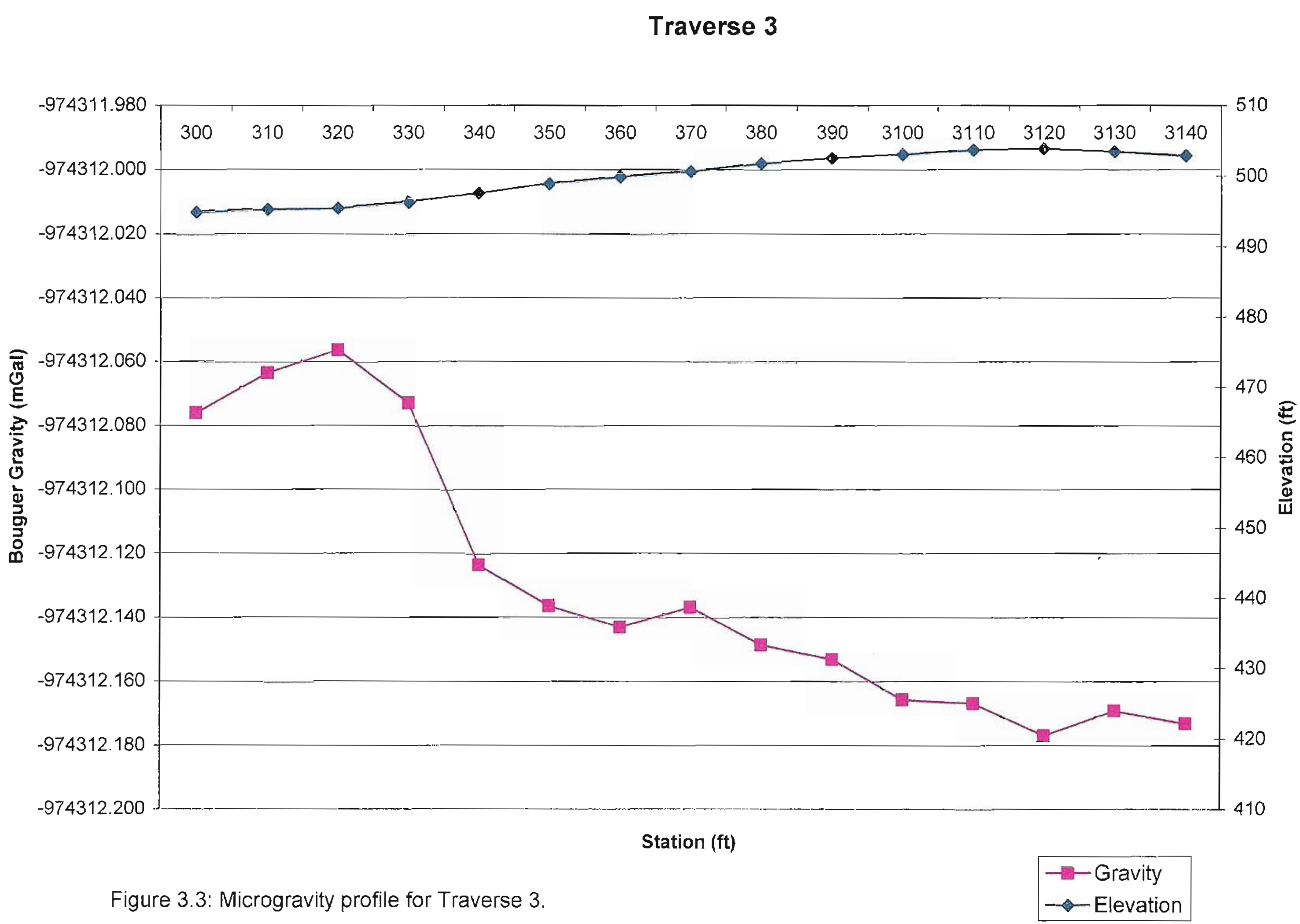

Figure 3.3: Microgravity profile for Traverse 3.

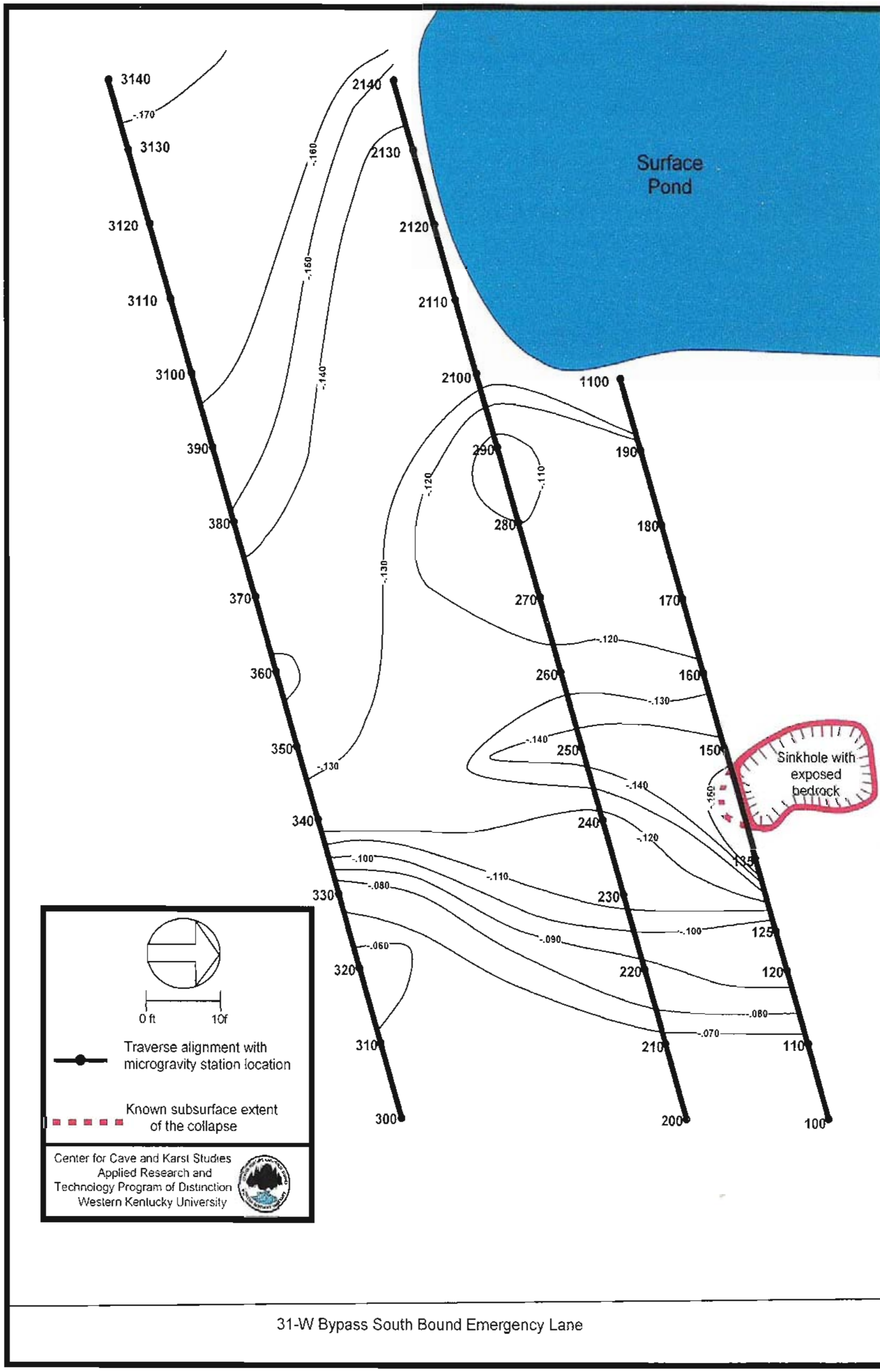

Figure 3.4: Contoured microgravity data.

APPENDIX C

KY 61 Report

MICROGRAVITY AND ELECTRICAL RESISTIVITY SUBSURFACE INVESTIGATION AT MILE POINT 12.9 ON KY HIGHWAY 61, LARUE COUNTY, KENTUCKY

October 30, 2003

Prepared for:

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MICROGRAVITY AND ELECTRICAL RESISTIVITY SUBSURFACE INVESTIGATION AT MILE POINT 12.9 ON KY HIGHWAY 61, LARUE COUNTY, KENTUCKY

Center for Cave and Karst Studies

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MICROGRAVITY AND ELECTRICAL RESISTIVITY SUBSURFACE INVESTIGATION AT MILE POINT 12.9 ON KY HIGHWAY 61, LARUE COUNTY, KENTUCKY

Center for Cave and Karst Studies

1. INTRODUCTION

The Center for Cave and Karst Studies was subcontracted by the Kentucky Transportation Center to perform a geophysical survey including microgravity traversing and electrical resistivity testing in response to a visional sagging of the roadway at mile point 12.9 on KY Highway 61, in Larue County, Kentucky.

1.1 Location

The investigated site is located along KY Highway 61 between Elizabethtown and Hodgenville, in Larue County, Kentucky in the vicinity of mile point 12.9. At this point, the roadway is a split highway with two eastbound and two westbound lanes that are separated by a grassy median. The section of roadway that appears to be sagging is in the two eastbound lanes, with more depression evident in the right lane.

1.2 Geology

The primary geologic units in this area are the St. Louis Limestone and the overlying Ste. Genevieve Limestone of the Mississippian Age (Figure 1.1). The most prominent rock unit in the vicinity of the investigated site is the St. Louis Limestone (Moore, 1966).

The Ste. Genevieve Limestone outcrops north west of the investigated site. It consists of limestone and dolomite with beds of oolitic limestone and some shale. Its thickness is approximately 80 feet thick in this area (Moore, 1966). The Lost River Chert Bed occurs near the top of the Horse Cave Member. The bottom of the Horse Cave

Member of the Ste. Genevieve is the contact with the underlying St. Louis Limestone. The Lost River Chert Bed consists of a10-foot zone of erosionally- resistant silicified limestone that contains coarse fossil fragments and abundant chert. Where the Lost River Chert is present, the chert serves to protect the underlying Horse Cave Member from chemical solution. Where the protective Lost River Chert Bed is not present, sinkholes can form in the underlying St. Louis Limestone. About 40 feet below the Lost River Chert Bed, at the top of the St. Louis Limestone, is another limestone unit with abundant balls and beds of chert referred to as the Corydon Chert Member. It is about 60 feet thick and cave streams are often perched upon it. Where one or both of these cherty layers is present, the landscape usually is characterized by large rather flat, bowl-shaped sinkholes. Where they are missing the landscape usually consists of deep more funnel-shaped sinkholes. From the geologic map (Figure 1.1) the investigated area contains numerous funnel-shaped sinkholes. This is in contrast to the areas to the northwest that are underlain with the Ste. Genevieve as well as those areas that are protected by the Late Mississippian age sandstone and shale caprock.

1.3 Microgravity

Microgravity measures relative gravity caused by lateral variations in subsurface density. The microgravity method employed in the investigation involved the use of a Scintrex CG-3M Autograv Microgravity Meter. The purpose of the study was to use Bouguer gravity techniques in order to detect and delineate possible voids in the regolith and/or bedrock. The data are presented documenting both the Bouguer gravity in microgals and the elevation in feet at each measurement location.

1.4 Electrical Resistivity

Electrical resistivity measures the resistivity of the subsurface material to the transmission of an induced electrical current. The method employed in the electrical resistivity testing involved the use of a Sting/Swift Resistivity meter. The purpose of the study was to use the Dipole-Dipole array of electrode placement to detect subsurface areas less conductive then their surroundings. The data are presented showing the modeled resistivity profile beneath the microgravity measurements at the same coordinates, along each traverse.

1.5 Area Investigated

The investigated area is in a section of KY Highway 61 that is divided. Two eastbound lanes are divided by a grassy median from two westbound lanes (Figure 1.2). On both the north and south sides of the highway there is pastureland that contains numerous sinkholes depressions. Drainage from the roadway and from within the right-of-way area between the road and the controlled access fence is routed into two drainage easements on the south side of the eastbound lane. The smaller drainage basin (A) to the south west of the roadway (Figure 1.2) is located within the right-of-way and is outfitted with a type B silt trap and concrete box to direct water into the subsurface. At the time of the investigation, this area was overgrown with weeds and did not appear to be functional. The larger drainage basin (B) is south of the right-of-way (Figure 1.2). Runoff is directed toward this easement through perforated pipes and "V" ditches that employ type A silt traps in various locations along the route parallel to the roadway. However, there is no drainage well designed for this basin. The water is allowed to percolate downward by gravity.

2. MICROGRAVITY RESEARCH PROCEDURES

2.1 Introduction

Gravity surveys are used to detect variation in the density of subsurface materials. Variations in the earth's gravitational field higher than normal indicate underlying material of higher density while areas of low gravity indicate areas of lower density. In order to detect voids or cavities, very high precision is required. Accurate gravity readings to 10 microGals (1 Gal = 1 cm/s^2) are necessary. This is equal to 1 part in 100,000,000 of the earth's normal gravity. A SCINTREX CG-3M Autograv Microgravity Meter which has a 0.5-microGal sensitivity was used for this investigation.

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Regolith or cave sediments = 1.5-2.2 g/cm^3 Limestone = 2.5-2.67 g/cm^3

Therefore, density contrasts of 0.5 to 2.7 g/cm^3 are anticipated for any subsurface cavity, depending on whether the cavity is filled with sediment, water or air and whether the cavity is surrounded by regolith or bedrock. Air-filled cavities in bedrock with a density contrast of approximately 2.5 g/cm^3 are the easiest to detect while water-filled voids in regolith with a density contrast of approximately 0.5 g/cm^3 are the most difficult. Shallow, large, air-filled voids are the easiest to detect with deep, small, water-filled voids in regolith the most difficult.

2.3 Detection of Subsurface Features in Karst Terrain

Bouguer gravity can identify locations on the earth's surface that have relatively higher or lower gravity caused by lateral variations in subsurface density. Crawford (1995) has used microgravity extensively to locate bedrock caves from the ground surface (Appendix I). The lower densities of the air, water or mud within a cave compared to the surrounding carbonate rock results in a low- gravity anomaly. Crawford has also used microgravity to locate voids in the regolith (unconsolidated material above bedrock) which are potential sinkhole collapses. Since regolith is less dense that limestone bedrock, Bouguer gravity can also identify variations in depth to bedrock.

2.4 Microgravity Used for Sinkhole Collapse Investigations

Crawford has used microgravity to investigate subsurface conditions in the vicinity of sinkhole collapses. Microgravity provides useful information concerning a) depth to bedrock, b) extent and shape of the void below the surface, c) location of the crevice, or crevices, through which regolith and water are sinking and d) additional regolith voids in the vicinity. Appendix I further details the use of microgravity for sinkhole collapse investigations.

2.5 Survey Layout

Microgravity traverses were set up in the grassy area to the south side of the eastbound emergency lane, along the center of the right eastbound lane, and in the median between the east and westbound lanes (Figure 1.2). The microgravity stations on the south side and in the median were placed overlying the locations where electrical resistivity measurements were taken. In the grass, survey lines were marked with an orange painted, labeled wooden stake at every station. All traverses had a 10-foot spacing between stations. In the roadway, the stations were marked with an orange paint mark at every station. A base station was established in a centralized location in order to measure changes in drift during the time measurements were being made.

2.6 Field Methods

The SCINTREX CG-3M Autograv microgravity meter used for this survey provided the following on-board data corrections:

1. Continuous Tilt Correction—for instrument level.
2. Seismic Filter—for interference caused by vibration.
3. Auto-Reject—for statistical rejection of anomalous readings.

At each measuring station the instrument was manually leveled to within +/- 5 arcseconds. Instrument height was measured to the nearest 1/10 inch for each station. Measurement read-time on the SCINTREX CG-3M Autograv was programmed for 60 seconds (one reading per second for resultant average). The time of measurement

(HH/MM) was accurately recorded for each measurement. Data was recorded digitally by the microgravity meter as well as field notes maintained by the survey team.

2.7 Data Reduction

Corrections to measured field gravity were applied based on latitude and longitude, time of measurement, elevation of measurement, and instrument height data recorded by the field personnel for each survey station. Data reduction was facilitated by a computer program called Geosoft Oasis Montaj. Data reduction includes the following corrections:

1. Instrument Drift
2. Reference Ellipsoid (a function of latitude)
3. Earth Tide
4. Elevation (free-air effect)
5. Bouguer slab effect (density)

After all corrections have been calculated, the reduced data consists of a Simple Bouguer Gravity value for each measured point. Increasingly negative values for Bouguer gravity indicate greater deficits in mass below each measurement point. Graphic plotting of data produces a trend line that illustrates the relative fluctuations in gravity within the survey area.

2.8 Criteria for Interpreting Reduced Data

Reduced survey data consist of Simple Bouguer Gravity. Fluctuations in measured gravity can be attributed to changes in depth to bedrock, variations in density of competent subsurface materials, regolith voids and bedrock voids. Existing information on depth to bedrock were used to facilitate interpretation. The following criteria were used to guide interpretation of the reduced microgravity data:

- Anomalies are interpreted based on disconformity between local trends in measurements. This includes data sets with essentially "flat" graphic trends as well as trends which increase or decrease with horizontal distance. A gradually increasing or decreasing trend across a data set is often representative of depth to bedrock trends or regional gravity trends. Anomalies within a data set are identified as variations within such trends.

- Anomalies are interpreted based on magnitude. While neither the magnitude of the actual subsurface feature nor the depth to the feature can be concluded from survey data, greater magnitudes of disconformity within the data set indicate more probable detections of actual subsurface features, such as sediment-filled, water-filled or air-filled voids in the limestone bedrock or regolith.

- Symmetry of an anomaly within the data set indicates a more probable detection of actual subsurface features. Data sets exhibiting a gradual decrease from local average in Bouguer microgravity followed by a gradual increase to local average (i.e. a "bowl" shape) are considered more positive indicators of a low-gravity anomaly with less likelihood of instrument error. Single point anomalies are generally considered unreliable indicators of actual anomalies.

3. ELECTRICAL RESISTIVITY RESEARCH PROCEDURES

3.1 Introduction

Resistivity surveys provide an image of the subsurface resistivity distribution. Features that are not good conductors of electricity, such as air filled voids in the overburden or a cave in the bedrock, result in high resistivity anomalies. This makes the resistivity method a good exploratory technique for investigating karst subsurface features, or where depth to bedrock is needed. For more information on resistivity profiling please refer to Appendix (III).

3.2 Resistivity Research Procedures

Several different electrode configurations can be used to collect resistivity data. These include the Schlumberger, Wenner, Pole-Pole, Pole- Dipole, Square arrays, and Dipole-Dipole. The Dipole-Dipole array generally provides the highest precision, permits reasonable depth investigation and has the greatest sensitivity to horizontal resolution and data coverage. (Loke,1999).

3.3 Survey Layout

One electrical resistivity traverse was set up parallel to the south side of the eastbound lane; a second traverse was set up parallel to the roadway in the median while the third traverse was set up parallel to the north side of the westbound lane (Figure 1.2). The traverse on the south side and in the median overlay microgravity stations so that the data could be compared. Survey lines were marked with a wooden stake at the beginning and end of each traverse. The electrodes had a 20-foot spacing on each traverse. A 20-foot spacing was necessary in order to pick up data approximately 100 feet down.

3.4 Data Reduction and Interpretation

The resistance measurements gathered by the field survey are reduced to apparent resistivity values. This conversion was performed by using the AGI Administrator Version 1.1.0.4 program. The RES2DINV Version 3.44 program was then used to convert the apparent resistivity values into a resistivity profile model that can be used for interpretation.

The modeled results along a traverse are calibrated by comparing observed anomalies with physical data, such as, topographic maps, geologic quadrangles, rock outcrops, and drilling/boring data. Data interpretation of two-dimensional resistivity information in karst terrain using the Sting/Swift system is presented in Appendix (III).

4. RESULTS

4.1 General

The Profile trends depicted have not been smoothed or fitted and are based on careful selection of the most accurate 60 second readings at each station based on the following.

1. Readings which exhibit the lowest standard deviation were plotted where repeated 60 second measurements were made at a single station.
2. Where repeated 60 second measurements were made at a single station, selection was based on which tilt value was within +/- 5 arcseconds.
3. Where repeated 60 second measurements yielded similar standard deviation, a conservative selection was made of the reading which best conformed to the general trend exhibited by the traverse, i.e. a "best fit".

4.2 Microgravity Results

The microgravity survey data taken in the field are included in Appendix IV. The data, once corrected by OASIS Montaj program are included in Appendix V. Figures 4.1 through 4.3 show the microgravity data profiled along with the elevation of the ground surface.

In each of the traverses there are low gravity anomalies, ranging from 40 to 65 μgals in size, in the vicinity of the sagging roadway. It is also observed, in each of the traverses, that there is a steep decrease in gravity towards the end. Normal single point gravity fluctuations can be seen in each traverse, however some single point anomalies reflect the location of buried pipes and drainage conduits.

4.3 Electrical Resistivity Results

The electrical resistivity traverse on the south side is presented as Figure 4.4, Figure 4.5 shows the resistivity traverse in the median, and Figure 4.6 shows the data from the resistivity traverse on the north side. Each traverse resulted in data with low percent errors and displayed clear results.

