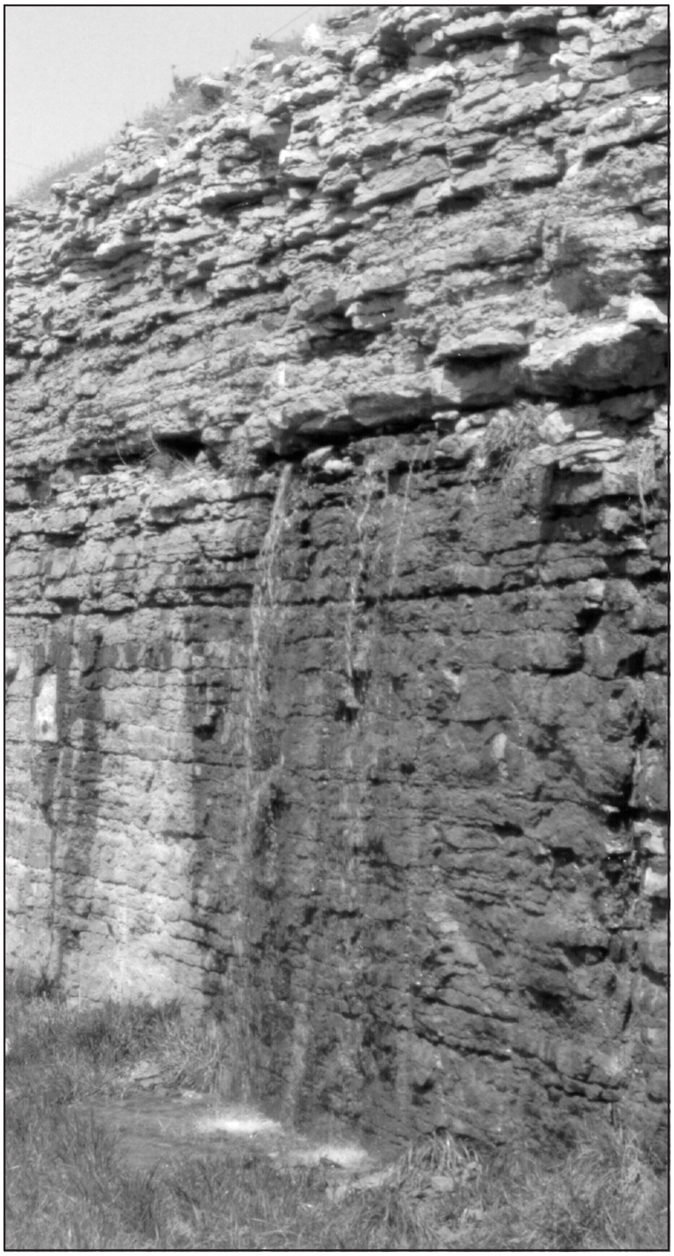
Kentucky Geological Survey
James C. Cobb, State Geologist and Director
University of Kentucky, Lexington

Electrical Resistivity Studies in the Inner Bluegrass Karst Region, Kentucky



C. Douglas R. Graham

Thesis Series 1

Series XII, 2000

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CONTENTS

Acknowledgments **viii**
Abstract **1**
Introduction **1**
Regional and Local Geology **5**
Methods **7**
  History **7**
  General Theory **7**
  Electrode Arrays Used in These Studies **11**
Equipment Used in This Study **15**
Previous Work **16**
Marshall Spring Diagnostic Sounding **17**
Kentucky Horse Park Study **18**
  Introduction **18**
  Interpretation **23**
  Layered-Earth Modeling **31**
  Studies Peripheral to the Royal Spring Conduit System **31**
    Line A' **31**
    Line D **31**
    Line E **35**
    Line F **35**
  Studies in the Central Kentucky Horse Park **45**
    Line C **45**
    Line A **58**
    Line T **63**
  Kentucky Horse Park Study—Discussion **70**
Diagnostic Profiles from Ironworks Pike **79**
Sinking Creek Karst Basin Study **79**
General Conclusions **87**
Bibliography **91**

FIGURES

1. Locations of the study areas in Fayette, Jessamine, and Scott Counties, Kentucky **2**
2. (a) Kentucky Horse Park and Ironworks Pike study areas, (b) Marshall Spring study area **3–4**
3. (a) Generalized stratigraphy of the Inner Bluegrass, Kentucky, (b) Schematic stratigraphic framework of the Lexington Limestone in the study areas **6**
4. Flow lines and equipotentials between two current electrodes, A and B **9**
5. Current-flow lines and equipotential surfaces **10**
6. Flowline configuration in layers of differing resistivity, lower resistivity at depth **11**
7. Flowline configuration in layers of differing resistivity, higher resistivity at depth **12**
8. Theoretical response of a Wenner array to a buried, perfectly conducting sphere **13**
9. (a) Position of electrodes in line during profiling with the Wenner Array or Tripotential profiling, (b) Electrode functions for different arrays using the Tripotential method at Array Position 1 above **14**
10. Expanding Schlumberger Array used for sounding **16**
11. Marshall Spring, Scott County, Kentucky **18**
12. Marshall Spring soundings, Scott County **19**
13. Interpretation of Marshall Spring soundings **20**
14. Profile locations, Kentucky Horse Park study area **21**
15. Conceptual basis for profiling in search of water-filled conduit **22**
16. Boreholes in the central part of the Kentucky Horse Park used in the interpretation of resistivity results **24**
17. Comparison of apparent resistivity ranges and the assumed background resistivity thresholds, Kentucky Horse Park profiles **25**
18. No karst or water-bearing features apparent in resistivity signature of profile or soundings **26**
19. (a) Profiles over small- and medium-sized conduits, Line B, Kentucky Horse Park, (b) Sounding over small-sized conduits, (c) Sounding over medium-sized conduits **28**
20. Profile and soundings over Royal Spring Conduit, Line A, Kentucky Horse Park **29**
21. (a) Influence of water at soil-bedrock interface on Profile A, central segment, (b) Low “background” of profile resistivity, G-4 vicinity, probably due to shallow groundwater, (c) Low resistivity in short-spacing readings in soundings **30**
22. Profile A-Prime, with sounding points indicated **32**
23. Soundings, Line A’, Kentucky Horse Park **33**
24. Modeled resistivities from soundings, Line A’ **34**
25. Profile D, with sounding points indicated **36**
26. Soundings, east end Line D, Kentucky Horse Park **37**
27. Soundings, west end Line D, Kentucky Horse Park **38**
28. Profile D, with interpretation **39**
29. Profile E, with soundings indicated **40**
30. Line E soundings, Kentucky Horse Park **41–42**
31. Profile E, central part, with sounding data overlain **43**
32. Line F, Tripotential Profile with sounding indicated, Kentucky Horse Park area **44**
33. Sounding L-10, Line B, repeated on 3/15, 3/27, and 4/4/87 **46**
34. Sounding HP-1A, Line A, repeated 11/13/86 and 12/14/86 **47**
35. Sounding L-1 (Line B) and L-1 redone after 8-centimeter drill hole to water at 13.4 meters **48**
36. Profile C, with sounding points indicated **49**
37. Soundings, central part of Line C, Kentucky Horse Park **50**
38. (a) Soundings from the west segment of Line C, (b) Soundings, east segment Line C **52**
39. Profile C, with interpretation **53**
40. Profile B, with sounding points indicated **54**
41. Soundings, west and central segments, Line B, Kentucky Horse Park **55**
42. East end, Line B. Resistivity profile and drilling results **56**
43. East end, Line B. Resistivity sounding and drilling results **57**
44. Profile B (eastern end), with sounding points indicated **59**
45. Soundings, east end Line B **60**
46. Profile B, with interpretation **61**

47. Stream of water running from a solutionally enlarged bedding plane along Ironworks Pike **62**
48. Profile A, with sounding points indicated **64**
49. Soundings, north end Line A **65**
50. Soundings, central part Line A **66**
51. Line A, southern and central segments **67**
52. Line A, southern and central segments **68**
53. Soundings, south end Line A **69**
54. Profile T (Tripotential profiling) with soundings indicated **71**
55. Soundings, Line T **72**
56. Central segment, Line T. Resistivity profile and drilling results **73**
57. Central segment, Line T. Resistivity sounding and drilling results **74**
58. Profile T (Tripotential profiling) with interpretation **75**
59. Comparison of sounding signatures of water-bearing zones **76**
60. Comparison of apparent-resistivity ranges and the assumed background resistivity thresholds **78**
61. Solutionally enlarged joint, east end of Ironworks Pike **80**
62. Tripotential profile run over solution-enlarged joint with clay filling **81**
63. Fan profile results **82**
64. Sinking Creek study area **83**
65. Location map, Sinking Creek Karst Basin study, Denver Dillingham farm, Jessamine County, Kentucky **84**
66. Sounding using Schlumberger array **85**
67. Profile between stationary-current electrodes (asymmetrical Schlumberger array), Line P1 **86**
68. Tripotential profile of Line P1, electrode space (a) 25 meters **88**
69. Interpretation of Line P1, Sinking Creek Karst Basin study **89**

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Electrical Resistivity Studies in the Inner Bluegrass Karst Region, Kentucky

C. Douglas R. Graham

ABSTRACT

Electrical resistivity was used in the Inner Bluegrass of Kentucky to examine known karst features and locate water-bearing conduits. A known spring conduit showed a signature in vertical electric soundings distinct from soundings 3 meters on either side, and this information was applied at the Kentucky Horse Park. Eight horizontal profiles and associated soundings revealed numerous anomalies in the central part of the park. Drilling concurrent to the resistivity surveying provided information vital to interpretation of the geophysical data. A drillhole on a very pronounced low-resistivity anomaly encountered a major water-bearing karst conduit, interpreted to feed Royal Spring in nearby Georgetown. A subsequent study examined the resistivity signature of a vertical soil-filled crevice 1 meter wide revealed in a roadcut. Resistivity of the crevice was higher than that of the surrounding limestone, but the contrast was slight at that electrode spacing, and the feature would probably not be remarked. Profiles in the Sinking Creek Karst Basin using two different electrode arrays located anomalies interpreted as corresponding to water-bearing conduits and to abandoned, air-filled conduits of that karst system.

We conclude that the electrical resistivity method is applicable to the prospection for water in the karst terrain of the Inner Bluegrass, particularly if there is local drillhole data available. Survey and interpretive methods relying on simple geometries in the subsurface can lead to errors in interpretation of the subsurface bodies causing resistivity anomalies. Recommendations for the use of electrical resistivity methods in this region include: consideration of topography and its effect on resistivity measurement; use of diagnostic signatures of known geological features; and use of multiple arrays to locate narrow anomalies accurately.

INTRODUCTION

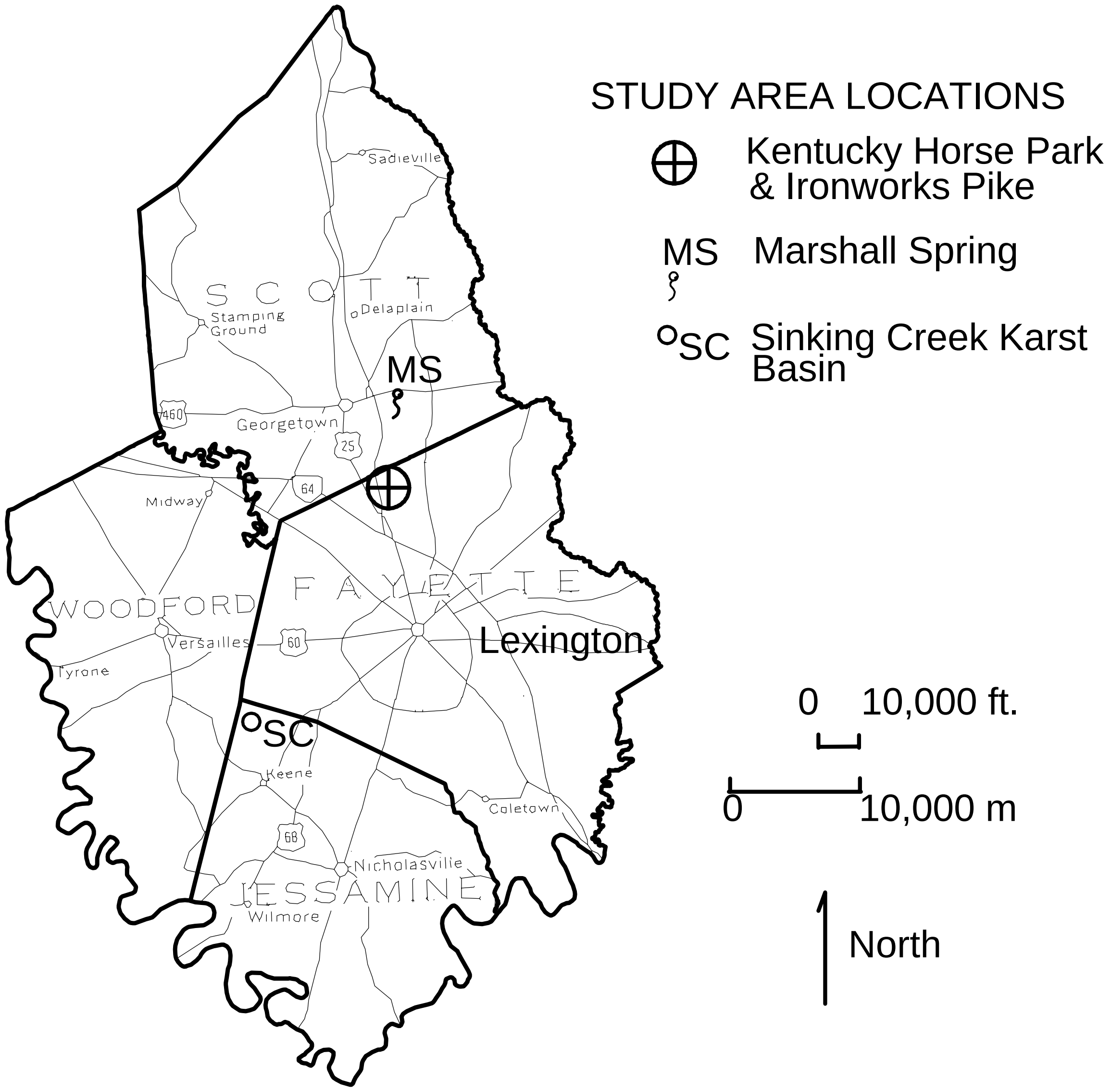
The purpose of this study was to investigate karst features associated with ground-water occurrence using the electrical-resistivity method. Data from four locations were used. Two localities were investigated for the purpose of siting water wells, and the other two localities were investigated for the purpose of determining the resistivity signatures of known karst features. The major study area was the Kentucky Horse Park, Fayette County, Kentucky. Other surveys in this report were Marshall Spring in Scott County, a site along Ironworks Pike in Fayette County, and a site in the Sinking Creek Karst Basin, Jessamine County. All the sites lie within the Inner Bluegrass Region, a gently rolling karst terrain (Figure 1).