Resistive areas appeared in the data below the road section experiencing sagging. These resistive areas could represent dry, competent bedrock or a non-conductive void. In the south and median traverses these resistive areas were isolated, such as with a void or pinnacle in the bedrock (Figure 4.4, Figure 4.5). In the north traverse, the resistive area appeared more as bedrock, stretching across the bottom of the profile and did not show any features of concern (Figure 4.6).

5. CONCLUSION

The low gravity anomalies indicated by the microgravity data and the resistive areas evident on the electrical resistivity in the traverses performed on the south and median sides of the eastbound lanes were compared. Figure 5.1 compares the microgravity data and electrical resistivity data along the south traverse. Figure 5.2 compares the microgravity data and electrical resistivity data along the median traverse.

It is possible that there could be a subsurface extension of the sinkhole depression approximately 200 feet south of the sagging section of the roadway (Figure 1.2). The water draining from the east and west of the investigated site collects in a low lying area approximately 50 feet to the south and then progresses towards the above mentioned sinkhole. The result of the downward movement of the water is illustrated in the resistivity along the south side traverse as an area of low resistivity in the vicinity of Station 400 (Figure 5.1). It is possible that this downward movement of water could be causing soil piping to occur subsurfacely into fractures in the underlying bedrock (Figure 5.3)

This could be the reason the microgravity anomaly on the south traverse appears larger than the anomalies indicated in the roadway and in the median. The small anomalies in the roadway and median could be a result of the subsurface extension of the collapse, only at a further distance. However, these smaller anomalies could also be depth to bedrock. According to the original ground surface, indicated on the map provided by the Kentucky Highways Department, the bedrock under this section of roadway was at a lower elevation. The microgravity and electrical resistivity data even appear to mimic the remnant contours of the bedrock (Figure 5.4).

6. RECOMMENDATIONS

This area needs to be further investigated in order to determine of sinkhole activity is extending into the vicinity of the sagging road. A direct approach, such as drilling, is recommended. Locations along the south side of the roadway should be explored for voids or unconsolidated material that may be moving downward with water. Stations 230, 330 and 460 should be drilled along the microgravity south traverse. This will help to better understand the low gravity anomaly by further investigating two stations outside of the anomaly, 230 and 460, and one station in the center of the anomaly, 330. It is also recommended to drill at station 400 in order to get a better detail to the low resistivity area below this point. It is also important to compare the low gravity anomalies seen in the south and median traverses. That way, it may be determined whether the low gravity detected underneath the median traverse is a result of the same conditions underlying the south traverse. To do this Stations 230, 320 and 460 should be drilled. A copy of the drilling records should then be returned to the Center for Cave and Karst Studies for further interpretation.

It is important to prevent water moving downward at the site from washing soil downward with it. Lined concrete ditches, rather than perforated pipes and "V" ditches should be used to direct water. If during the drilling investigations at least one unclogged crevice of sufficient size is discovered a drainage well should be installed at that location. Usually, a drainage well is "punched-in" with a cable tool drilling rig. The pounding motion of the cable tool bit forces water in and out of small mud-filled crevices within the limestone, such as a solutionally enlarged joint or bedding plane parting. This develops the well by washing mud out of the crevices. However, since drainage wells should develop themselves naturally by repeatedly filling and draining, development during the drilling process is inconsequential and a rotary drilling rig can be used. The well should also be cased to bedrock, and sealed at the regolith-bedrock interface (Crawford, 1989). If during the drilling investigation no crevice is discovered through which a drainage well can be established, the lined drainage ditches should extend into the basin so that if further subsidence and/or a possible collapse occurs, it will be further from the roadway.

7. REFERENCES

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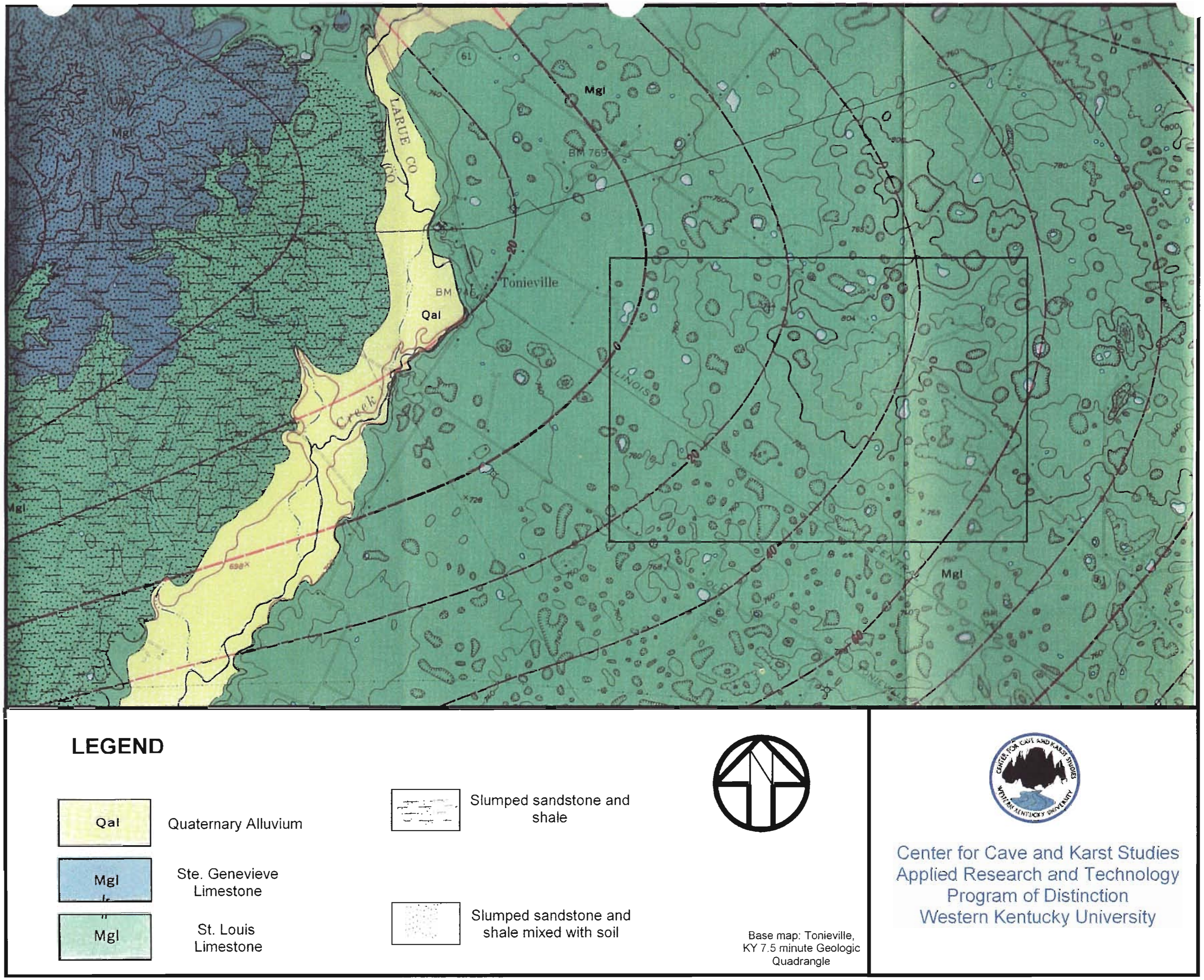

Figure 1.1: Portion of the Tonieville, KY 7.5 minute Geologic Quadrangle that contains the investigated site.

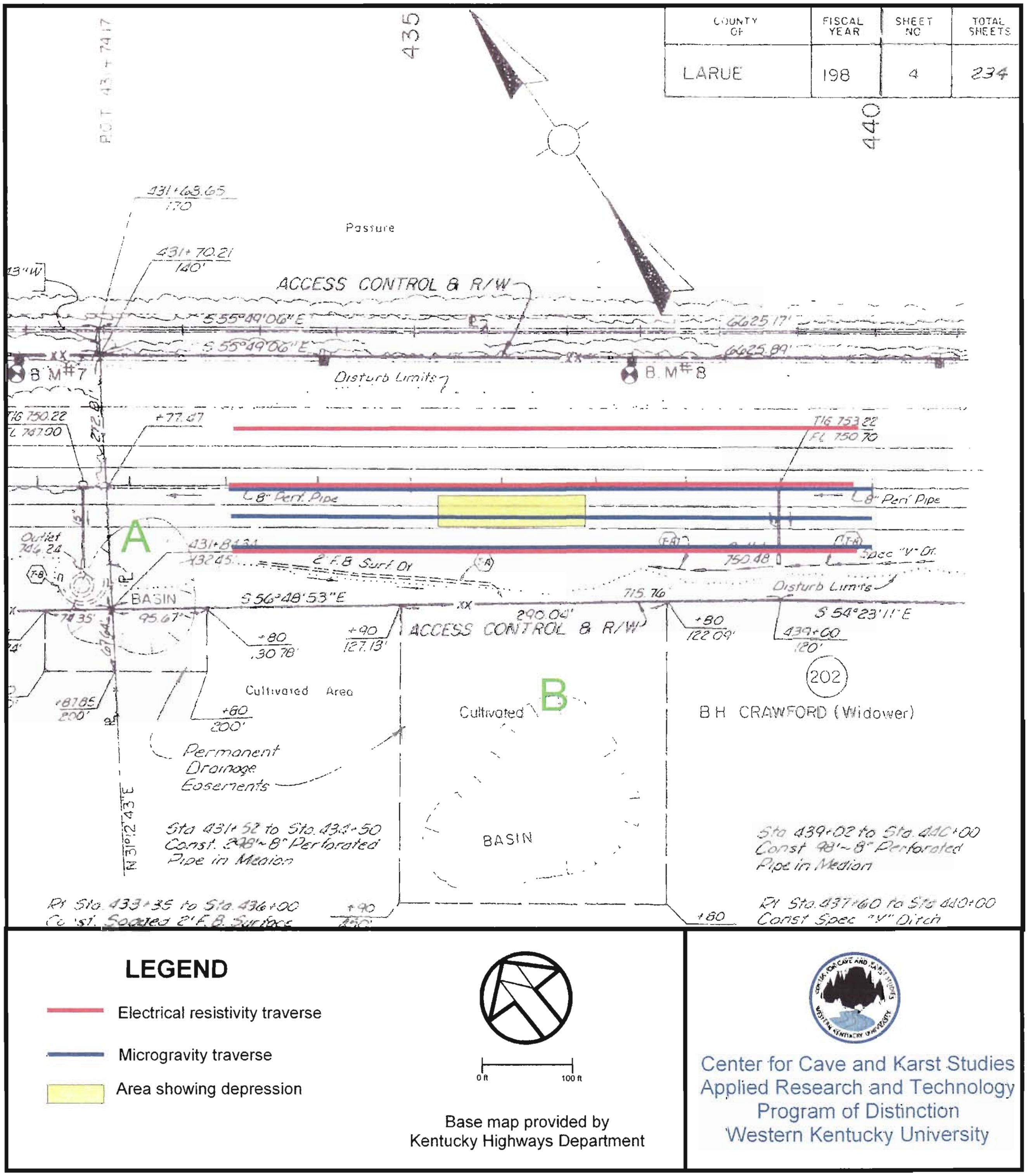

Figure 1.2: Map showing investigated area including microgravity and electrical resistivity traverse layout.

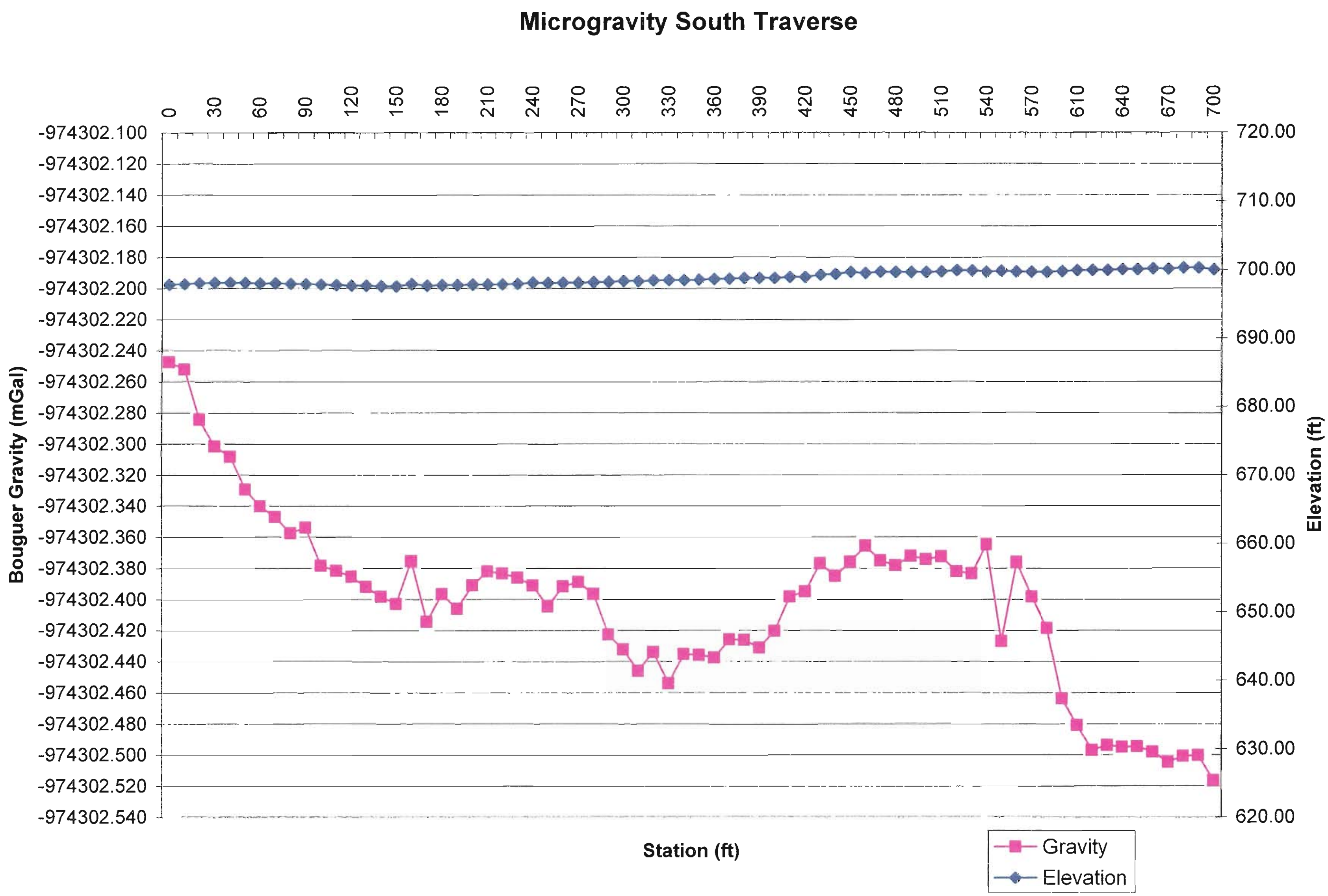

Figure 4.1: Microgravity data profile with surface elevation along the south side.

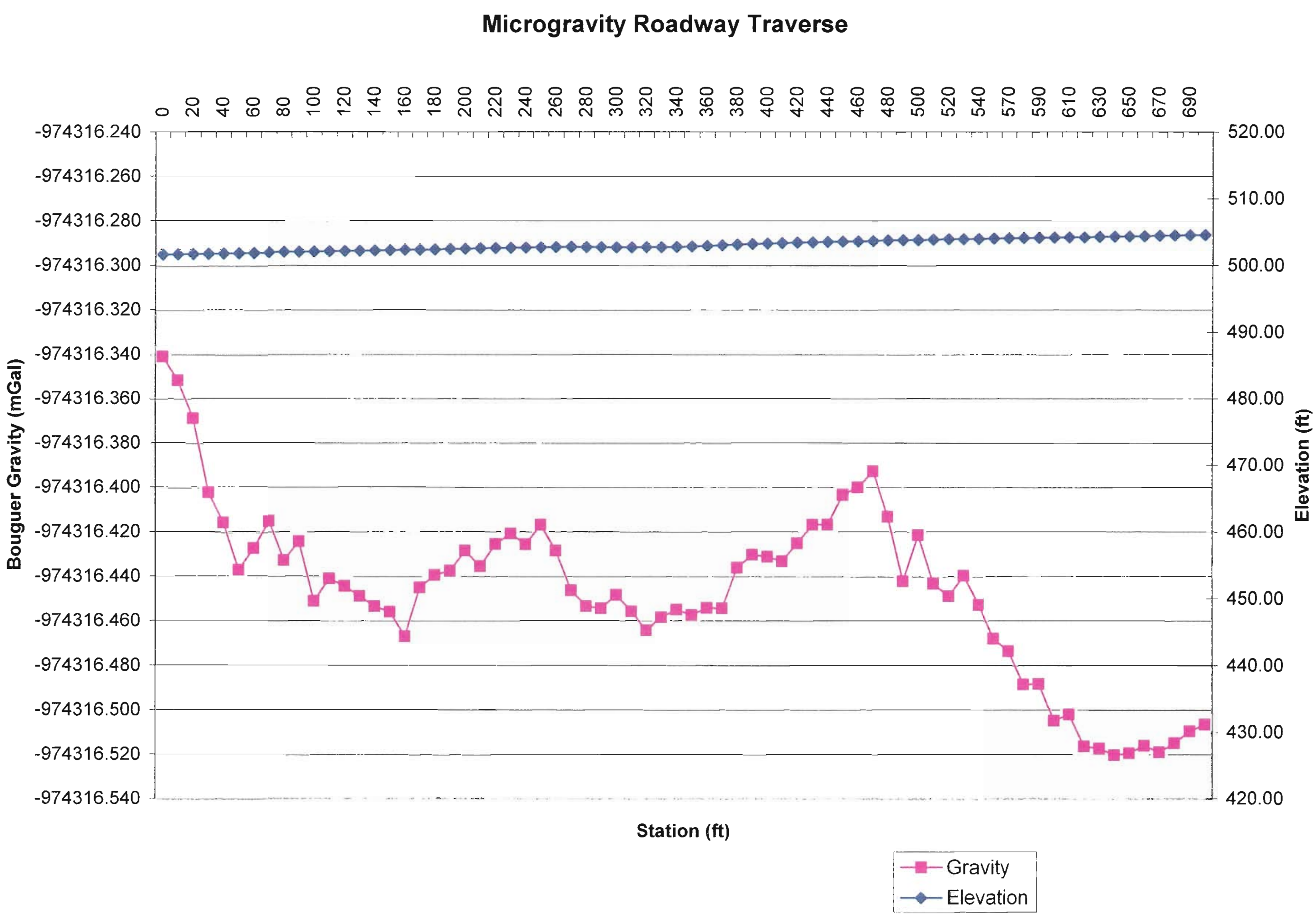

Figure 4.2: Microgravity data profile with surface elevation along the roadway.

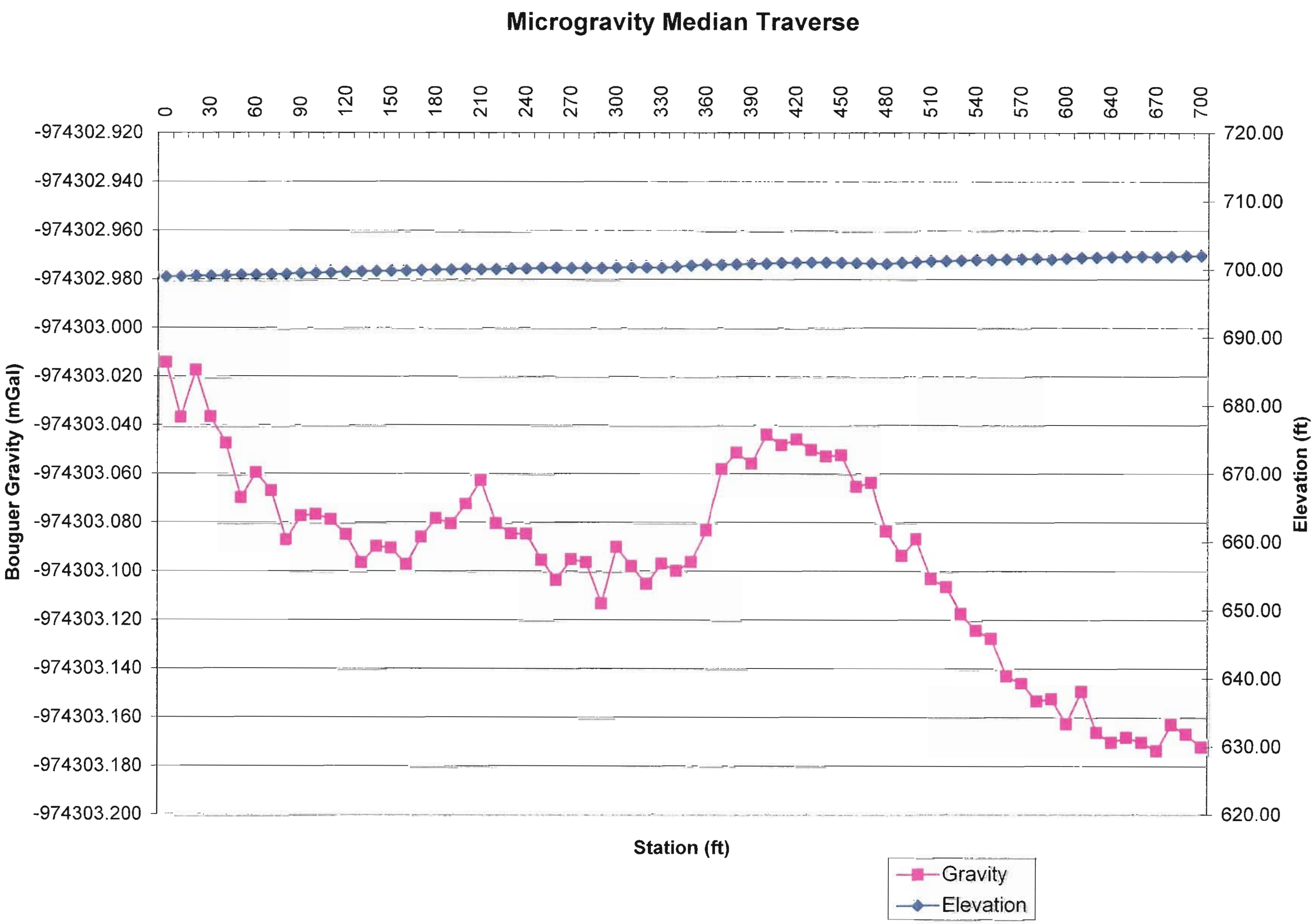

Figure 4.3: Microgravity data profile with surface elevation along the median.

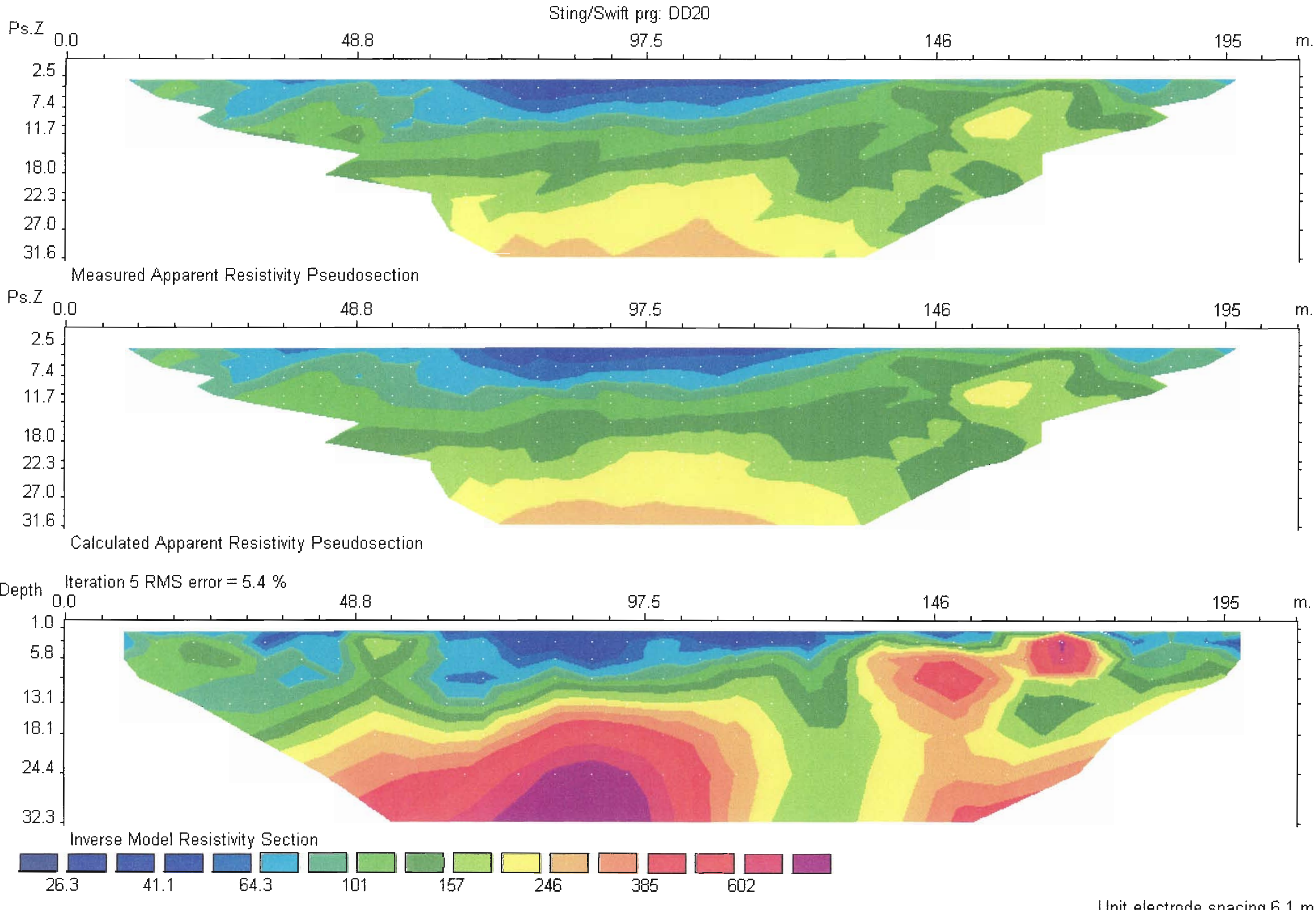

Figure 4.4: Electrical resistivity profile along the south traverse.

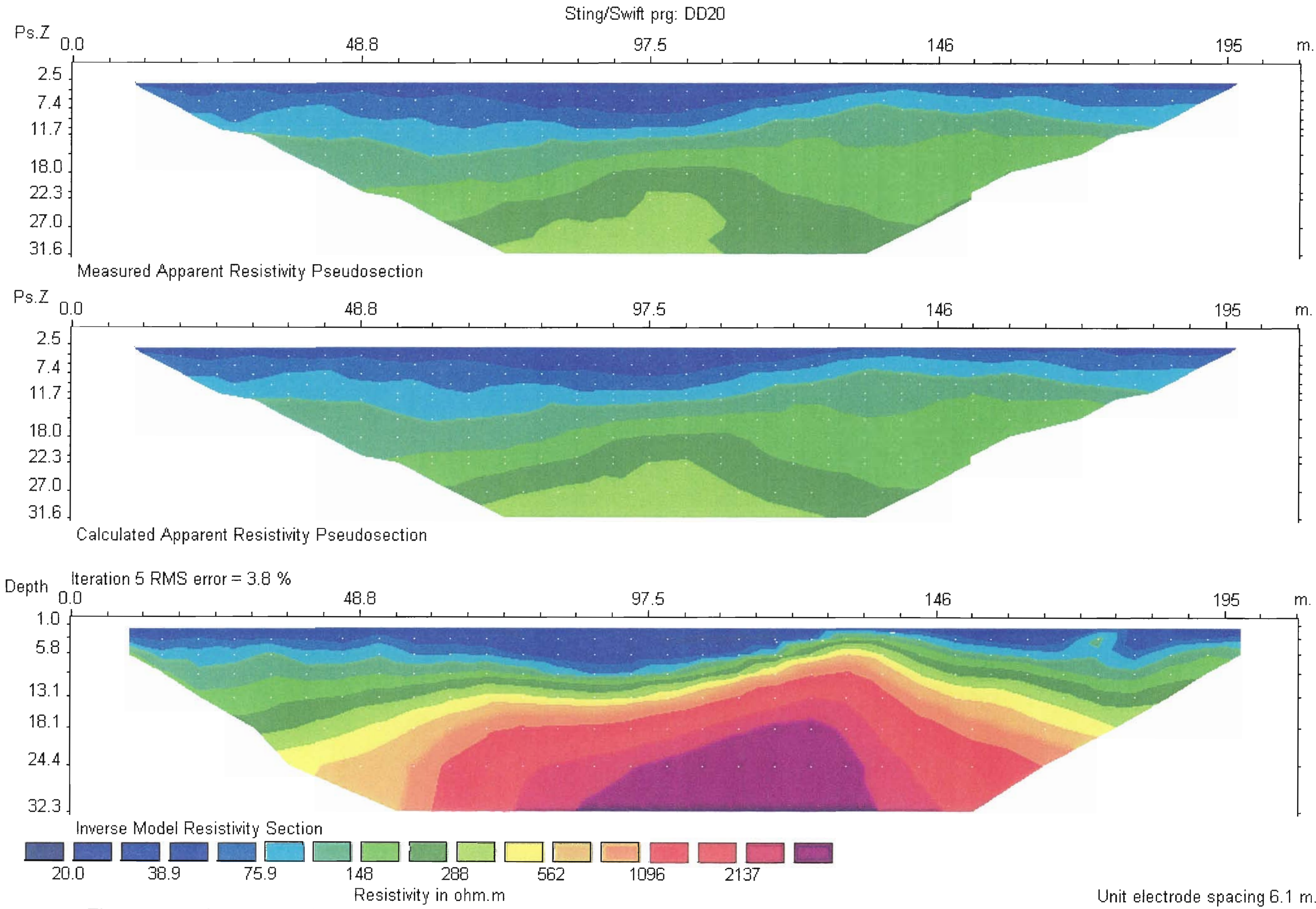

Figure 4.5: Electrical resistivity profile along the median traverse.

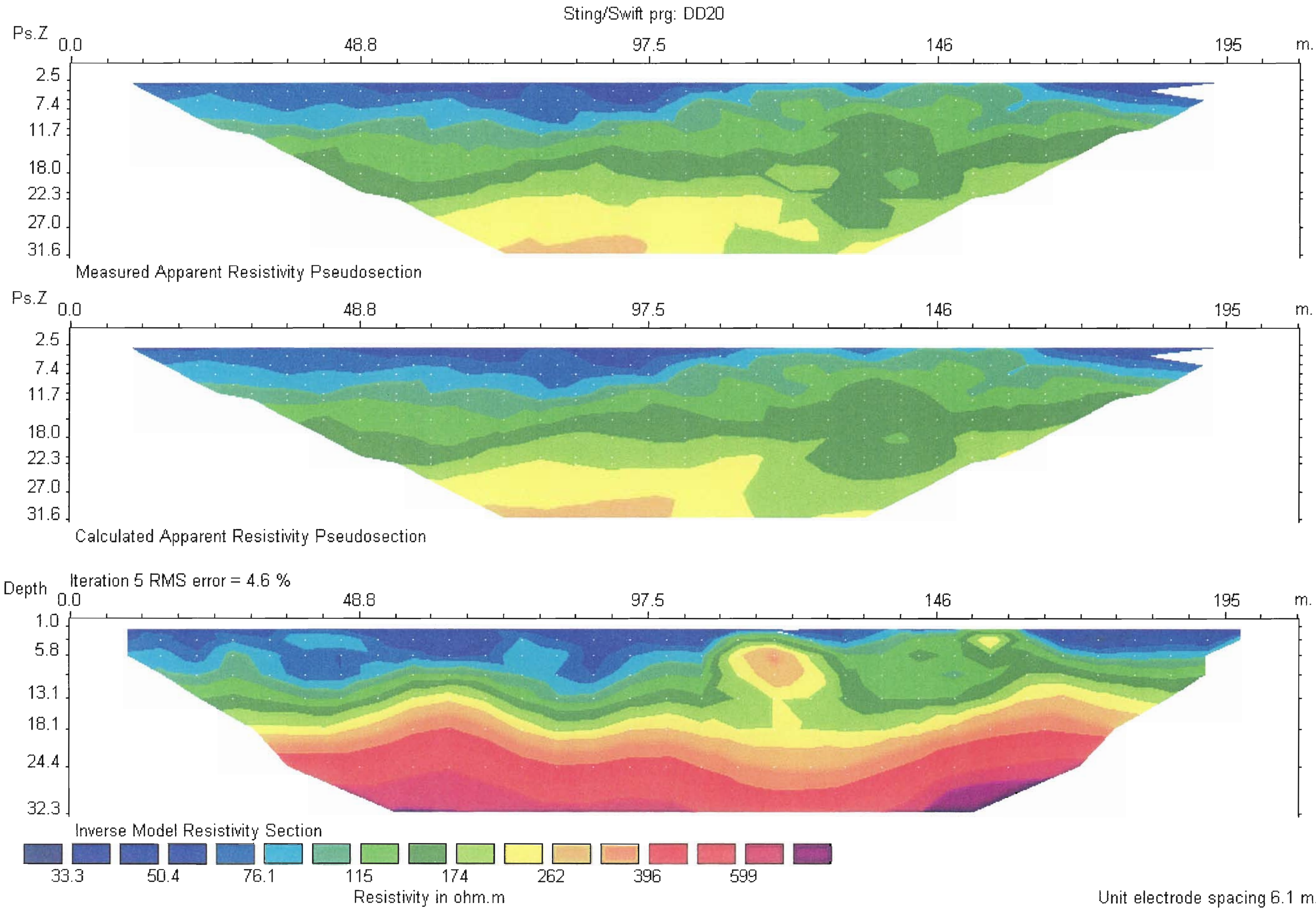

Figure 4.6: Electrical resistivity profile along the north traverse.

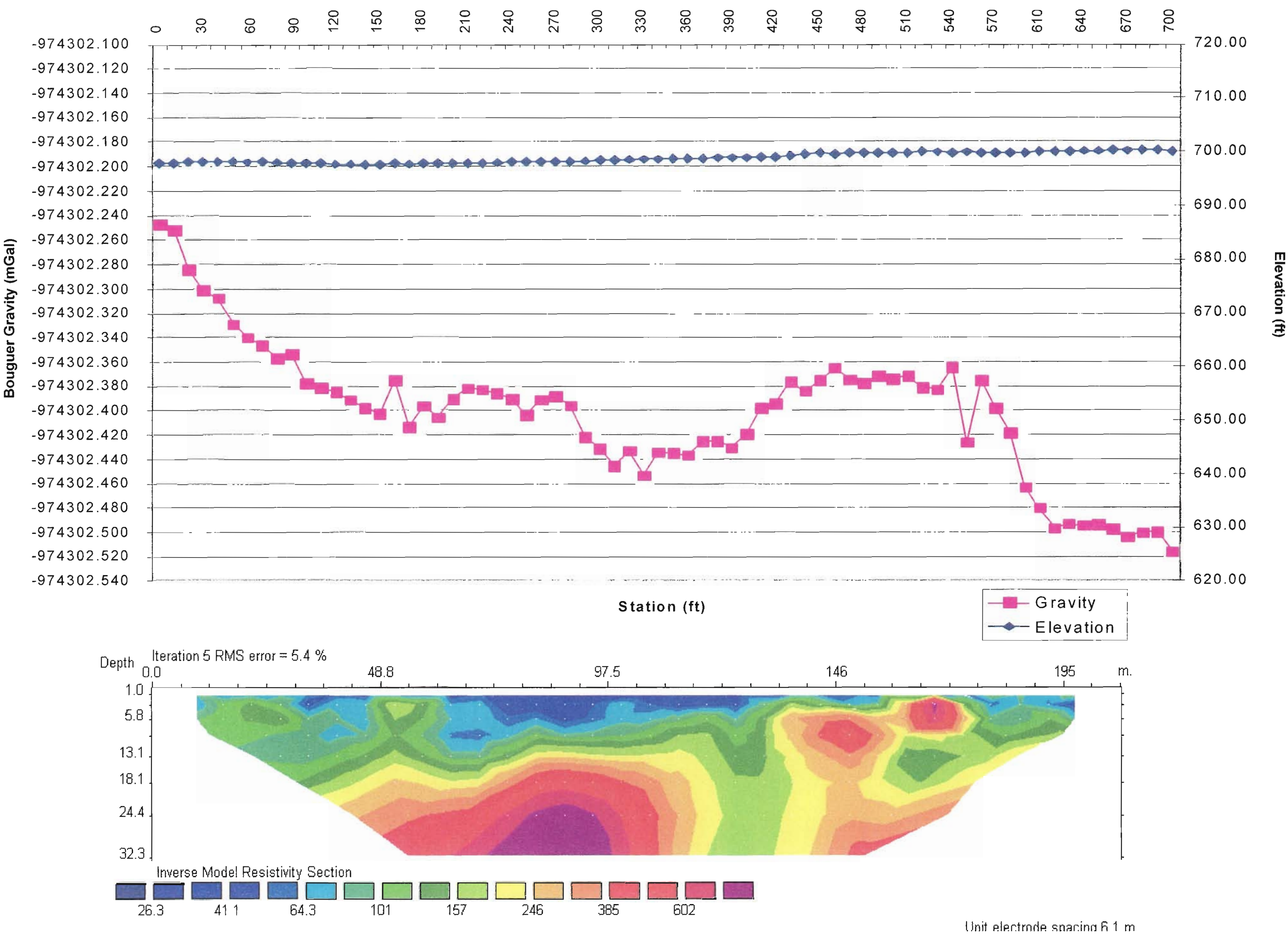

Figure 5.1: Microgravity overlying electrical resistivity from the south traverse.

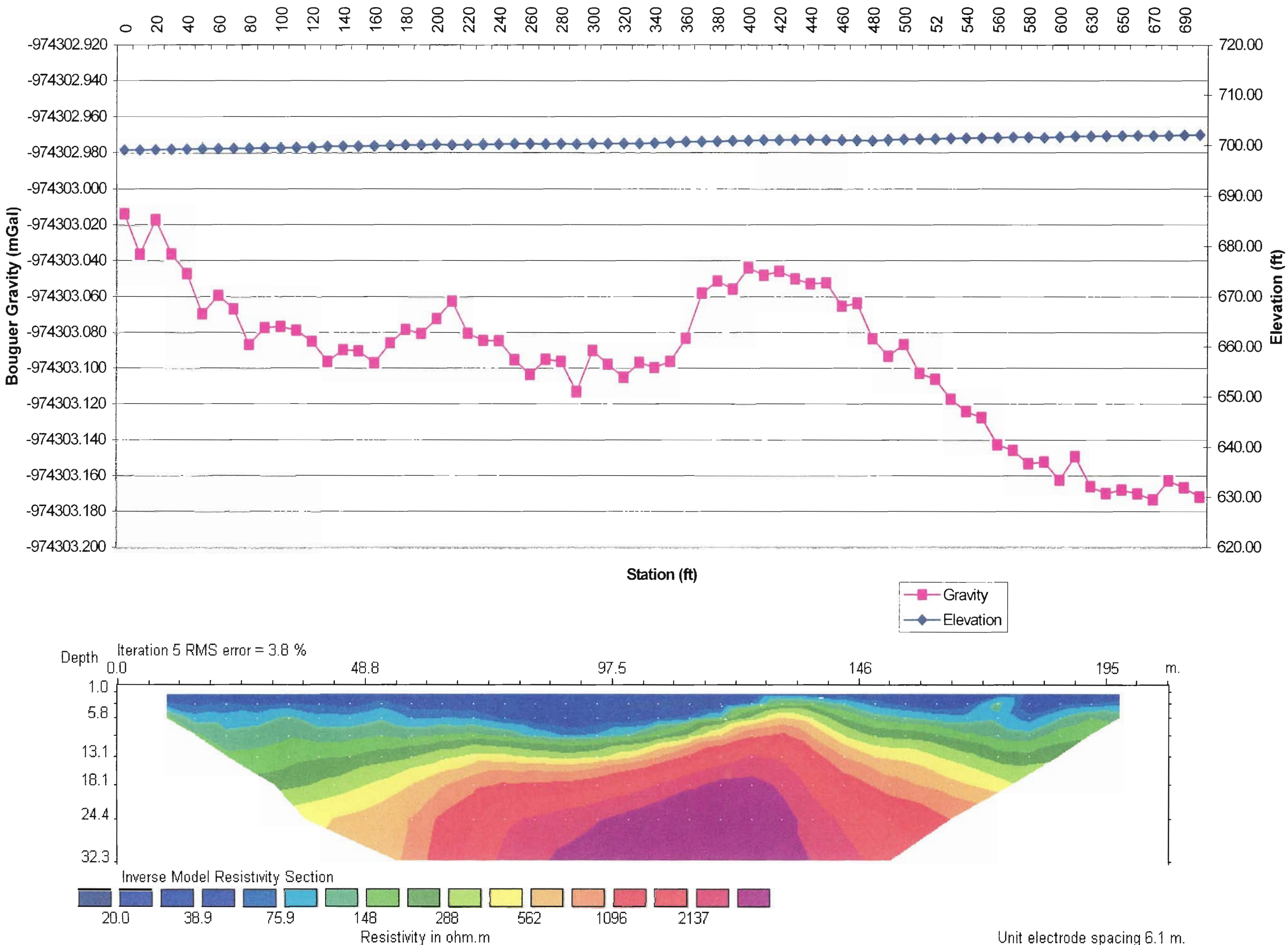

Figure 5.2: Microgravity overlying electrical resistivity from the median traverse.