In the summer of 1986 Tom Dugan, a consulting geologist, was contracted by the Kentucky Horse Park to investigate ground-water sources for the abundant supply of water necessary to irrigate existing and proposed polo fields (Figure 2a). In order to better understand the behavior of electrical resistivity in karst terrains, Dugan undertook a diagnostic study of a known karst conduit at Marshall Spring (Figure 2b). Drilling followed the geophysical surveys in the Kentucky Horse Park (records filed with the Kentucky Department of Natural Resources and Environmental Protection, Division of Water, indicate that 43 holes were drilled), and the detailed geologic logs of 12 of those holes provided a geological basis for the interpretation of the resistivity data (Tom Dugan, unpub. data).

Later work by this author in a highway right-of-way near the Kentucky Horse Park along Ironworks Pike examined the resistivity signature of a large, clay-filled solution channel in limestone. A fourth study area was located in the Garretts Spring Basin (Sinking Creek Karst Basin) in Jessamine County, Kentucky (Figure 1).

The Kentucky Horse Park is drained by Cane Run, a north-northwesterly flowing stream that enters the park from the south (Figure 2a). Cane Run has been demonstrated by water-tracing techniques to lose water at various points along its course into a karst groundwater system that emerges at Royal Spring in Georgetown, Scott County, Kentucky, 7.6 kilometers (25,000 feet) northwest of the park (Thrailkill and others, 1982). Fluorescent dyes were introduced into swallow holes into which water flowed from the stream bed at points 2.9 and 8.2 kilometers (9,500 and 26,900 feet) upstream (south) of the park; the dyes were subsequently detected in water flowing from Royal Spring. Much of the Kentucky Horse Park lies within the Royal Spring Groundwater Basin as defined by Thrailkill and others (1982), and the entire property lies within the surface-water drainage of Cane Run. As many as 12 additional swal-

Figure 1. Locations of the study areas in Fayette, Jessamine, and Scott Counties, Kentucky



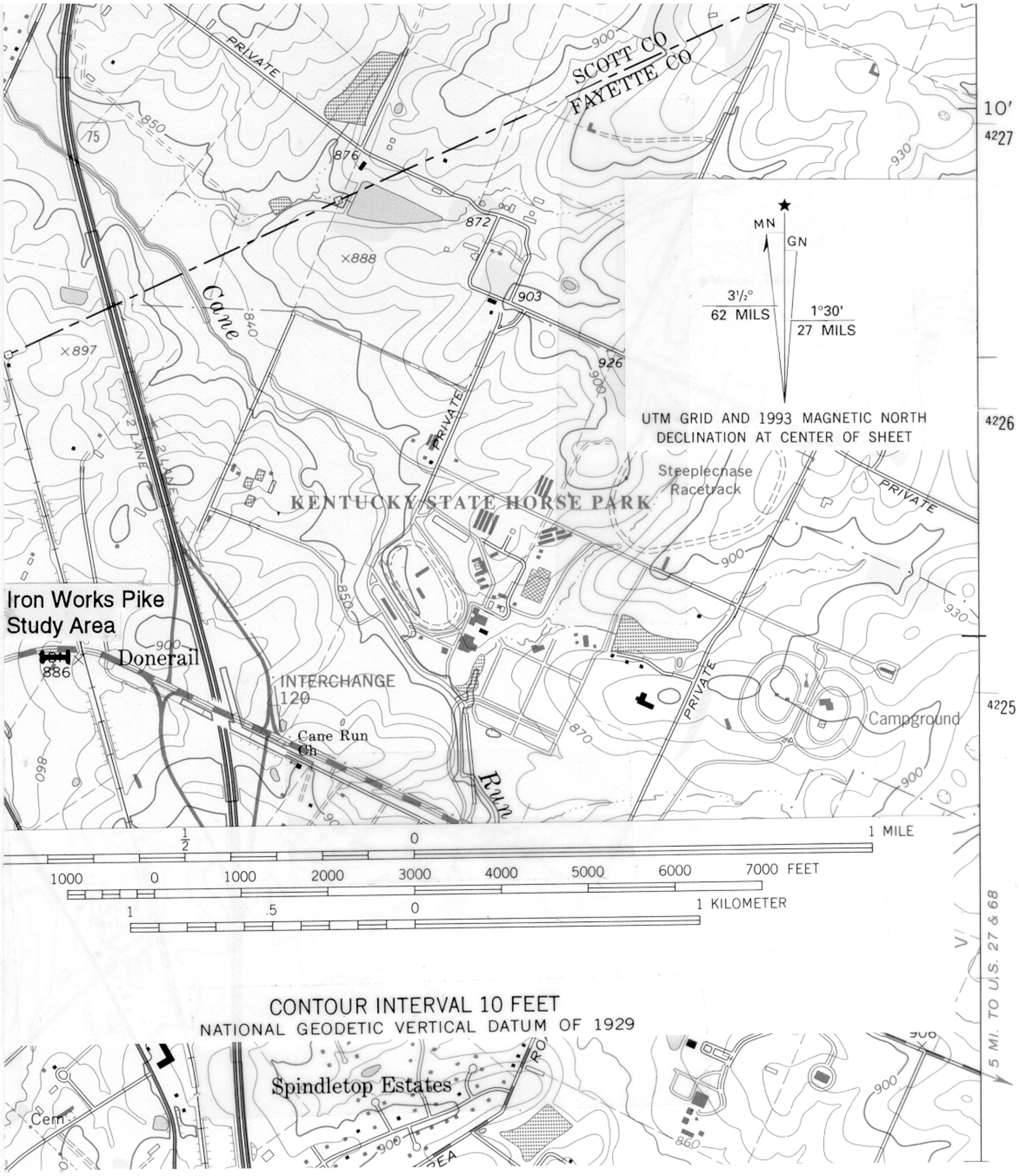


Figure 2a. Kentucky Horse Park and Ironworks Pike study areas, southeastern part of the Georgetown 7.5' quadrangle (USGS 1:24,000), Kentucky.