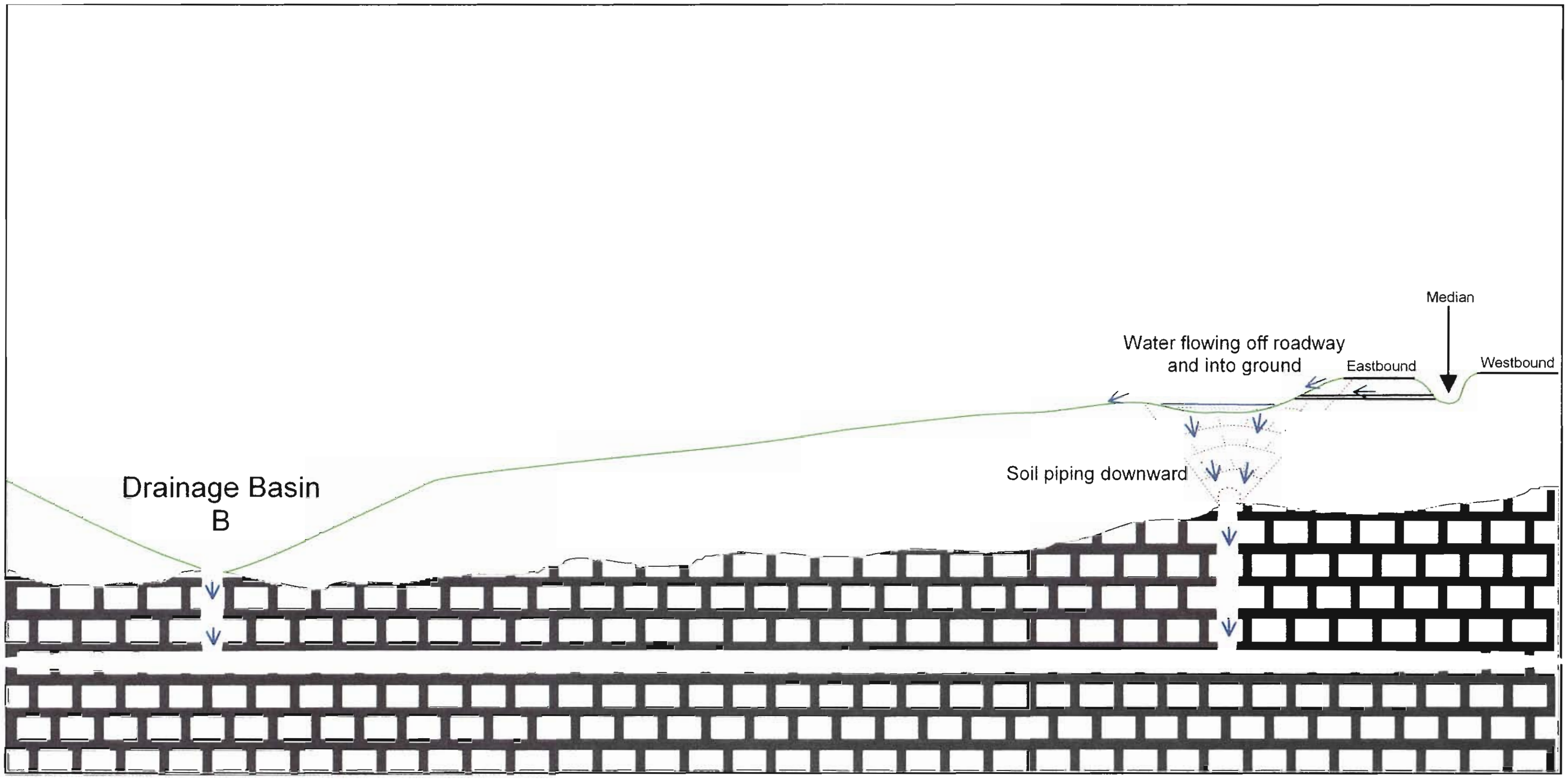

Figure 5.3: Conceptual diagram of soil piping occurring south of the eastbound lane.

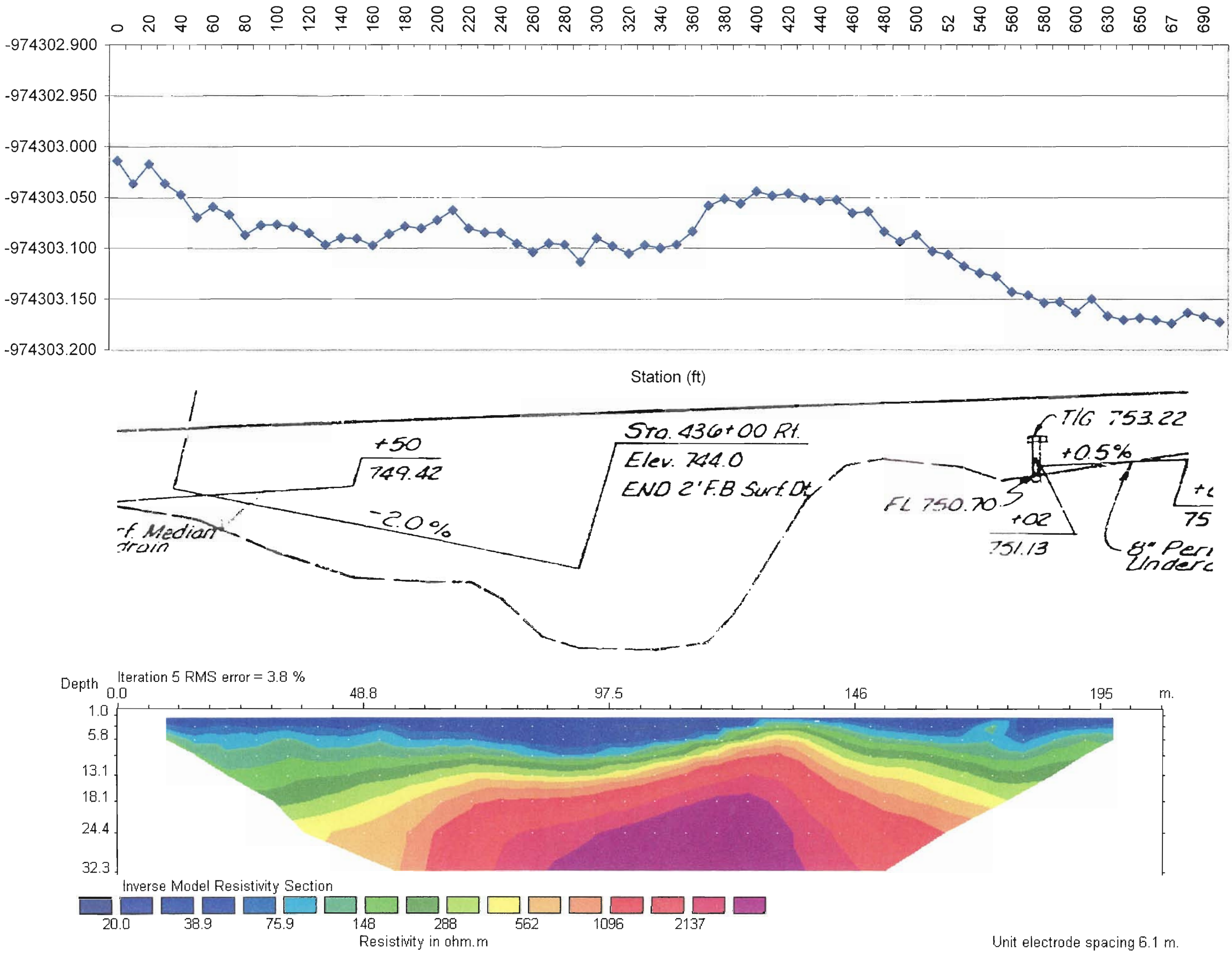

Figure 5.4: Micrgravity and electrical resistivity compared to the original ground profile in the median.

APPENDIX D

US 27 Report

MICROGRAVITY SUBSURFACE INVESTIGATION AND CAVE SURVEY OF THE PROPOSED US HWY 27 ROUTE, SOMERSET, KENTUCKY

Prepared for:

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Submitted by:

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MICROGRAVITY SUBSURFACE INVESTIGATION AND CAVE SURVEY OF THE PROPOSED US HWY 27 ROUTE, SOMERSET, KENTUCKY

Center for Cave and Karst Studies

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Center for Cave and Karst Studies

INTRODUCTION

The Center for Cave and Karst Studies was subcontracted by Florence and Hutcheson, Inc. to perform a geophysical survey including microgravity traversing and electrical resistivity testing along with cave exploration and mapping in the vicinity of the proposed US Hwy 27 in Pulaski County, Kentucky between markers 1064+00 and 1088+00.

1.1 Location

The site is located near the town of Somerset, Kentucky (Figure 1-1). The investigated site is contained in a section of the proposed route that runs parallel to the current Hwy 27 route.

1.1 Geology

Geology in the vicinity of the site consists of one exposed lithologic unit: the St. Louis Limestone. Based on the Geologic Map of the Delmer Quadrangle (Lewis, 1971) this unit is exposed at the surface in the vicinity of the Site (Figure 1-2). Within the St. Louis Limestone there are limestones, siltstones, and chert. The uppermost facies is a limestone that can be very dark to medium gray, sublithographic to medium grained, thin to thick bedded. It is also interbedded with siltstone. This siltstone is more abundant in the lower portions of the unit. A more courser grained, cleaner limestone is found in the upper levels of the unit. The limestone is also commonly cherty, with chert as pods, stringers and irregular masses. The base of the unit contains greenish-gray claystone that weathers to green clay.

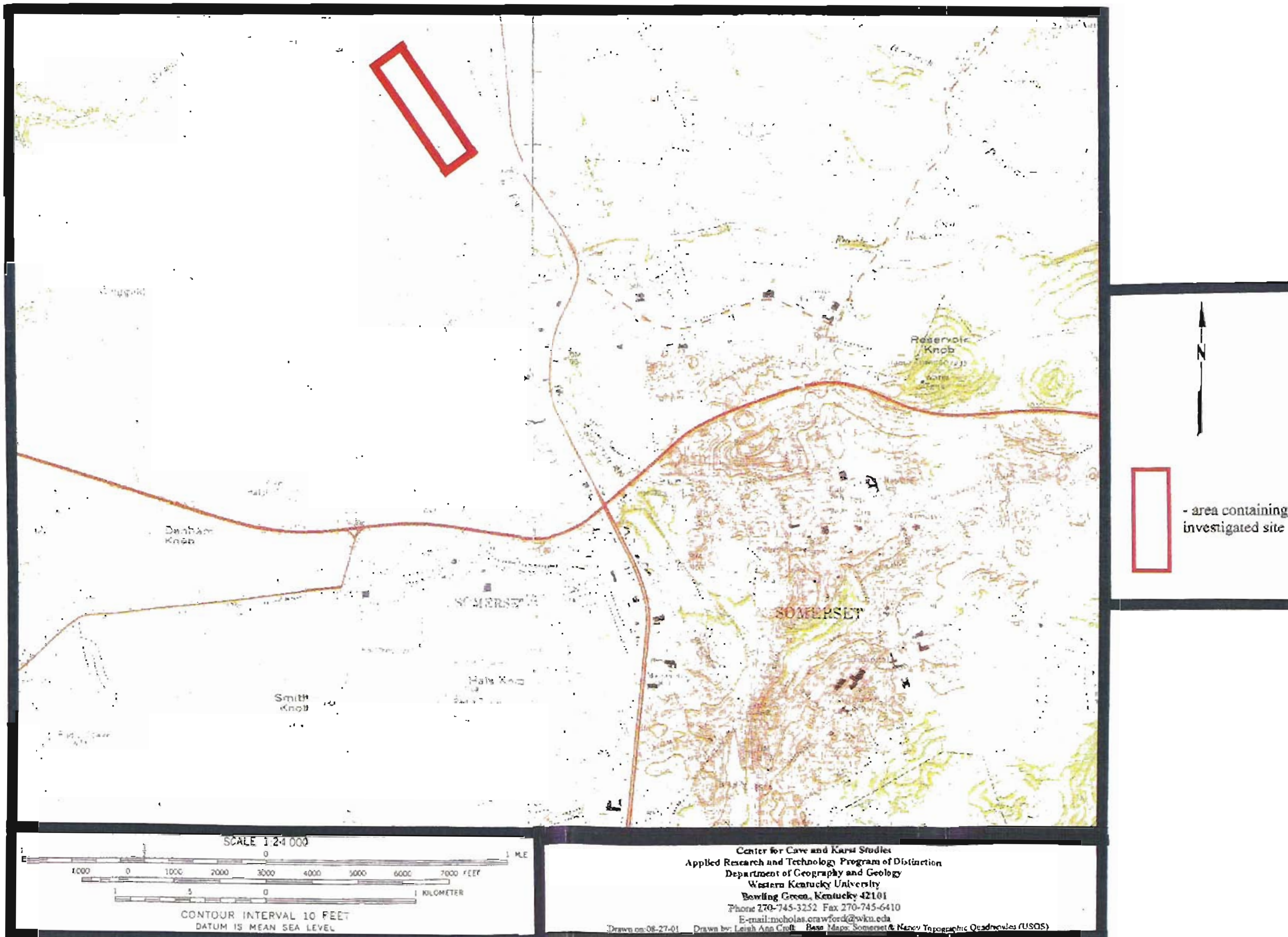
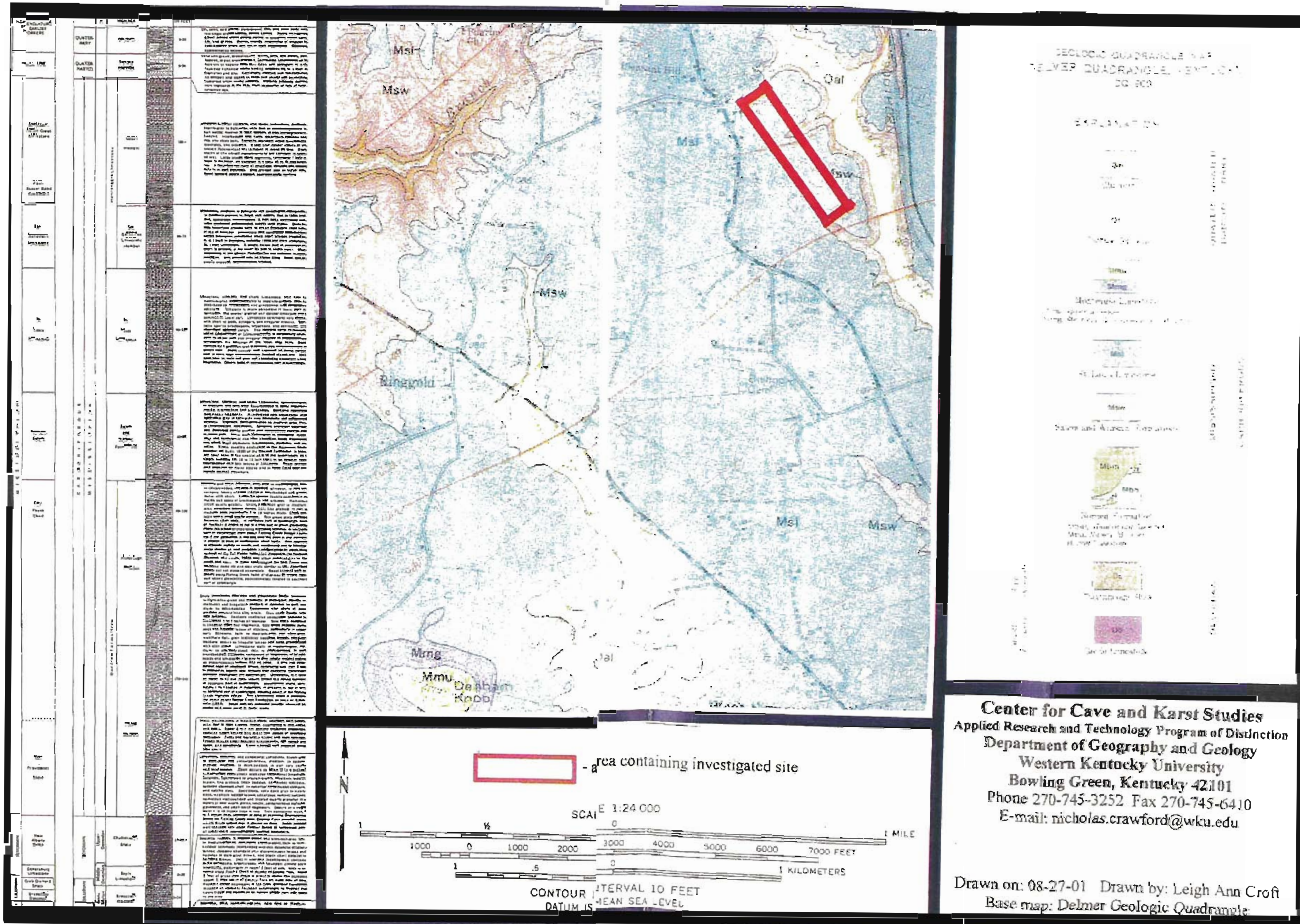


Figure 1-1 Map showing location of investigated site.


GEOLOGIC QUADRANGLE MAP
DELMER QUADRANGLE, KENTUCKY
GQ 903
EXPLANATION
Msl
Msw
Qal
Mmg
Mmu
Denham Knob
Ringgold
- area containing investigated site
SCALE 1:24 000
1 MILE
7000 FEET
1 KILOMETERS
CONTOUR INTERVAL 10 FEET
DATUM IS MEAN SEA LEVEL
N
Center for Cave and Karst Studies
Applied Research and Technology Program of Distinction
Department of Geography and Geology
Western Kentucky University
Bowling Green, Kentucky 42101
Phone 270-745-3252 Fax 270-745-6410
E-mail: nicholas.crawford@wku.edu
Drawn on: 08-27-01 Drawn by: Leigh Ann Croft
Base map: Delmer Geologic Quadrangle

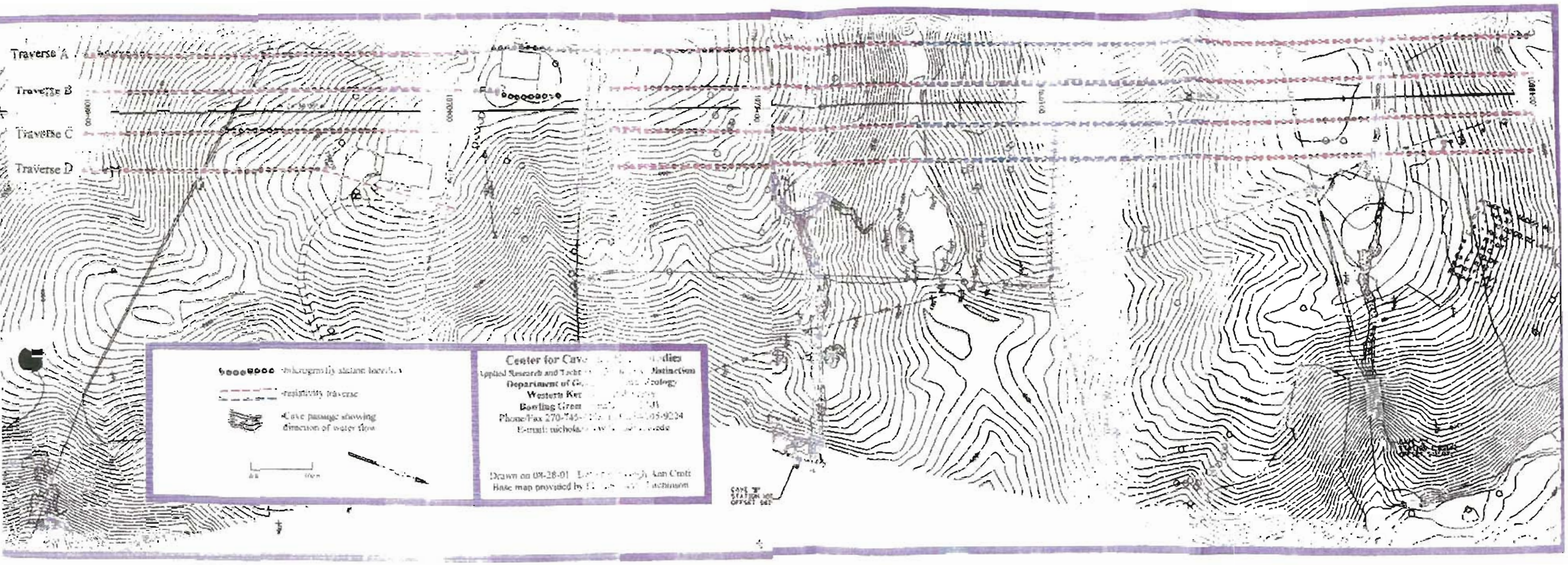


Figure 1-3 Map showing site layout

1.3 Area Investigated

The area contained four traverses 64 feet apart. Line A was established 96 feet from the centerline, beyond the ditch area of the proposed southbound side of the highway. Line B ran 32 feet from the centerline, down the center of the two southbound lanes. Line C was established 32 feet off the centerline, down the center of the two northbound lanes. Line D was 96 feet off the center. This is beyond the ditch area for the northbound side. Each line was approximately 2400 ft long. The area investigated ran across three individually owned tracts of land, each containing a cave that was surveyed in order to determine if it ran underneath the proposed road site (Figure 1-3).

1.4 Microgravity

Microgravity was run along each of the four traverses. The method used in the investigation involved the use of a Scintrex CG-3M Autograv Microgravity Meter. The purpose of this study was to use Bouguer gravity techniques in order to detect and further delineate possible voids in the overburden and/or bedrock caves existing or potential sinkhole collapses and variations in depth to bedrock under the proposed roadway. Microgravity traverses were established parallel to the centerline on both the northbound and the southbound lanes and measurements were taken at a ten feet spacing interval. The data are presented showing both the Bouguer gravity in Microgals and the elevation along the traverse.