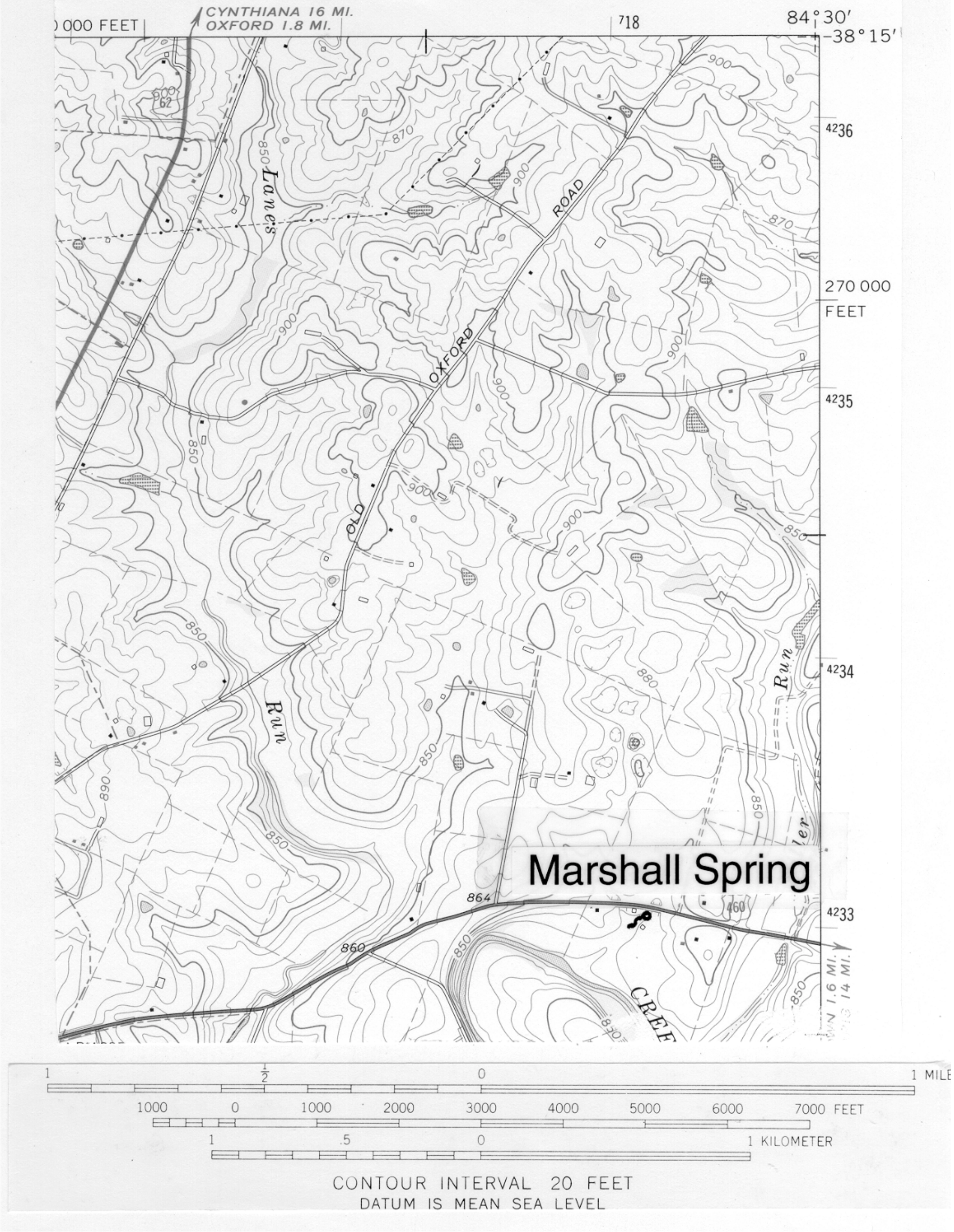


Figure 2b. Marshall Spring study area, approximately 2.5 kilometers (8.2 miles) east of Georgetown, Kentucky. Georgetown 7.5' quadrangle (USGS 1:24,000).

low holes within the park drain water from Cane Run or its tributaries to a subsurface flow system (Dugan, unpub. data). Flow in Cane Run out of the park only occurred during high-flow events. North of the park an additional injection of dye into the karst system was successfully traced to Royal Spring (Thrailkill and others, 1982). On the same property bordering the park to the north, a well had been drilled that intersected a water-filled void nearly 1 meter (3.3 feet) in height, which appeared to be capable of yielding a substantial quantity of water (Figure 2a, Barton's well). The elevation of that void approximated the elevation of Royal Spring (244 meters, or 800 feet; all elevations are reported in reference to the MSL, or Mean Sea Level, datum), and the void was interpreted to be the trunk cave or a major tributary or distributary connected to the Royal Spring system. Thrailkill and others (1982) used the term "conduit" in their discussion of subsurface flow in the Inner Bluegrass Karst Region, and defined it as "solutionally enlarged openings larger than ... capillary size openings ..." (Thrailkill and others, 1982, p. 88). One of the objectives of the present study was to detect large conduits; the term "conduit" is applied here in the same fashion as in Thrailkill and others (1982).

The weight of the information cited above led Dugan to the interpretation that a major karst conduit passes beneath the Kentucky Horse Park, which might be exploited as a water supply; it is referred to in this study as the Royal Spring Conduit. Dugan contacted faculty of the Department of Geological Sciences at the University of Kentucky for technical assistance. Dr. Rene Rodriguez, a member of the faculty at that time, suggested that a method for measuring the electrical resistivity of the earth might disclose the location of an otherwise concealed underground conduit. Dugan invited student participation in the project in November of 1986 after the initial stages of the investigation were under way.

REGIONAL AND LOCAL GEOLOGY

The Inner Bluegrass Karst Region lies on the Jessamine Dome, which exposes carbonate rocks of Ordovician age (Thrailkill and others, 1982). Rock units, in ascending order, are the High Bridge Group (composed of the Camp Nelson Limestone, the Oregon Formation, and the Tyrone Limestone) of Middle Ordovician age, and the Lexington Limestone of Middle Ordovician age (Figure 3a). Overlying the Lexington Limestone and occupying the flanks of the dome, the outcrop belt of the Clays Ferry Formation of Late Ordovician age borders the Inner Bluegrass Region. The Jessamine Dome is one structural high along the larger, north–south-trending Cincinnati Arch. Three major fault zones extending outside the Jessamine Dome converge near its crest, and numerous smaller and more discontinuous fault systems and fault swarms cut the rocks of the region (McDowell and others, 1981).

Thick-bedded, relatively pure, carbonate rocks of the High Bridge Group crop out almost exclusively in the deeply incised valleys of the Kentucky River and its tributaries at or near the crest of the Jessamine Dome. These units do not host regionally widespread karst groundwater systems (Thrailkill and others, 1982). Most of the Inner Bluegrass Karst Region is underlain by the Lexington Limestone, the members of which are composed of alternations of coarse- and fine-grained limestone, argillaceous limestone, and minor intercalated shale and siltstone. The Lexington Limestone stratigraphic unit was revised by Black and others (1965), and is made up of 11 members, as described by Cressman (1973), in a complex mosaic of vertical and lateral facies relationships. The Clays Ferry Formation is composed of approximately equal parts of calcareous shale and thin-bedded limestone and contains enough insoluble material (shale) to inhibit the formation of solution features and karst terrain (Thrailkill and others, 1982). Because of its stratigraphic position and composition, only isolated inliers of the Clays Ferry Formation lie within the areas of prominent karst topography as topographic highs or faulted structural lows. Thrailkill and others' (1982) definition of the Inner Bluegrass Karst Region included all 2.5-minute quadrangles (one-ninth of the standard published 7.5-minute quadrangle map) having a sinkhole resolvable on the published 1:24,000-scale topographic map at that map's contour interval, usually 3 meters (10 feet) or 6.1 meters (20 feet).

Figure 3b shows the stratigraphic position of members of the Lexington Limestone included in this study. The Tanglewood Member is the uppermost rock unit in the Kentucky Horse Park and the study area along Ironworks Pike (Cressman, 1967). The Grier Member lies below the Tanglewood Member in this area, probably at a depth not exceeding 10 meters (33 feet). The study area in the Sinking Creek Karst Basin, in northern Jessamine County, is underlain by the Tanglewood and Grier Members, and in the uplands by the Brannon Member. These are the only members of the Lexington Limestone significant to this study, and detailed description will concentrate on these members and those distinctive rock units that occur near the contact.