1.5 Resistivity

Resistivity was measured along each of the four traverses. Electrical resistivity measures the resistivity of the subsurface material to the transmission of an induced electrical current. The method used in the electrical resistivity testing involved the use of a Sting/Swift Resistivity meter. A Dipole-Dipole array of electrode placement was used to detect subsurface areas less conductive then their surroundings. The data are presented showing the modeled resistivity profile beneath the microgravity measurements at the same coordinates, along each traverse.

1.6 Cave Survey

The three known cave at the site were explored and the caves mapped using a Suunto compass, clinometer and cloth tape. Backsites were taken to within one degree. The cave passages were surveyed and sketched and profile sections of the cave dimensions are provided on the cave maps.

2. MICROGRAVITY RESEARCH PROCEDURES

2.1 Introduction

Gravity surveys are used to detect variation in the density of subsurface materials. Variations in the earth's gravitational field higher than normal indicate underlying material of higher density while areas of low gravity indicate areas of lower density. In order to detect voids or cavities, very high precision is required. Accurate gravity readings to 10 microGals (1 Gal = 1 cm/s^2) are necessary. This is equal to 1 part in 100,000,000 of the earth's normal gravity. A SCINTREX CG-3M Autograv Microgravity Meter that has a 0.5-microGal sensitivity was used for this investigation. Microgravity data gathered within the investigated site can be seen as Figures 2-1 through 2-18. For a more detailed discussion of microgravity as a method for detection of subsurface features in highway situations and Center for Cave and Karst Studies experience with this method, please refer to Appendices (I) and (II).

2.2 Microgravity Research Procedures

The SCINTREX CG-3M Autograv underwent a 48-hour stabilization period prior to field use. Field calibration was performed on the instrument and consisted of a long-term drift correction and temperature compensation adjustment.

The following corrections was calculated for each gravity measurement:

- Instrument Drift (short term),
- Earth Tides,

- Reference Ellipsoid (latitude),
- Free-Air Effect (elevation), and
- Bouguer Slab Density

A base station was established at the survey site and gravity was repeatedly measured at this base station approximately every two hours in order to derive instrument drift. A base station derived instrument drift curve was interpolated to the time of each survey station reading and each station reading was then corrected for instrument drift by the Geosoft OASIS Montaj reduction program.

Earth tide corrections are based on latitude and longitude of the survey station and the gravitational effect of the sun and moon at any given point in time. This correction was made for each gravity reading using latitude and longitude derived from a GPS measurement made at the site and determined by recording date and time for each instrument reading (converted to UTC for calculations). The reference ellipsoid correction is necessary because the earth is an imperfect sphere with gravitational variation as a function of latitude.

Differences in elevation between each survey station and the base station were compensated for using the free-air correction calculation. The free-air effect compensates for the decrease in gravity with elevation due to increasing distance from the center of the earth. Elevation for each microgravity survey station was sighted to the nearest hundred of a foot and instrument height was measured to the nearest 1/10 of an inch at each station.

Theoretical gravity is modified to obtain simple Bouguer gravity by applying the Bouguer slab effect correction. This correction refers to the attraction of the slab of material, which is caused by variation in density, between the station elevation and sea level. Topographic relief across the survey site did not require terrain corrections to be applied to the data set.
In most karst areas, the following average density values are assumed:

Air = 0 g/cm^3 Water = 1.0 g/cm^3 Clay = 2.21 g/cm^3 Sandstone = 2.35g/cm^3

Regolith or cave sediments = 1.5 g/cm^3 Limestone = 2.5 g/cm^3

Therefore, density contrasts of –1.0 to 2.5 g/cm^3 are anticipated for any subsurface cavity, depending on whether the cavity is filled with air, water or sediment.

Although microgravity subsurface investigations usually consist of measuring at stations established in a grid pattern, Crawford, Webster, and Winter (1989) have demonstrated the effectiveness of using traverses established perpendicular to linear subsurface features and groundwater flow paths for the detection of caves.

2.3 Detection of Subsurface Features in Karst Terrain

Bouguer gravity can identify locations on the earth's surface that have relatively higher or lower gravity caused by lateral variations in subsurface density. Crawford (1995) has used microgravity extensively to locate bedrock caves from the ground surface (Appendix II). The lower densities of the air, water or mud within a cave compared to the surrounding carbonate rock results in a low- gravity anomaly. Crawford has also used microgravity to locate voids in the regolith (unconsolidated material above bedrock) that are potential sinkhole collapses. Since regolith is less dense that limestone bedrock, Bouguer gravity can also identify variations in depth to bedrock.

2.4 Microgravity Used for Sinkhole Collapse Investigations

Crawford has used microgravity to investigate subsurface conditions in the vicinity of sinkhole collapses. Microgravity provides useful information concerning a) depth to bedrock, b) extent and shape of the void below the surface, c) location of the crevice, or crevices, through which regolith and water are sinking and d) additional regolith voids in the vicinity. Appendix I further details the use of microgravity for sinkhole collapse investigations.

2.5 Survey Layout

Survey lines were marked parallel to the centerline by placing a labeled wooded stake at each location a microgravity measurement was to be taken. The stakes were labeled with both the letter of the line and the location of the stake in feet along the traverse. The locations of the stakes were determined by using a compass to remain perpendicular to the centerline survey stakes provided, and a cloth tape to set each station 10 feet apart. Base stations were established at multiple locations in the study area in order to measure the changes in drift during the time microgravity measurements were being made.

2.6 Field Method

The SCINTREX CG-3M Autograv microgravity meter used for this survey provided the following on-board data corrections:

1. Continuous Tilt Correction—for instrument level.
2. Seismic Filter—for interference caused by vibration.
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2.7 Data Reduction

Corrections to measured field gravity were applied based on latitude and longitude, time of measurement, elevation of measurement, and instrument height data recorded by the field personnel for each survey station. A computer program called Geosoft Oasis Montaj facilitated data reduction. Data reduction includes the following corrections:

1. Instrument Drift
2. Reference Ellipsoid (a function of latitude)

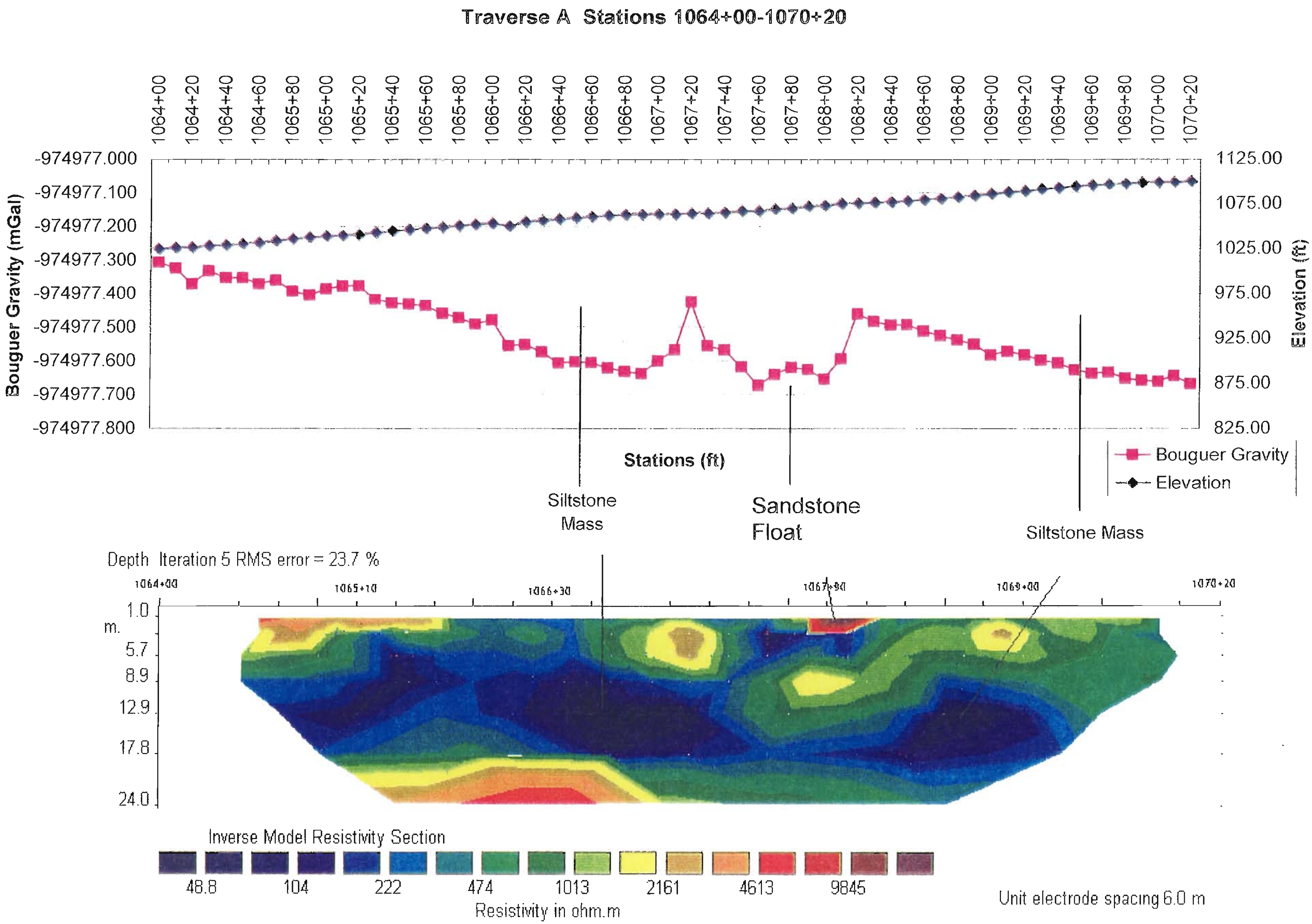
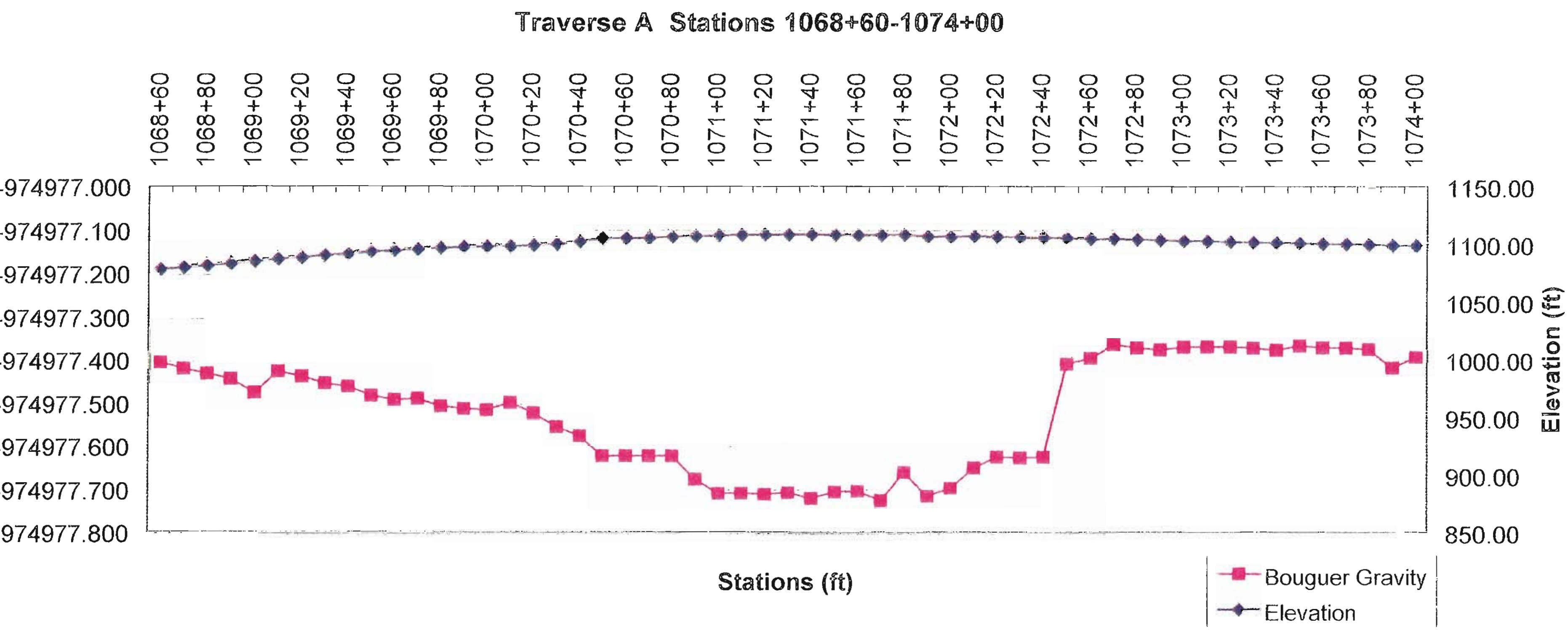


Figure 2-1 Microgravity, elevation, and resistivity data for Traverse A, stations 1064+00-1070+20



DATA NOT INTERPRETABLE

Figure 2-2 Microgravity, elevation and resistivity data for Traverse A, stations 1068+60-1074+00

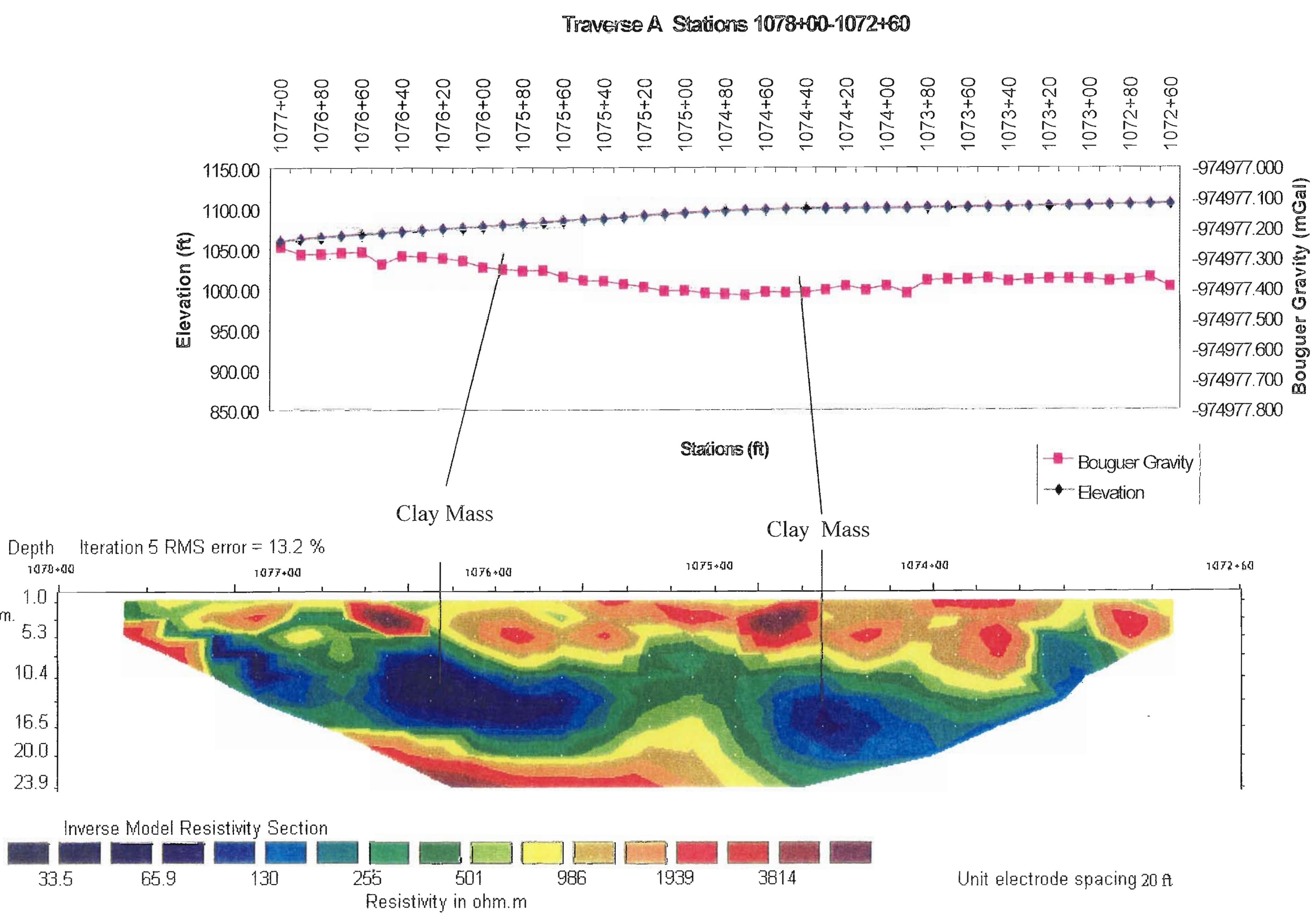


Figure 2-3 Microgravity, elevation and resistivity data for Traverse A, stations 1078+00-1072+60

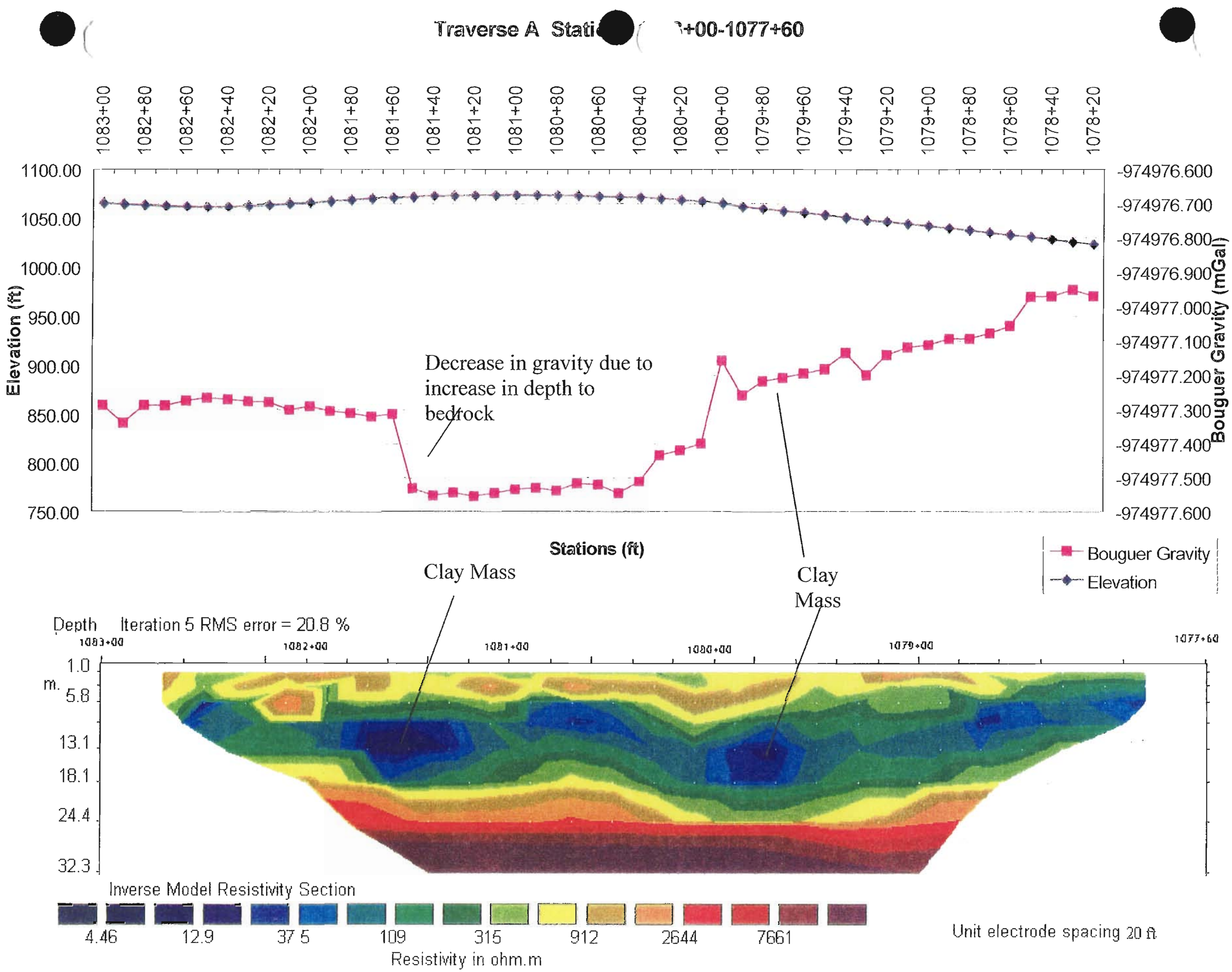


Figure 2-4 Microgravity, elevation and resistivity data for Traverse A, Stations 1083+00-1077+60

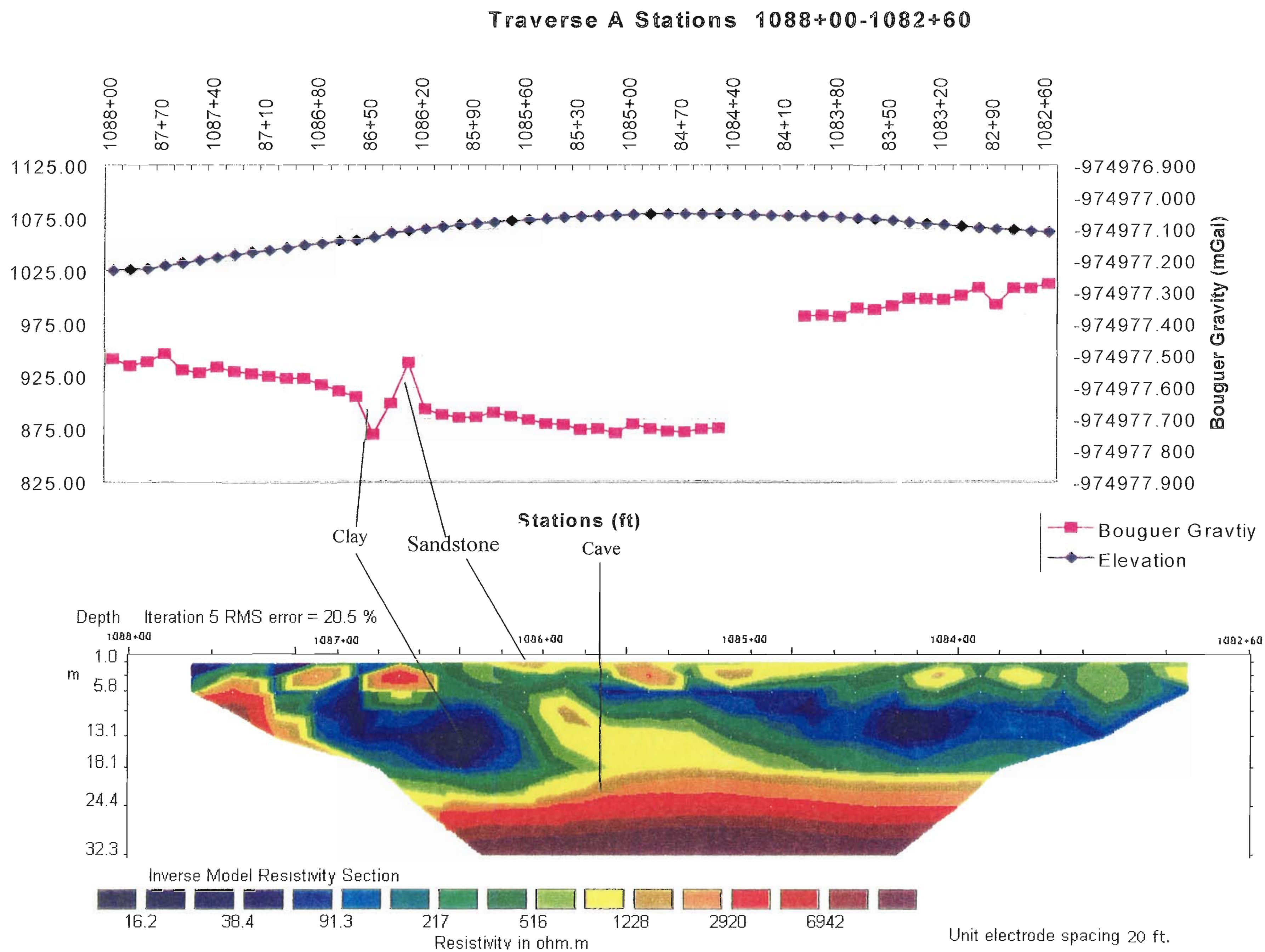
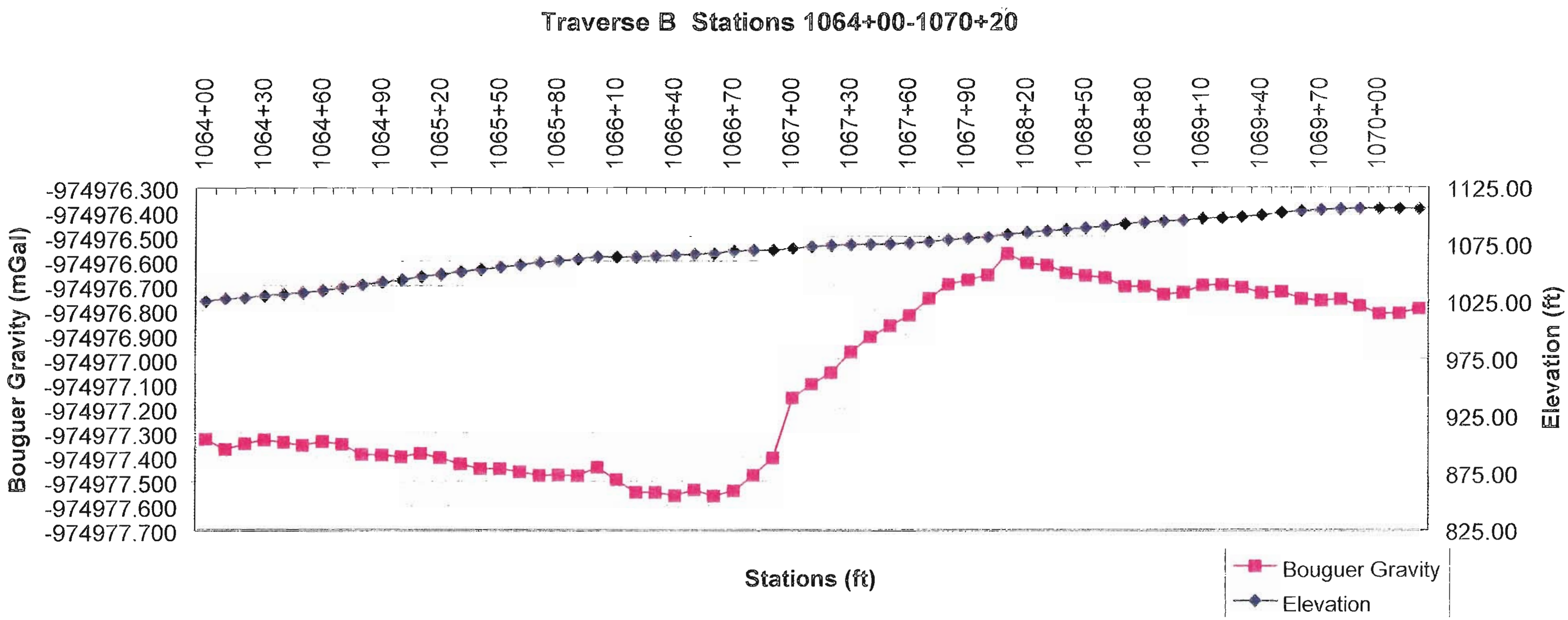


Figure 2-5 Microgravity, elevation and resistivity data for Traverse A, stations 1088+00-1082+60



DATA NOT INTERPRETABLE

Figure 2-6 Microgravity, elevation, and resistivity data for Traverse B, stations 1064+00-1070+20

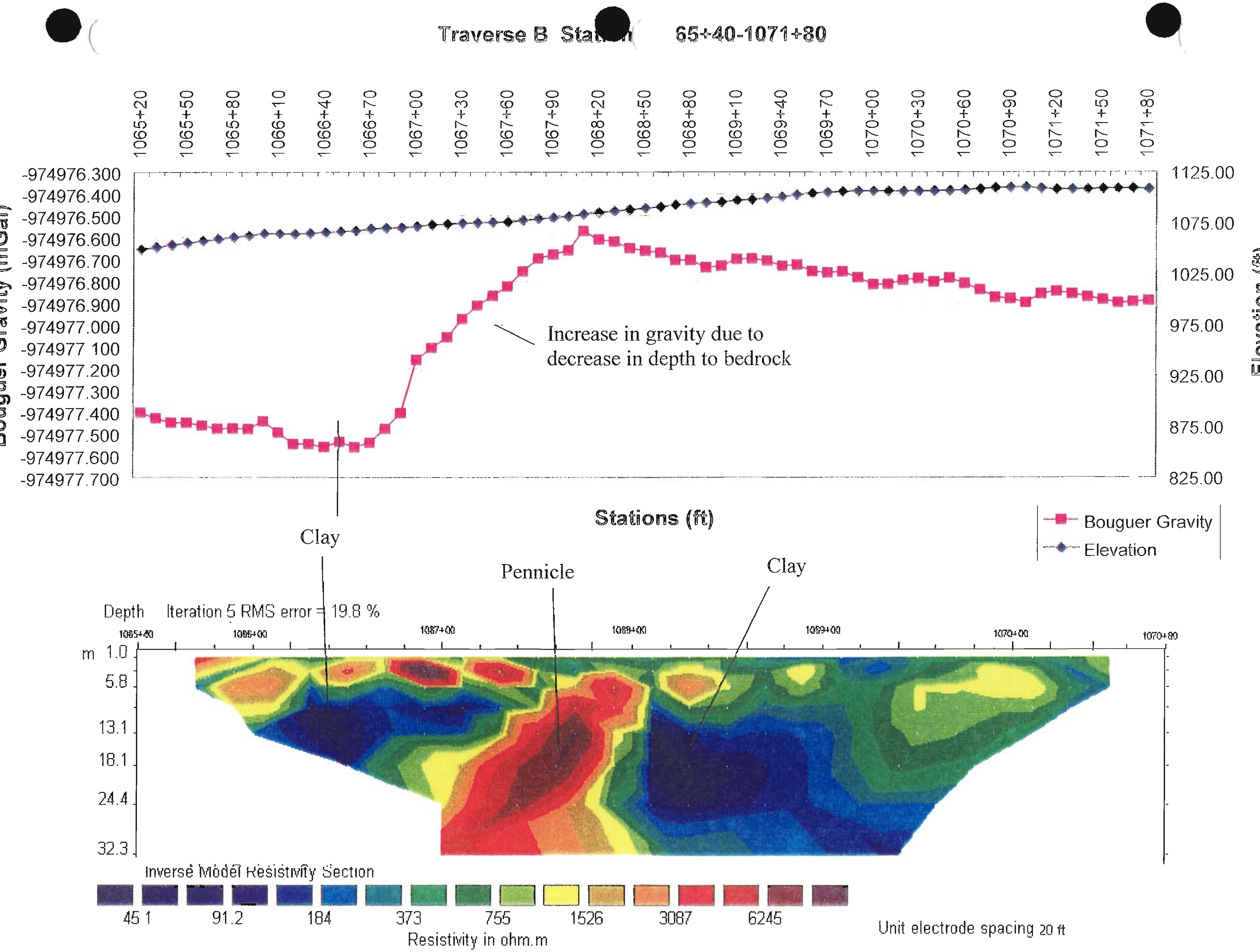


Figure 2-7 Microgravity, elevation, and resistivity data for Traverse B, stations 1065+40-1071+80

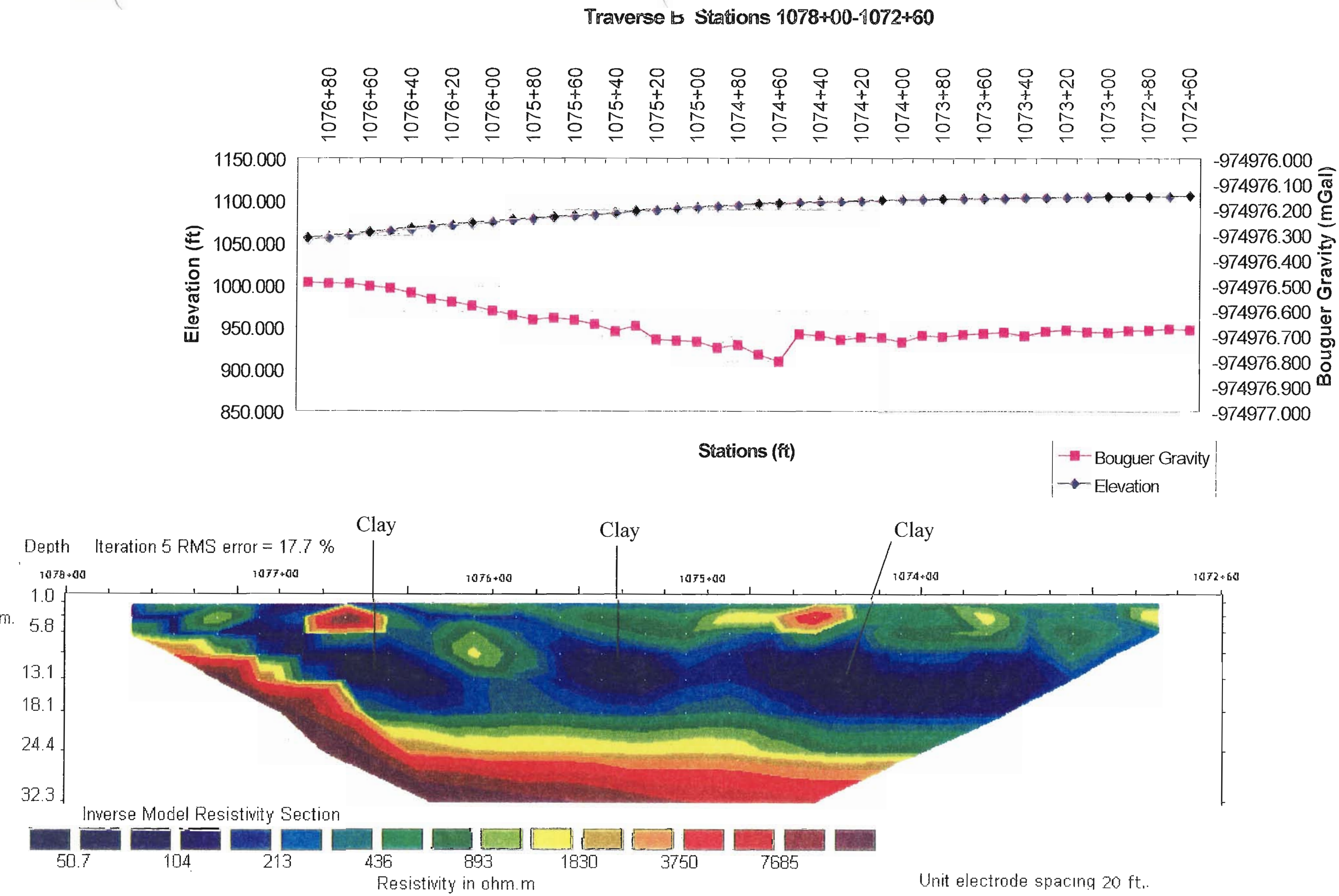
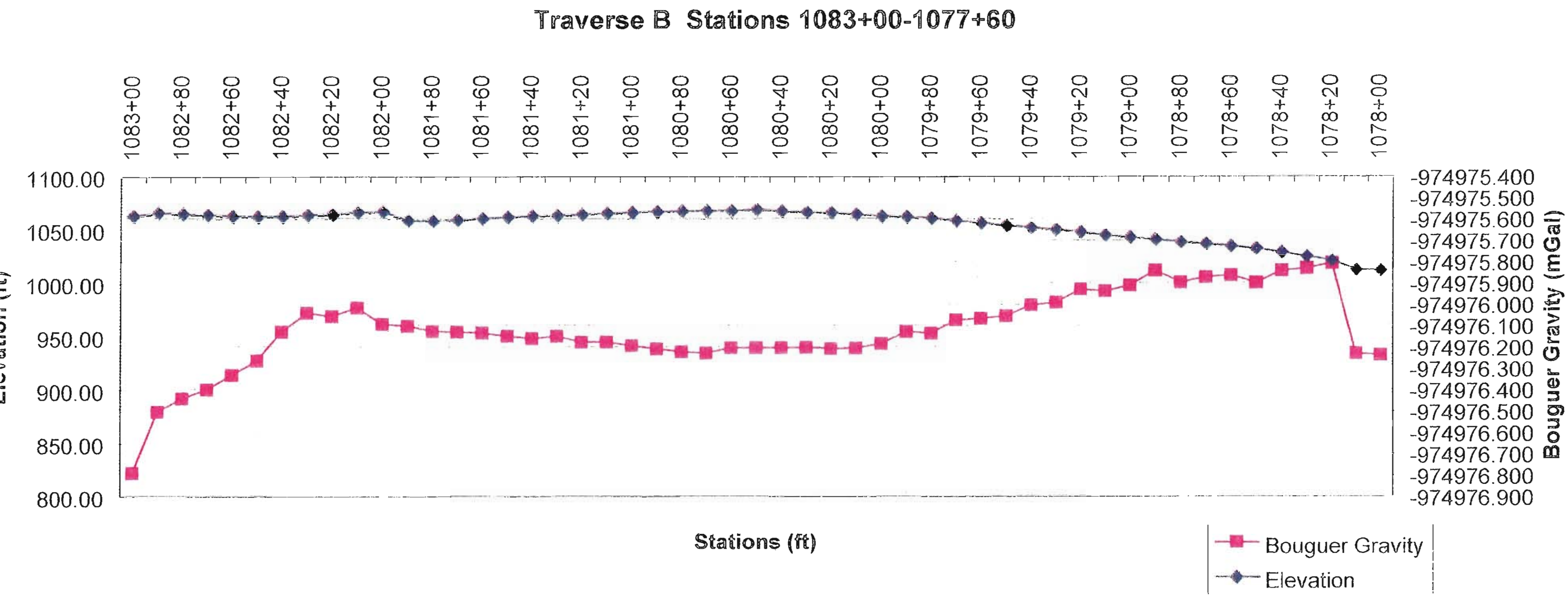


Figure 2-8 Microgravity, elevation, and resistivity data for Traverse B, stations 1078+00-1072+60



DATA NOT INTERPRETABLE

Figure 2-9 Microgravity, elevation, and resistivity data for Traverse B, stations 1083+00-1077+60

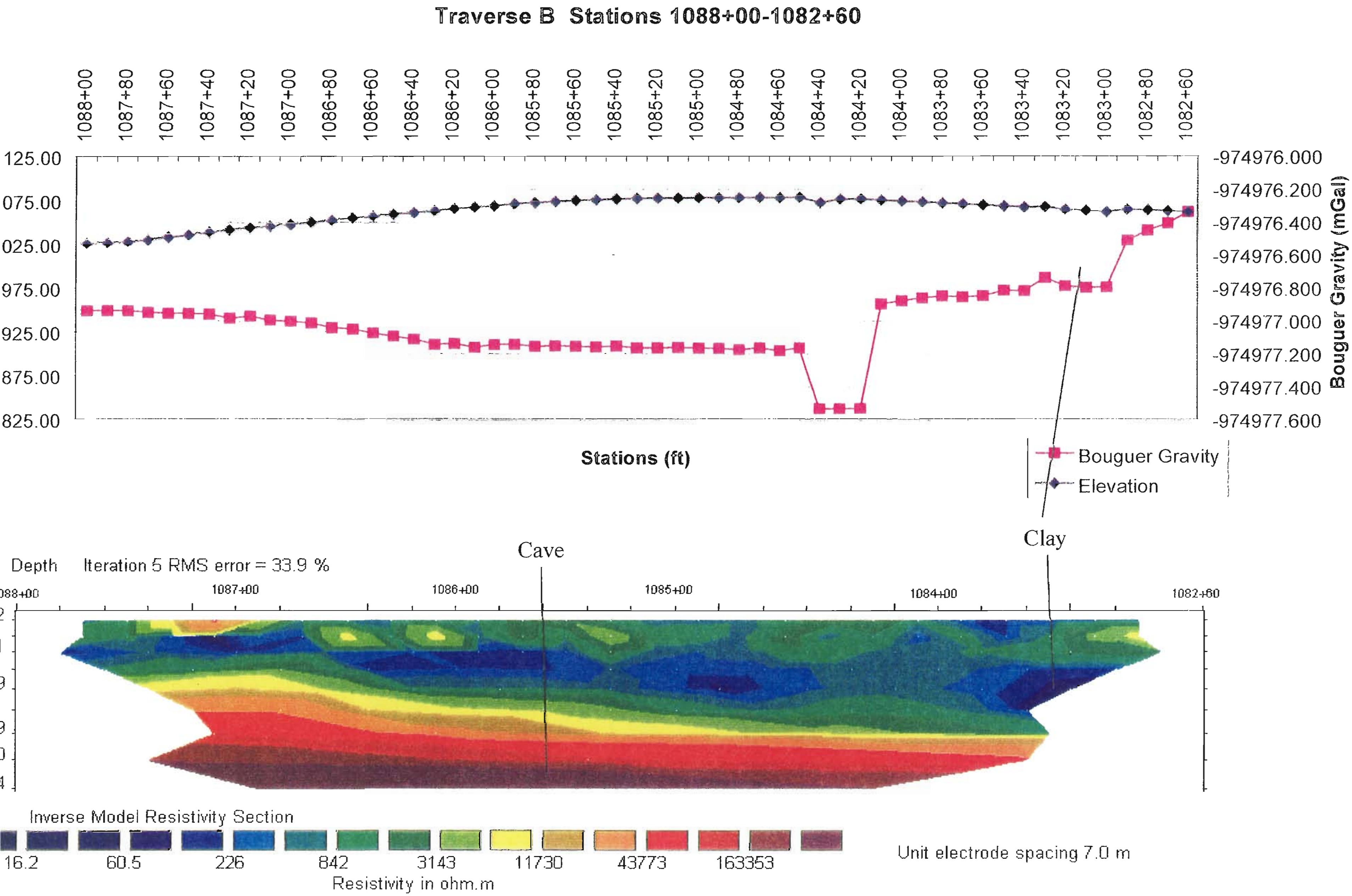


Figure 2-10 Microgravity, elevation, and resistivity data for Traverse B, stations 1088+00-1082+60