The Grier Member of the Lexington Limestone consists of irregular but continuous beds of coarse- to fine-grained limestone up to 12 centimeters (0.39 foot) thick. The limestone beds are separated by wavy beds or partings of shale or silty limestone up to 1 centimeter (0.03 foot) thick. The limestone beds of the Grier Mem-

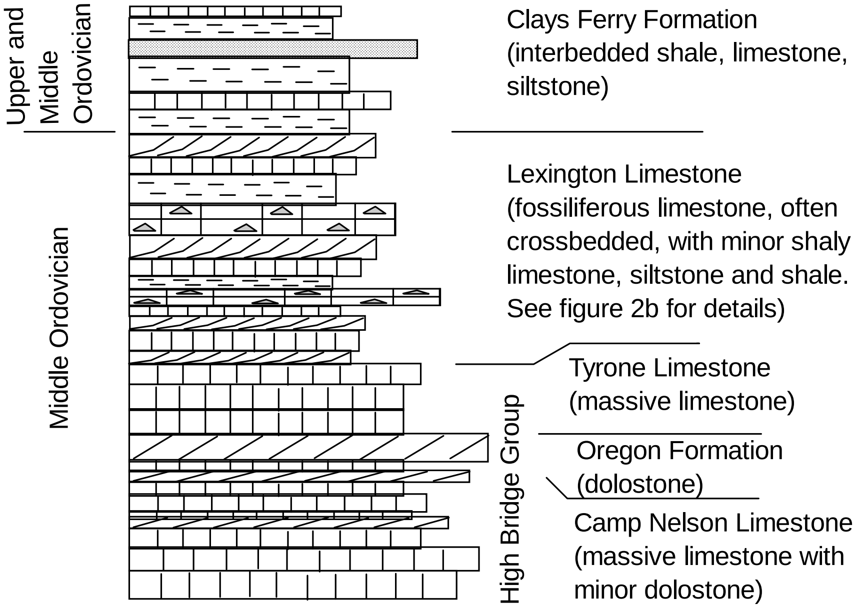


Figure 3a. Generalized stratigraphy of the Inner Bluegrass, Kentucky (after Cressman, 1965).

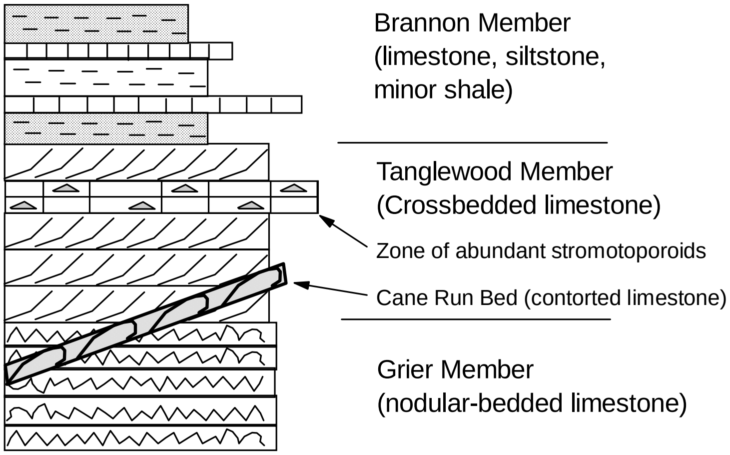


Figure 3b. Schematic stratigraphic framework of the Lexington Limestone in the study areas (after Cressman 1965, 1967, 1972).

ber pinch and swell, giving it an overall "knobbly" or nodular appearance (M.C. Noger, pers. commun., 1992). Near the top of the unit (or within the lower part of the Tanglewood Member, depending on the mapper and the locality) occurs the distinctive Cane Run Bed, which is composed of fine-grained limestone with spectacularly contorted bedding in which the bed appears to have rolled while still unlithified, in places bringing the original top of the bed into contact with the underlying stratum.

The Tanglewood Member of the Lexington Limestone is composed of beds of coarsely crystalline limestone made up mostly of fossil fragments, with few unbroken fossils present. Beds are 5 to 15 centimeters (0.16 to 0.49 foot) thick and commonly occur in low-angle crossbeds. Minor silty layers or shaly partings separate the beds, usually less than 2 centimeters (0.06 foot) in thickness. Within the Tanglewood Member, a zone up to 3 meters (10 feet) thick containing prominent stromotoporoids (fossils of an algal or sponge-like organism preserved as lenticular masses or mounds up to a meter in diameter and half a meter in height) was identified during mapping (Cressman, 1967). This informal marker unit crops out in the Kentucky Horse Park and is important to the interpretation of the structural geology of the vicinity of the Kentucky Horse Park, as discussed below (Figure 3b).

The Brannon Member, where it occurs in the vicinity of the Sinking Creek Karst Basin study area, is composed of subequal amounts of interbedded shale and fine-grained argillaceous limestone (Cressman, 1965). It was mapped in the high ground in the Sinking Creek karst basin study area, but the mapped contacts were indefinite and rock exposure at that site is very poor. It is not known if it exists under the profile line established there.

Local downwarping and offset of the stromotoporoid layer within the Tanglewood Member provided the basis for the delineation of a shallow northwest-trending syncline shown by structure contours and the mapping of a fault in its axis (concealed for much of its length) through the axis of the study area (Cressman, 1967). These structural features parallel the long axis of the Royal Spring Groundwater Basin of Thrailkill and others (1982), and where the fault dies out its azimuth passes within a few degrees of Royal Spring Groundwater Basin. The only exactly located segment of the fault is near a small quarry in the southern part of the Kentucky Horse Park, and the exposure is so concealed by vegetation that the existence of the fault can no longer be confirmed on the basis of that outcrop (John Thrailkill, pers. commun., 1986). The offset on the fault is small, apparently less than 3 meters (10 feet). For purposes of this study, the effects of activity on that fault are not considered, though there may be a genetic relationship with the Royal Spring Conduit.

METHODS

History

Conrad Schlumberger of France and Frank Wenner of the United States are two of the better-known early workers to have investigated the behavior of electrical fields in the earth and to measure the resistivity of it, but the contributions of numerous other workers who investigated naturally occurring and artificial electrical phenomena were significant (Van Norstrand and Cook, 1966). Schlumberger mapped the potential fields created by electrode pairs fixed in the earth, and noted that in the presence of inhomogeneities the mapped equipotential lines were distorted from the normally simple geometries demonstrated by electrical fields acting on homogeneous ground. Later he found that the resistivities of earth materials vary over a wide range of values, which were replicable and could be mapped laterally and vertically by placing electrodes in the ground, setting up an electrical field, and measuring the drops in potentials at various electrode geometries. Wenner was employed by the U.S. Bureau of Standards, and though his own studies focused on precisely measuring the resistivity of the earth in areas no more than a few square meters, his observations that resistivity could be measured by the same method over larger areas led others of the Bureau to methods that allowed them to locate buried conductors. A thorough history of the study of electrical methods of earth prospecting can be found in Van Norstrand and Cook (1966); the lively story of the pioneers of the field is recommended to the interested reader, and credit is given to those excluded from the present account.

General Theory

The method of electrical resistivity as practiced today is relatively fast and nondestructive, can be used to locate a variety of subsurface features, and has rapidly gained popularity. Analytical solutions and mathematical models were derived by various workers to describe the behavior of an electrical field in materials of a range of electrical properties in various geometries. The most commonly applied of these solutions are (1) the behavior of an electrical field as it is carried laterally across a high-angle discontinuity, and (2) the changes in the apparent resistivity measured at the surface as an electrical field is expanded to impinge on successively deeper layers or segments of the earth. The section that follows sets out the basic principles of practical application of measurement of electrical resistivity, and is not intended to substitute for the more rigorous and broadly based treatises on the subject such as those by Kelley (1962), Keller and Frischknecht (1966), Kunetz (1966), Van Norstrand and Cook (1966), or Zhody and others (1974).

Placing two electrodes in the ground at a distance from each other and generating a current between them causes an electrical field to spread into the earth around them. The potential of the field decreases with distance from the electrodes, and is always at its maximum on a line between them (Figure 4). Configuration of current-flow lines around two electrodes with an electrical field between them (A and B, referred to hereafter as "current electrodes") is illustrated in Figures 5a and 5b. Note that the electrical field penetrates more deeply into the subsurface when the current electrodes are farthest from each other (Figure 5b) rather than when they are relatively close together (Figure 5a). By measuring the difference in potentials between two electrodes within that induced electrical field (M and N, hereafter referred to as "potential electrodes"), the resistance of the earth can be measured. Multiplying the resistance by a geometric constant derived from the relative positions of the current and potential electrodes yields the resistivity of the material beneath the electrodes. Resistivity of a material is defined as the electrical resistance of a unit volume of the material. The general equation for the geometric constant, K, is

$$K = 2*Pi \;/\; [(1/AM)-(1/BM)-(1/AN)+(1/BN)] \quad (1)$$

where AM, BM, AN, and BN refer to the distances between electrodes A, B, M, and N (Zhody and others, 1974). Resistivity, reported in ohm-meters (less commonly in ohm-feet), is an inherent property of a material independent of scale, analogous to density.