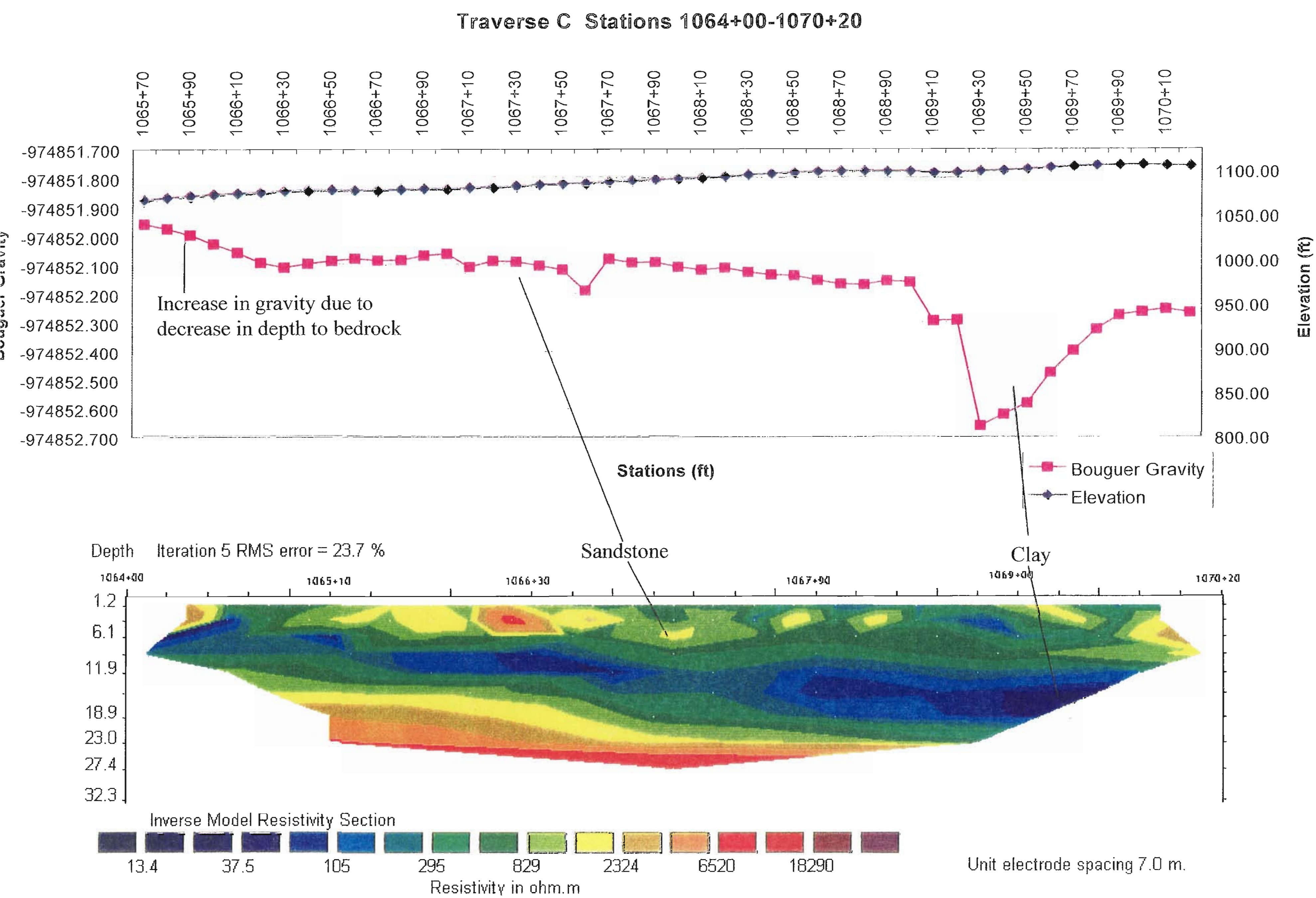


Figure 2-11 Microgravity, elevation and resistivity data for Traverse C, stations 1064+00-1070+20

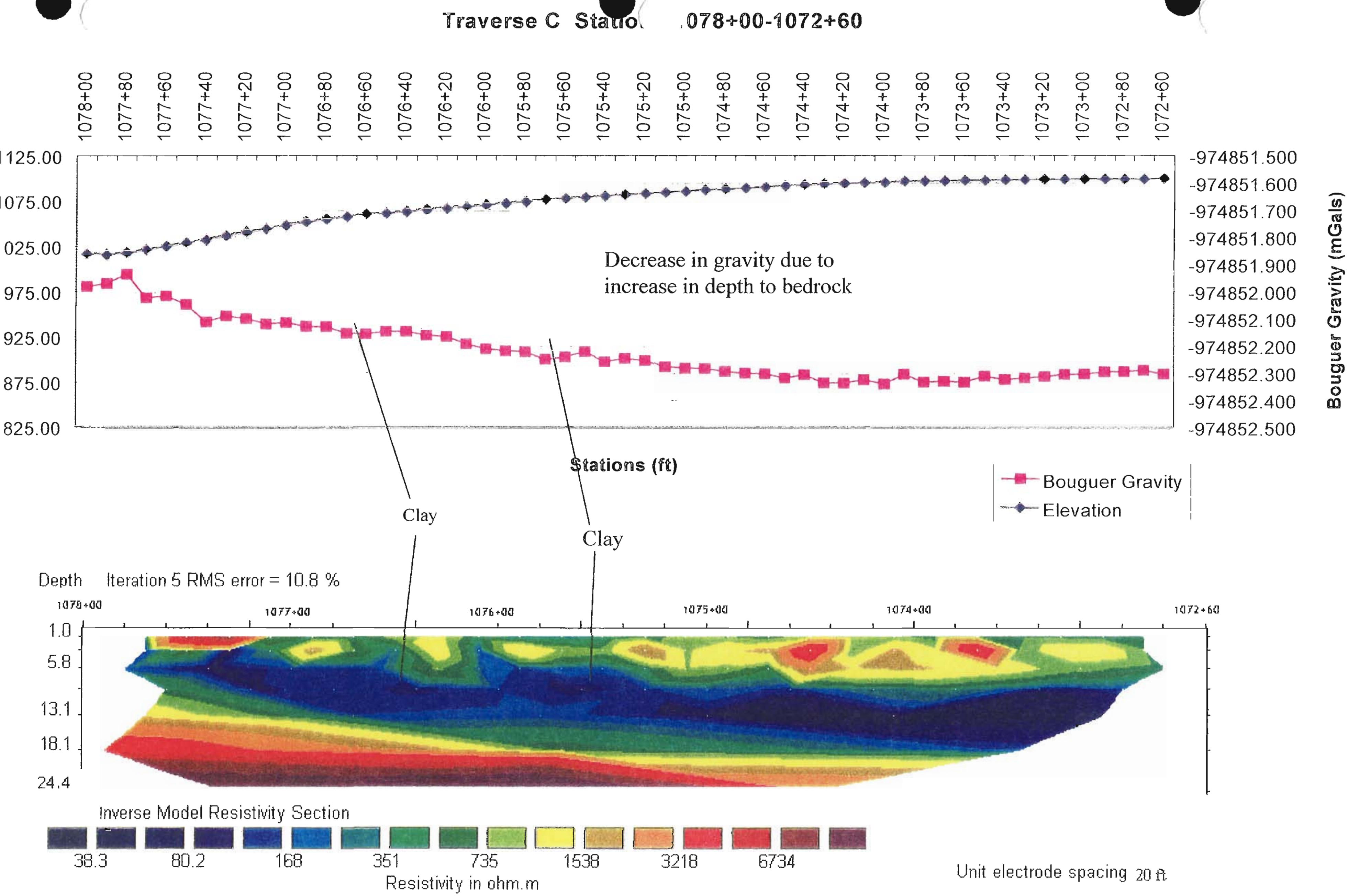


Figure 2-12 Microgravity, elevation and resistivity data for Traverse C, stations 1078+00-1072+60

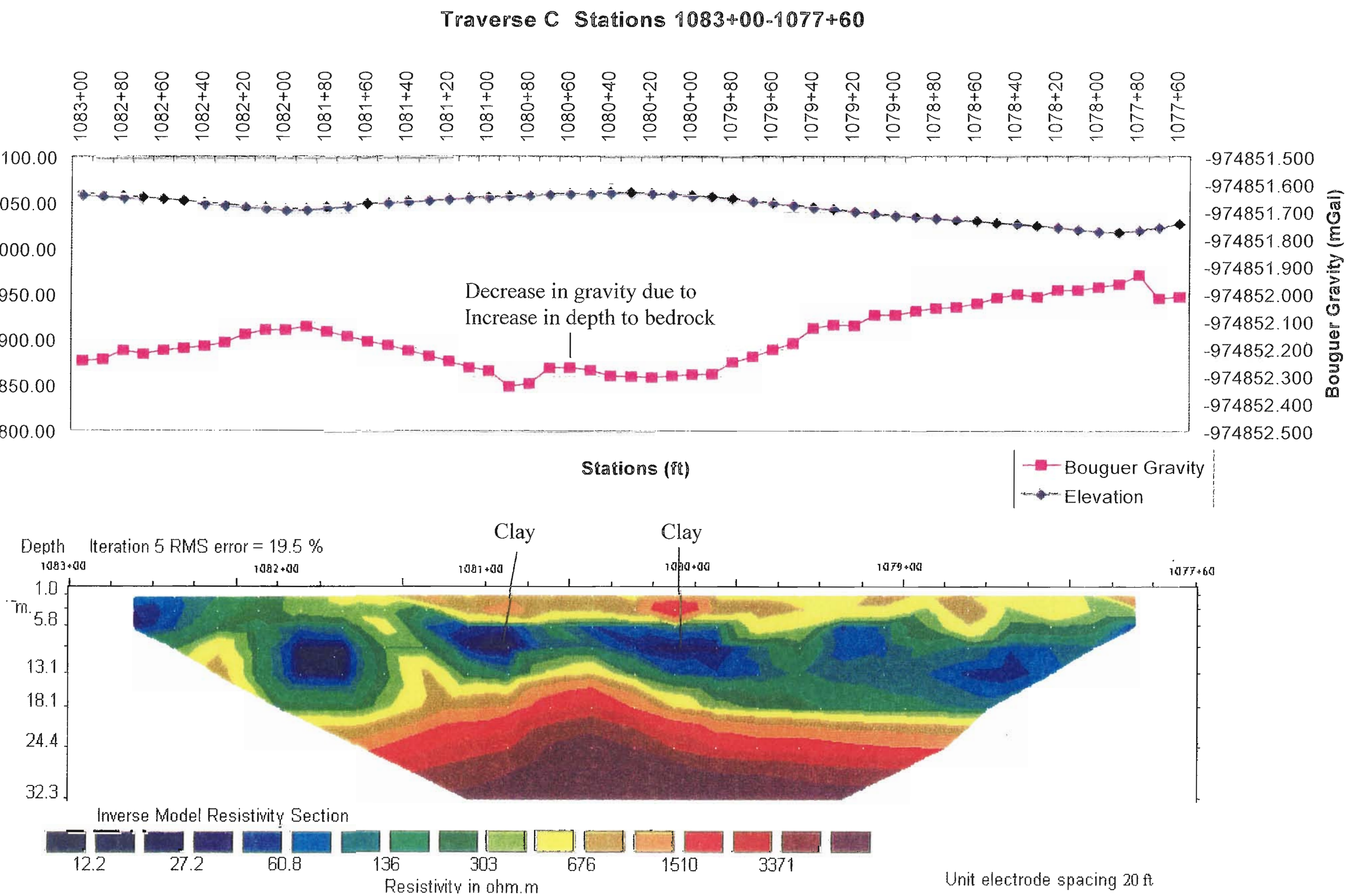


Figure 2-13 Microgravity, elevation and resistivity data for Traverse C, stations 1083+00-1077+60

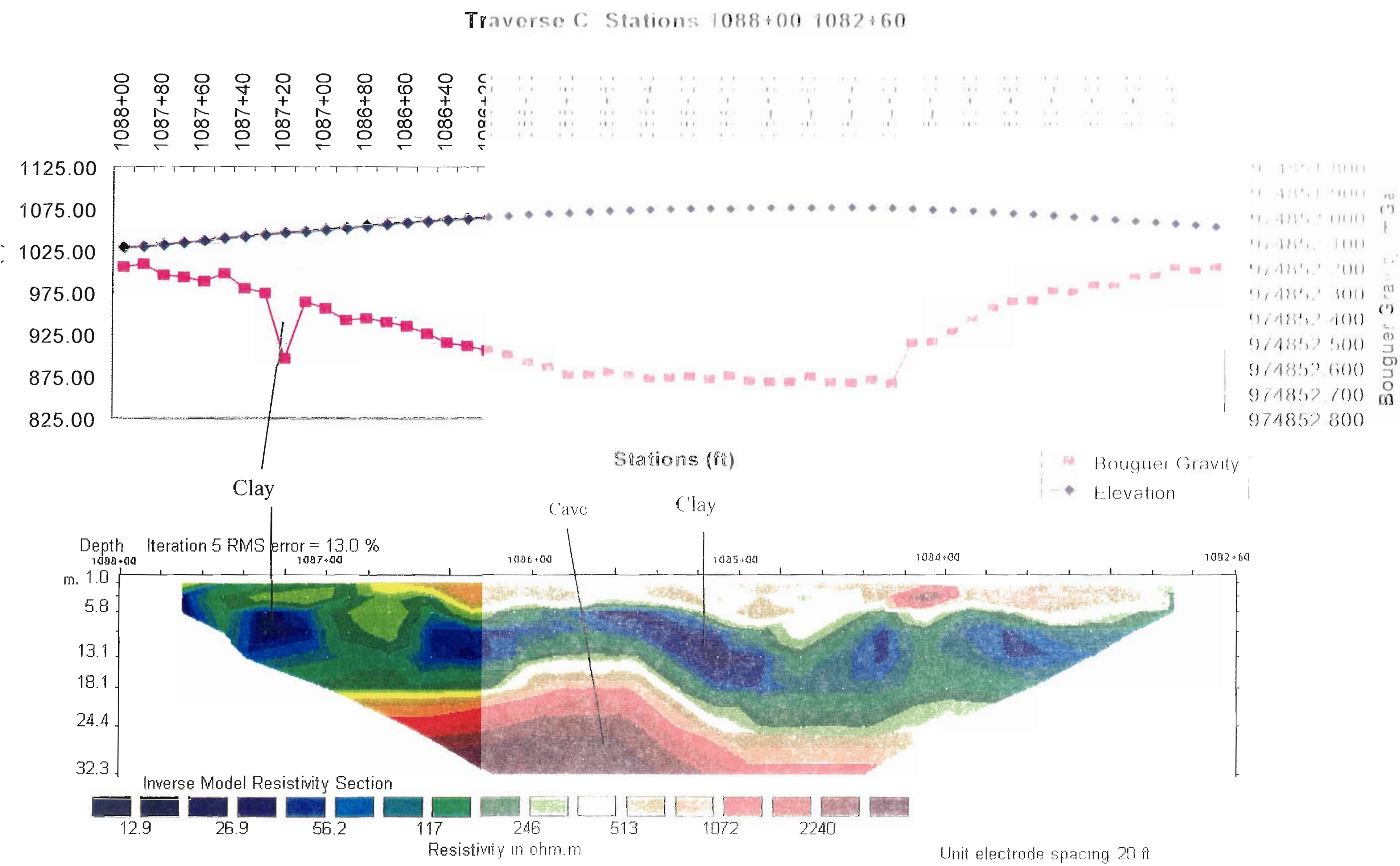


Figure 2-14 Microgravity, elevation, and resistivity data for Traverse C, stations 1088+00-1082+60

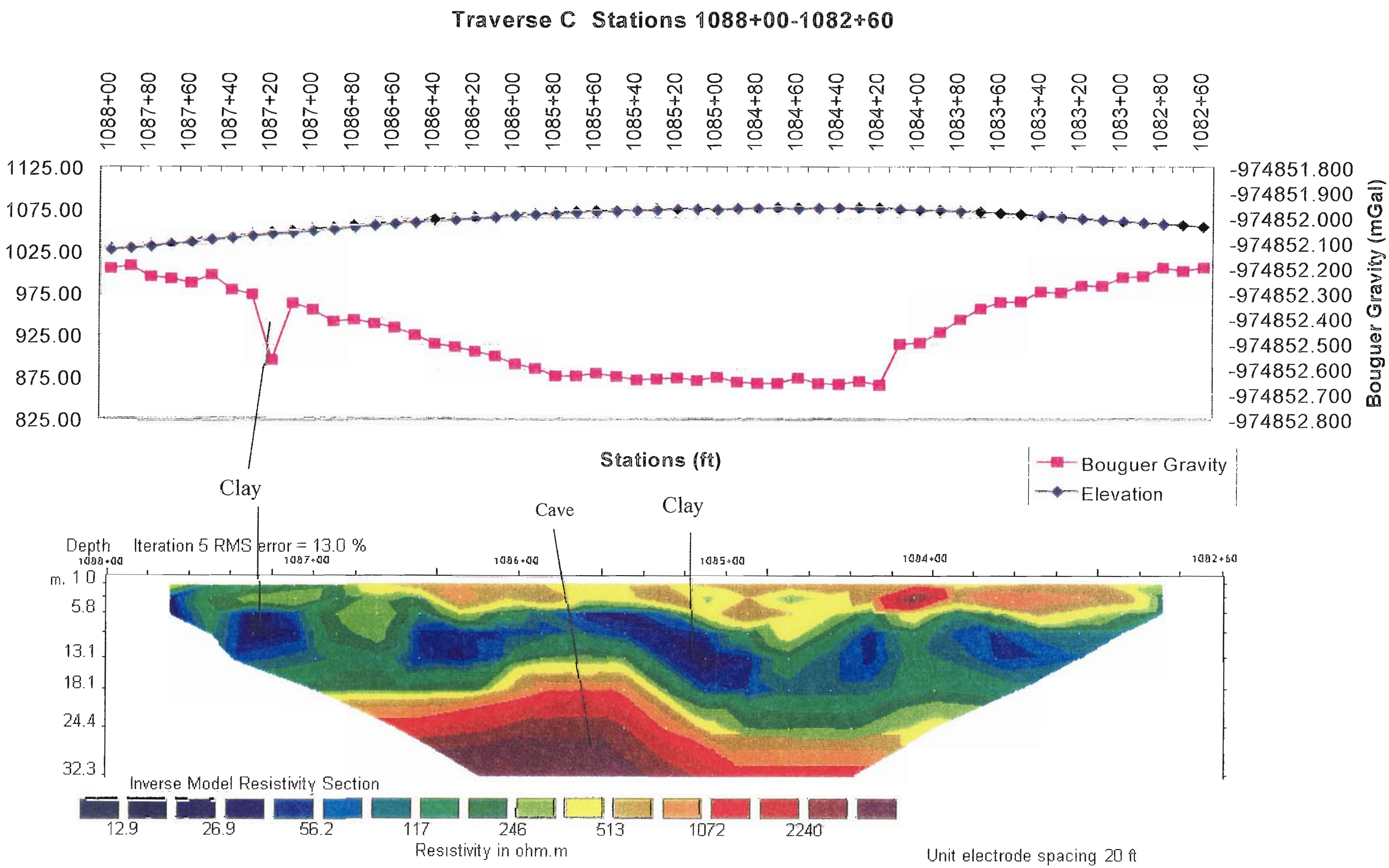


Figure 2-14 Microgravity, elevation, and resistivity data for Traverse C, stations 1088+00-1082+60

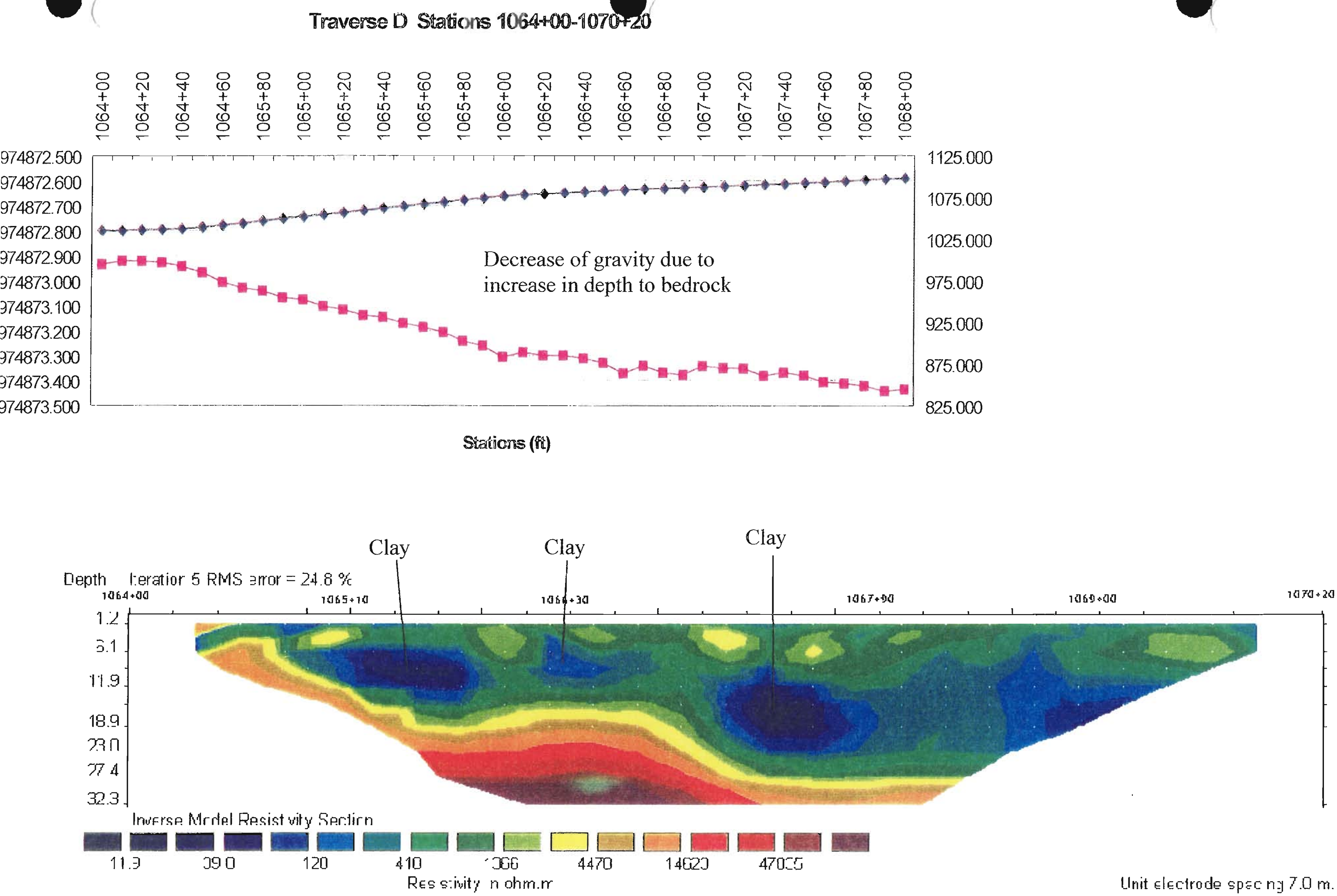


Figure 2-15 Microgravity, elevation and resistivity data for Traverse D, stations 1064+00-1070+20