The relationship between the intervals AB and MN and the configuration of the electrical field is illustrated in Figure 4. Note that if the potential electrodes are placed at interval I-1, the potential drop measured will be of current that has penetrated to shallow depths. At interval I-2, equidistant from the current electrodes, the equipotentials are subject to the influence of the electrical resistivity of materials at depth as well as that of shallow materials.

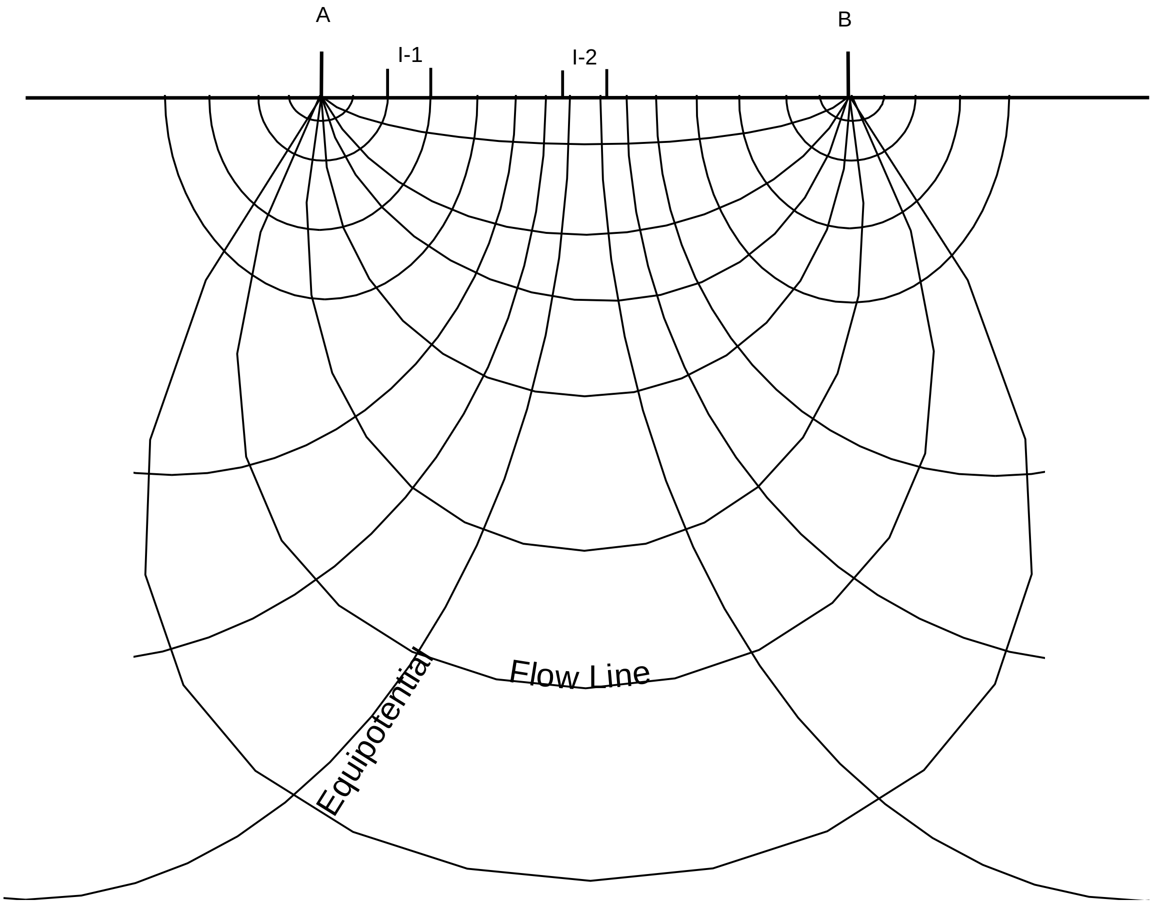
The term "apparent resistivity" is applied to readings taken in geophysical measurement of resistivity. True resistivity of the materials is best measured in a laboratory, where homogeneous bodies can be subjected to electrical fields in isolation from materials with differing electrical properties. True resistivity is usually not represented by the data gathered in the field, where the ground is almost always laterally and vertically heterogeneous in its electrical properties. Rock resistivities differ widely, and the presence of fluids (notably water) in the pores of rocks can have a strong influence on measured resistivity (Zhody and others, 1974).

All the preceding scenarios have illustrated the behavior of an electrical field in a medium of uniform resistivity. Figures 6 and 7 are schematic illustrations of the flow of electricity in a field that encompasses two layers of differing resistivities, after Mooney (1958). Current will preferentially flow through media of the lowest resistivity, but the effect of the resistivities of all of the materials to the maximum vertical and lateral extent of current penetration will contribute to the magnitude of drop in potential measured at the surface. Figures 5a and 5b schematically illustrate the extent of the subsurface materials that will affect the measurement of a potential change between two electrodes, and how that volume grows as the spacing of the electrodes is increased. Successively larger spacings of the current electrodes allow deeper penetration of the electrical field, and the potential drops created are due to the cumulative resistivities of both shallow and deep earth materials. The practice of taking repeated measurements over a single center while moving the current electrodes outward by steps is referred to as "vertical electric sounding" (VES, or simply "sounding," as used in this report) or "electric drilling" (Telford and others, 1976).

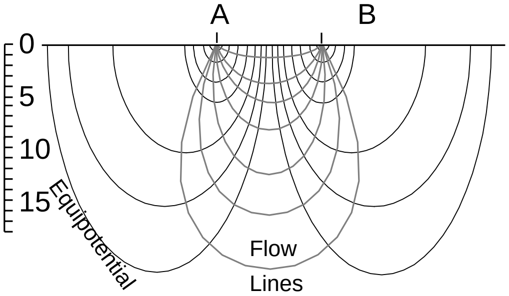
Interpretation of sounding data has received a great deal of attention in the published literature. Published families of curves for differing layer thicknesses and resistivities were popular for many years: field data could be compared to published curves normalized to the ratio of adjacent resistivities and a layer thickness could be determined; this would be carried out for each successively deeper layer based on the previously determined resistivity of the layer above it (Mooney and Wetzel, 1956). The vertical resistivity structure could thus be determined for every sounding along a traverse, and the data could be plotted and either contoured in section or plan view, or pseudo-sections could be constructed to present the hypothetical layers of the earth. Modern computer technology has brought about the availability of specialized programs for the interpretation of vertical electric soundings (such as the software package discussed later in conjunction with the Kentucky Horse Park study); in addition, at least one article has been published describing the design of a program to model VES data on spreadsheet software (Sheriff, 1992).

Determination of contrasts in electrical properties at a constant depth by taking successive measurements of induced electrical fields in regularly spaced intervals along the surface is referred to as "resistivity profiling" (or "electric trenching") (Telford and others, 1976). Profiling is usually accomplished by moving colinear elec-

Figure 4. Flow lines and equipotentials between two current electrodes, A and B.