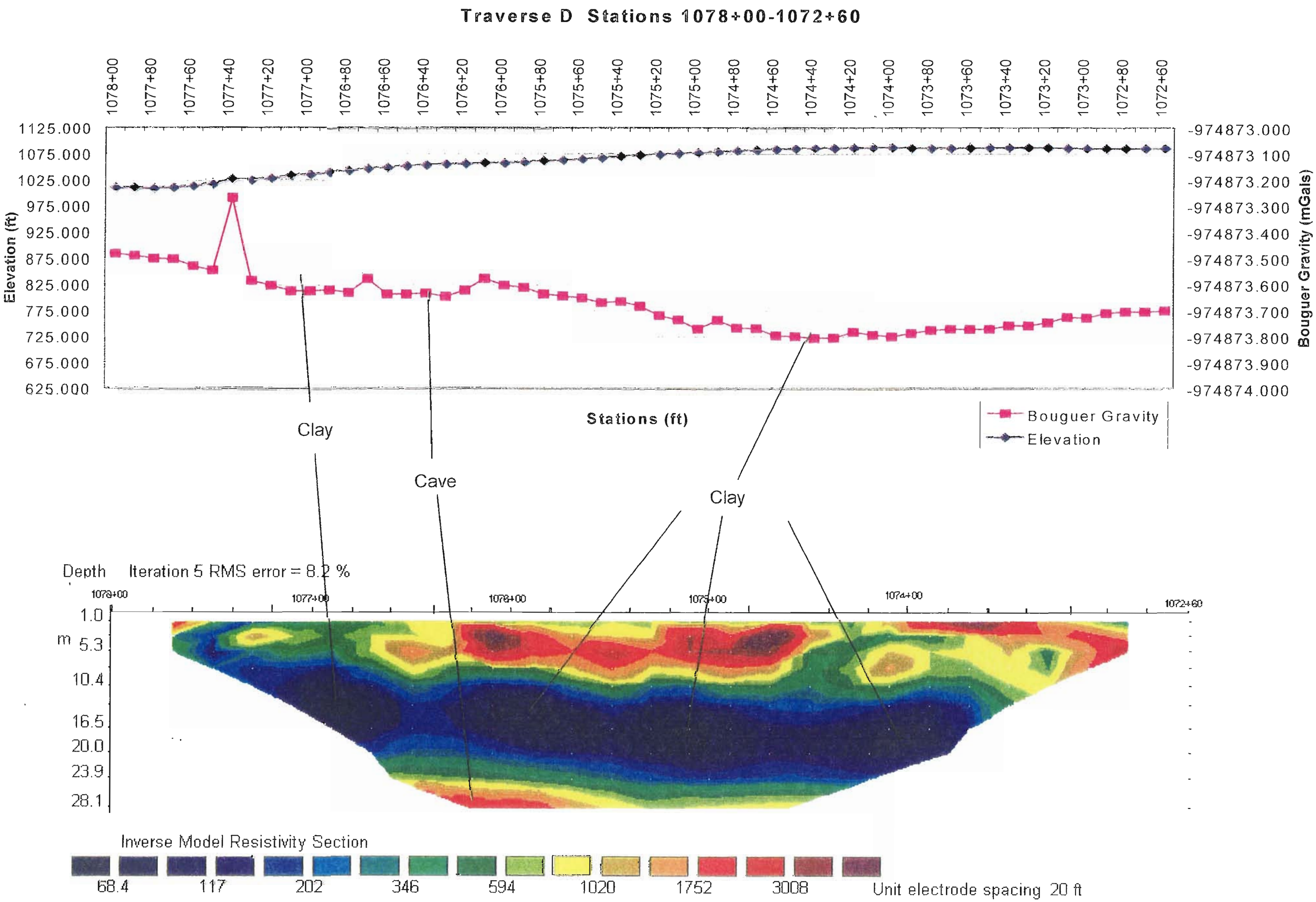


Figure 2-16 Microgravity, elevation and resistivity data for Traverse D, stations 1078+00-1072+60

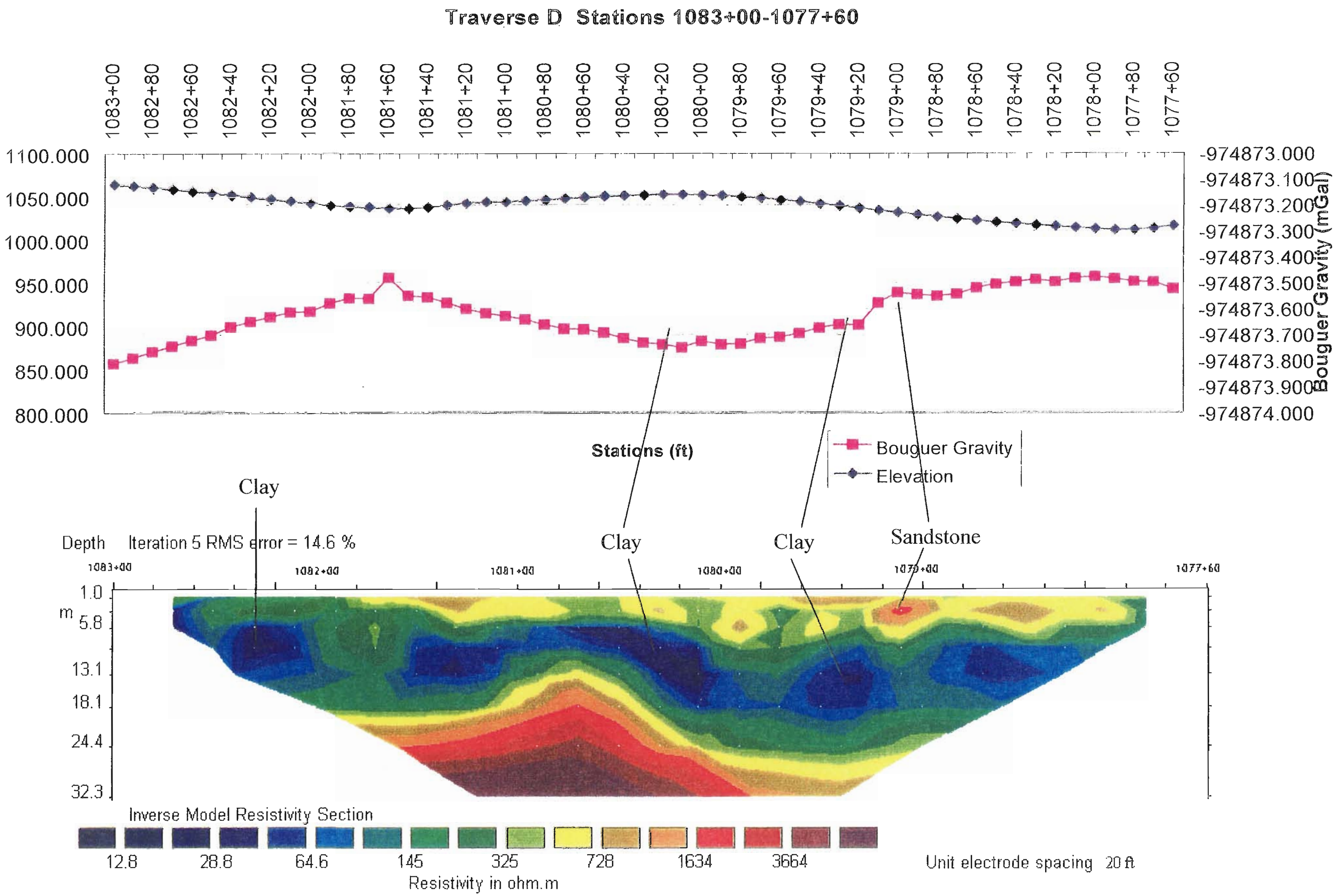


Figure 2-17 Microgravity, elevation and resistivity data for Traverse D, stations 1083+00-1077+60

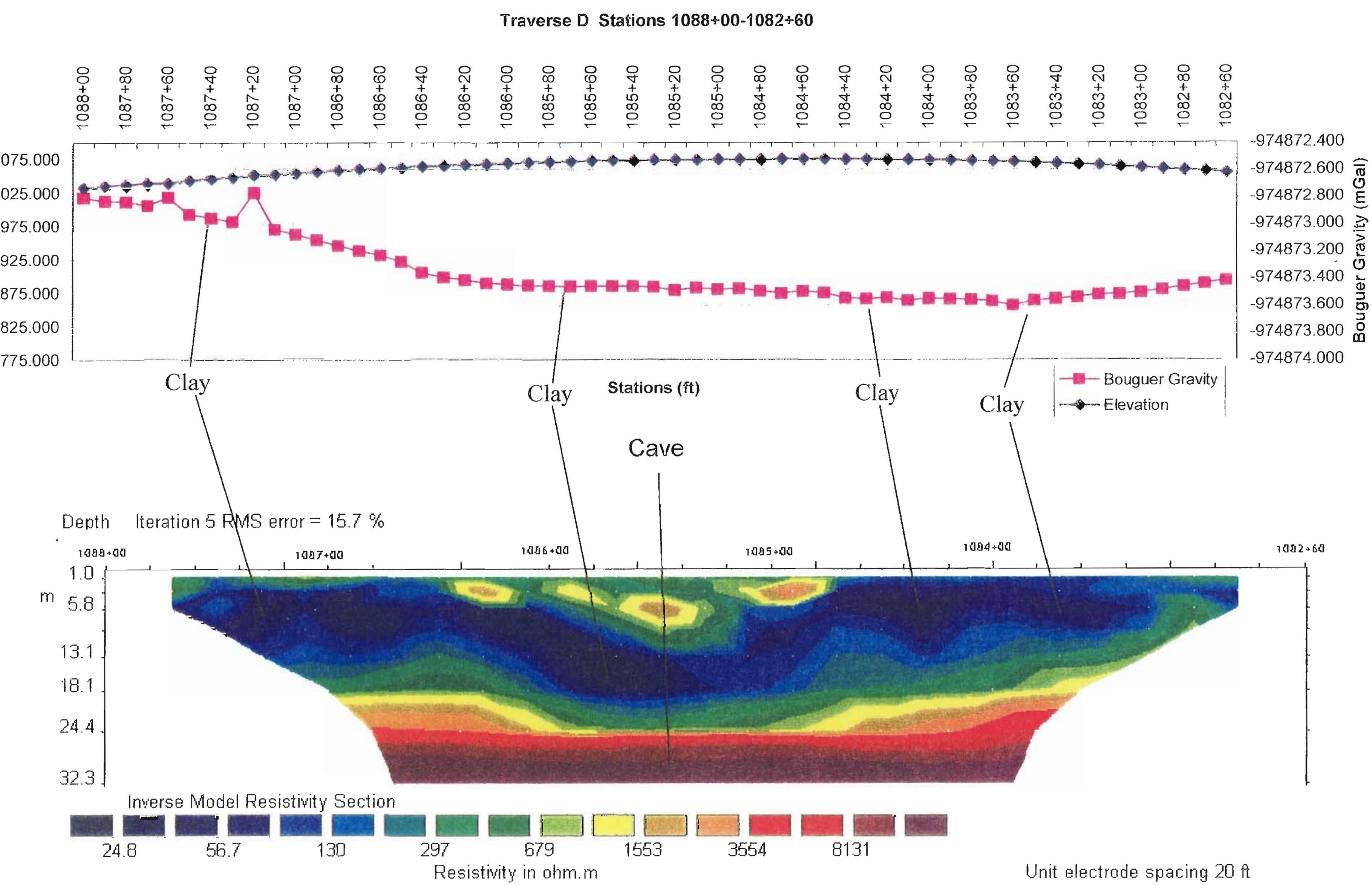


Figure 2-18 Microgravity, elevation and resistivity data for Traverse D, stations 1088+00-1082+60

3. ELECTRICAL RESISTIVITY RESEARCH PROCEDURES

3.1 Introduction

Resistivity surveys provide an image of the subsurface resistivity distribution. Features that are not good conductors of electricity, such as air filled voids in the overburden or a cave in the bedrock, result in high resistivity anomalies. This makes the resistivity method a good exploratory technique for investigating karst subsurface features, or where depth to bedrock is needed. Modeled resistivity data obtained along the traverses at the site are presented in Figures 2-1 through 2-18. For more information on resistivity profiling please refer to Appendix (III).

3.2 Resistivity Research Procedures

Several different electrode configurations can be used to collect resistivity data. These include the Schlumberger, Wenner, Pole-Pole, Pole- Dipole, Square arrays, and Dipole-Dipole. The Dipole-Dipole array generally provides the highest precision, permits reasonable depth investigation and has the greatest sensitivity to horizontal resolution and data coverage. (Loke, 1999).

3.3 Survey Layout

Survey lines were marked parallel to the centerline by placing a labeled wood stake at the beginning, middle, and end of each traverse. Having 28 electrodes, the space between electrodes 14 and 15 served as middle. The stakes were labeled with both the letter of the line and the traverse number with designation as either the beginning, middle or end. The electrodes were placed overlying the location where the microgravity measurements was taken. The electrode spacing for Traverse 1 for each line A, B, C, D was at 23 ft, the remaining traverses had a spacing of 20 ft.

3.4 Data Reduction and Interpretation

The resistance measurements gathered by the field survey are reduced to apparent resistivity values. This conversion was performed out by the AGI Administrator Version 1.1.0.4

program; The RES2DINV Version 3.44 program was then used to convert the apparent resistivity values into a resistivity profile model that can be used for interpretation.
The modeled results along a traverse are calibrated by comparing observed anomalies with physical data, such as, topographic maps, geologic quadrangles, rock outcrops, and drilling/boring data. Data interpretation of two-dimensional resistivity information in karst terrain using the Sting/Swift system is presented in Appendix (III).

4. RESULTS

4.1 General

Not all of the gravity measurements made during the survey are depicted on the profiles. The trends depicted have not been smoothed or fitted and are based on careful selection of the most accurate readings based on:

1. Readings which exhibit the lowest standard deviation were plotted where repeated measurements were made at a single station.
2. Selection was based on values which exhibited a ≤ 5 μgal spread where measurements yielded a range of values.
3. Where repeated measurements yielded similar standard deviation, a conservative selection was made of the readings that conformed to the general trend exhibited by the traverses, i.e. a "best fit".

4.2 Microgravity and Resistivity Results

The microgravity survey data taken in the field can be seen in Appendix (IV). The data, once corrected by the OASIS Mataj program can be seen in Appendix (V). The modeled microgravity profile derived from the corrected data along with the elevation and the corresponding resistivity data reduction profiles of each traverse can be seen as Figures 2-1 to 2-18.

Apparent in all resistivity traverses are irregular masses of very conductive substances. Reviewing the information provided on the geologic quadrangle (Lewis, 1971) these areas could be attributed to masses of siltstone or possibly clay, a weathered product of claystone, a component of the unit. These areas also exhibit low gravity, apparent on the microgravity profiles, which would be indicative to a substance such as siltstone or clay that is less dense.
Traverse D 1078+00-1072+60 (Figure 2-16) crosses the area above Fisher Cave, Cave "B"(Figure 1-3). Referencing the maps in Appendix (VI) and survey data gathered from an established benchmark, the entrance of Fisher cave is at an elevation of 993.58 ft, while the section of cave extending under traverse D station 1075+50 is 4 ft below that of the entrance datum. Therefore the area of cave at intersection with traverse D is at an elevation of 989.58 feet. This is 80.37 ft (24.5 m) below ground surface elevation. The cave at the location is approximately 2 feet high and 17 feet wide. This traverse shows a more resistive area approximately 24m below which probably represents the top of bedrock. Although there is a small microgravity anomaly at this location it is probably random variation in the microgravity readings since the cave is too small and too deep for detection.
Resistivity traverses A1088+00-1082+60 (Figure 2-5), B 1088+00-1082+60 (Figure 2-10), C 1088+00-1082+60 (Figure 2-14) and D 1088+00-1082+60 (Figure 2-18) cross the area over which Sweet Potato Cave, Cave "C", is located (Figure 1-3). The entrance to Sweet Potato Cave is at an elevation of 1001.37 feet. The section of cave extending under traverse D, stations 1085+40 is 994.73 ft, and is 79.76 ft (24.3 m) below ground. Under traverse C, station 1085+50, the cave passageway has an elevation of 993.73 ft and is therefore 80.92 ft (24.66 m) below the surface. The cave elevation under traverse B, is 993.79 ft, 81.4 ft (24.8 m) below; while the section under traverse A, is at 992.79 ft and 80.47 ft (24.53 m) below the surface. Each of the cave sections is no larger than 3 ft high and 5 ft wide. As seen in these profiles, the cave depth is located within the bedrock and is too small and too deep to be detected as a low gravity anomaly.
Other low gravity anomalies, large enough for possible dection, were not apparent; therefore it is believed that no large voids exit within the investigated area.

4.3 Cave Survey

Within the site investigated, three caves were explored and mapped. The cave referred to as Cave “A” located on the property of Danny and Lannie McLothlin was named Natural Bridge Spring. The cave referred to as Cave “B” located on the land owned by New Life Industries was named Fisher Cave. This is the cave that we were told was “Seven Rooms Cave”. However we have been told, by local cavers that Seven Rooms Cave is located further south, near the Cumberland Parkway. The cave referred to as Cave “C” located on the property owned by Herbert Cecil and Edna Opal Fisher was named Sweet Cave Cave. The maps produced for these caves can be found in Appendix (VI), while the location of the cave passages relative to the investigated site can be seen on Figure 1-3. During the exploration of the caves, no indication of bat habitation was reported. Evidence such as guano, scratches on the walls/ceiling, and oil darkened stains left by bats were not found.

It was also reported during exploration of Fisher Cave that the short branch extending north approximately 425 ft down the main channel contained glass bottles and other garbage debris. This could be a result of a connection between that passage and the sinkhole located directly north (Figure 1-3).

5. Conclusions

After examination of both the electrical resistivity and microgravity data gathered over the areas containing Fisher Cave and Sweet Potato Cave, it appears that the caves are located with the underlying bedrock. This portion of the bedrock containing the cave passageways, according to the resistivity profile, is approximately 80 feet below ground level. Both caves are too small and too deep to be detected as either low gravity or high resistivity anomalies The third cave under investigation, Natural Bridge Spring, did not cross under the proposed highway site.

An estimation of the depth to bedrock can be derived from the resistivity profile. Limestones exhibit a resistivity range from 100 to 10000 ohm.meters. In ground that is not homogeneous, limestone will usually appear as the most resistive material, along with void space. Therefore, the boundary between the high clay content regolith, with low resistivity and the high resistivity limestone bedrock is usually easily recognized in the modeled resistivity profile. Depth to bedrock is estimated throughout the investigated site, to range from shallow depths in the areas containing pennicles to as deep as 100 ft below ground. The average depth to bedrock appears to be deeper than originally speculated, although nearby boring support the resistivity profile. Due to the comparative aspect of the program used to analyze the resistivity data, a shadowing effect will appear around objects whose resistivity values vary greatly from its surrounding material. This effect is seen moving from moving from highly conductive clays into highly resistive limestone bedrock. Therefore, it is difficult to distinguish abrupt contacts between layers.

Actual depth to bedrock can only be derived in areas corresponding to drilling data, therefore, areas not included in ground truthing investigations are subject to estimation only based on comparison with those areas where ground truth is known. The modeled resistivity data at this is unusually complex and this makes interpretation difficult. However, after the installation of additional borings for ground truth, the modeled resistivity data shall provide a good estimate of the regolith-bedrock contact.

6. REFERENCES

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