5b. Electrode separation 13 units



5a. Electrode separation 6.5 units

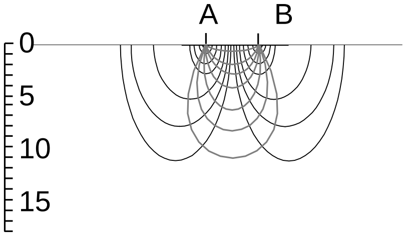


Figure 5. Current-flow lines and equipotential surfaces (schematic representation).

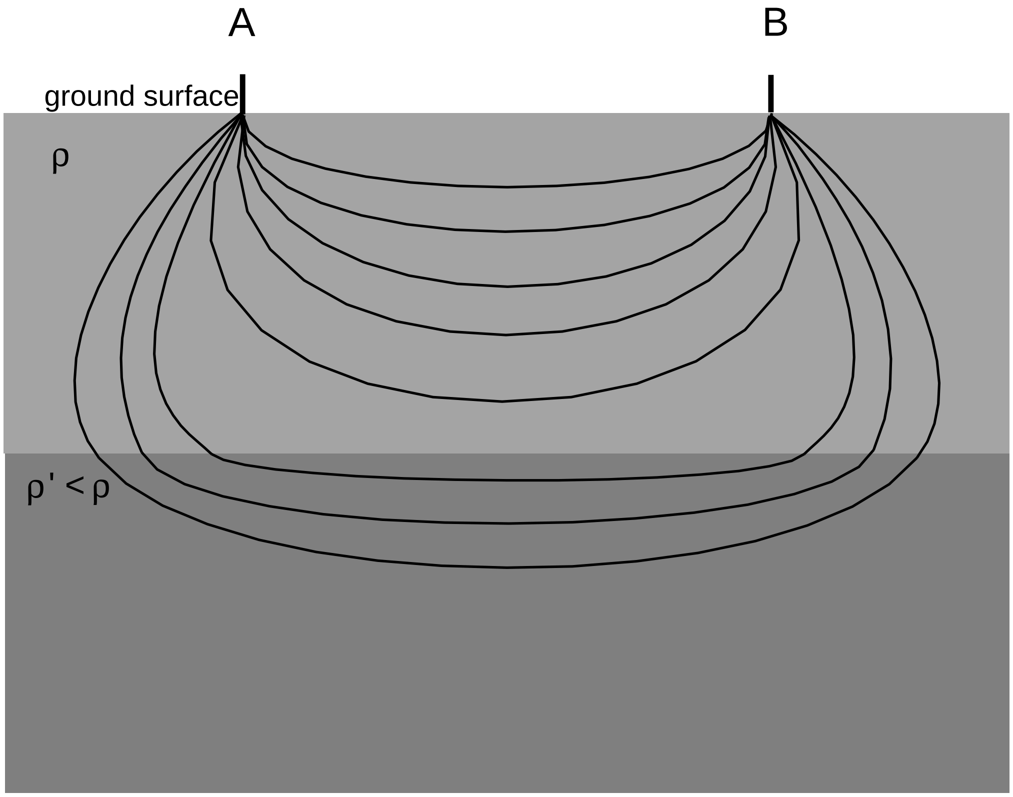


Figure 6. Flow-line configuration in layers of differing resistivity, lower resistivity at depth. The symbol for resistivity is ρ, scale arbitrary. After Mooney, 1958.

trodes incrementally along a fixed bearing, the increments set such that the potential-electrode interval overlaps the previous interval, thus achieving full coverage of the subsurface. Occasionally, the electrode array is pivoted by angular increments around a fixed center, or swung fan-wise from a single point, to test for anisotropy of current flow or for inhomogeneity on a scale smaller than the length of the array. Measurements are plotted in two dimensions, position versus resistivity, and trends and deviations noted. Large deviations to higher or lower resistances (or resistivities) are termed "anomalies."

Figure 8 illustrates the theoretical effect on apparent-resistivity readings as a traverse is carried across the surface over a buried perfectly conductive body. Although the true resistivity of the buried body is lower than that of the surrounding material, the apparent resistivity registered at the surface displays a complex behavior. The low in measured resistivity centered above the low-resistivity body is flanked by large, symmetrical peaks of high resistivity. The flanking highs can be explained by the theory of images; that is, as the array center approaches the wall of the geophysical boundary, the apparent resistivity registered between M and N is augmented by its own image, as light measured from a lamp in front of a mirror is augmented by its own reflection. Thorough treatment of this phenomenon can be found in Van Norstrand and Cook (1966). The strong "image effects" on apparent resistivity at these contacts is important, and interpreters of resistivity data must be aware of their presence. In three of the studies presented here, the large, water-filled conduit was expected to behave as a highly conductive body.

Electrode Arrays Used in These Studies

A common strategy used in electrical-resistivity studies involves a combination of profiling and sounding. Soundings are placed at intervals along profiles to investigate high- or low-resistivity anomalies in the profile data, to bracket suspected boundaries, or to furnish data for cross sections. The Kentucky Horse Park study employed profiles and soundings in this fashion. The presence of abrupt lateral inhomogeneities in the elec-

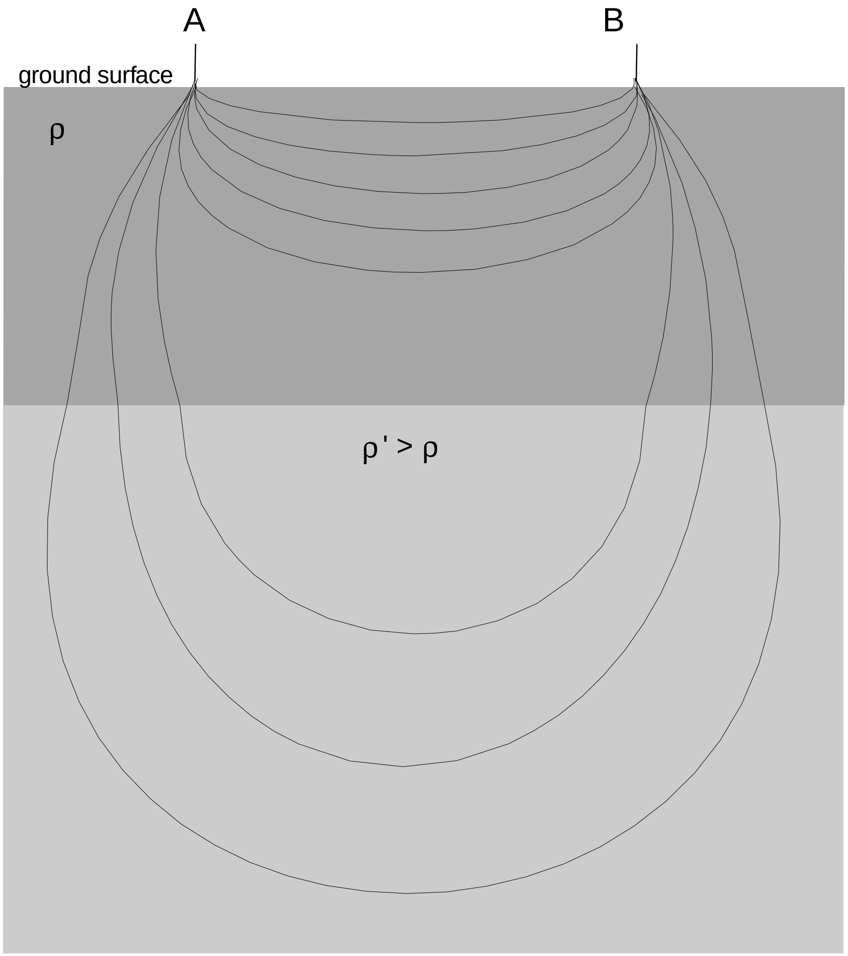


Figure 7. Flow-line configuration in layers of differing resistivity, higher resistivity at depth. The symbol for resistivity is ρ, scale arbitrary.

trical properties of the rocks of the study areas made contouring of resistivities or construction of pseudo-sections (wherein resistivities are plotted as a function of depth and contoured in cross section) impractical. Data collected along Ironworks Pike were in two profiles, including one “fan” profile where the electrode array was pivoted about one electrode at the end of the array. Sounding and two methods of profiling were applied in the Sinking Creek Karst Basin.

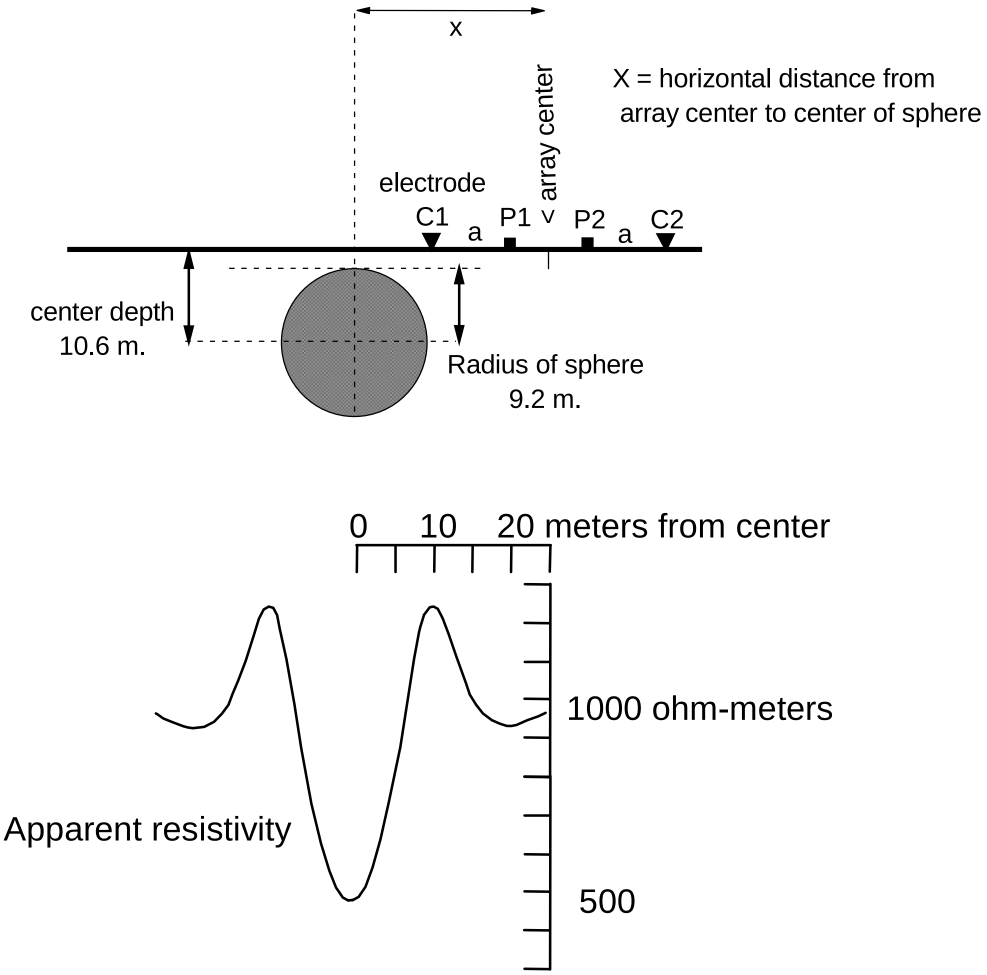
The Wenner electrode array, named for its originator, Frank Wenner, consists of four colinear electrodes at equal intervals from each other (Kelly, 1962). Current electrodes are placed at either end, and potential electrodes in the middle. Figure 9a shows the configuration of electrodes and the position of the array as profiling is carried out. Advantages of employing the Wenner array in the field include the simplicity of maintaining the intervals and data reduction. In the case of the simple geometry of the Wenner array, the geometric factor, K, is reduced to

$$K=2*Pi*a \tag{2}$$

(where a is the spacing between the electrodes) and multiplied by the measured resistance to obtain resistivity.

The main disadvantage of the Wenner array is that the subsurface volume influencing the measured resistance is rather large (Figure 7). Resistivity anomalies

Figure 8. Theoretical response of a Wenner array to a buried, perfectly conducting sphere (resistivity=0). Resistivity of surrounding material is 1000 ohm-meters, electrode spacing (a) 10 meters (modified from Van Norstrand and Cook, 1966, Figure 177).



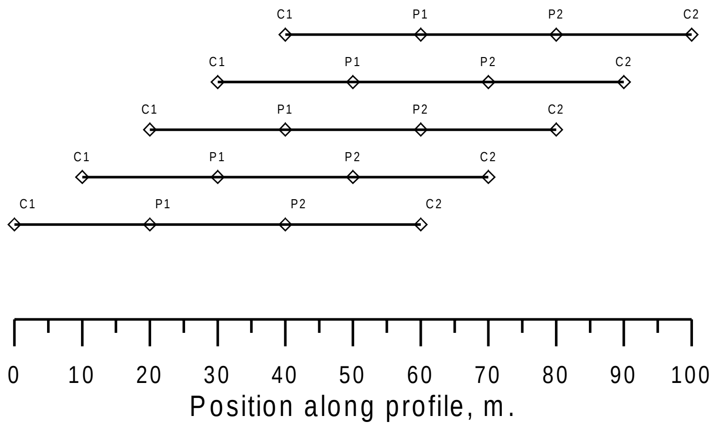


Figure 9a. Position of electrodes in line during profiling with the Wenner array or Tripotential profiling. Each resistivity reading is plotted at the position of the center of the array.

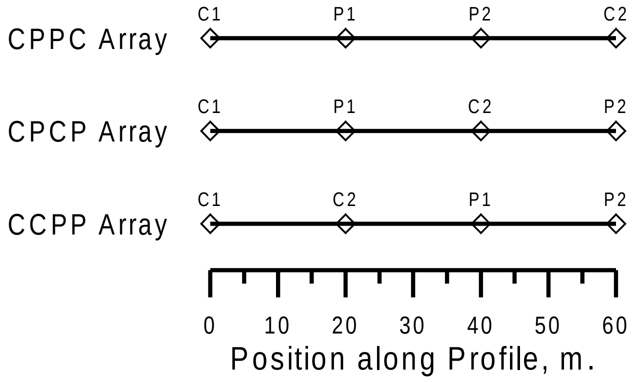


Figure 9b. Electrode functions for different arrays using the Tripotential method at Array Position 1 above. Cables running to the electrodes are reconnected at the junction with the instrument to switch between potential and current functions.

determined using the Wenner array can be ambiguous because it is not known if the part of the electrical field measured by the potential electrodes encompassed a small body whose resistivity contrasts strongly with that of the surrounding material (such as a water-filled conduit), or if the anomaly is due to a large volume of less contrasting material.

A simple means of augmenting the data available from a Wenner-array profile is called the Tripotential method (Habberjam, 1956; Ackworth and Griffiths, 1985). At each position where the Wenner array electrode configuration is placed and the resistance read, the cable inputs to the instrument are switched to an arrangement in which the current and potential electrodes alternate (Figure 9b). A resistance measurement is taken in this "CPCP" array. The cables are switched again to place both current electrodes at one end of the array, while the electrodes at the other end are connected as potential electrodes in a "CCPP" arrangement, and a third resistance is read. According to Ohm's Law, the CPPC resistance should equal the sum of the CPCP and CCPP resistances, and if the resistance of a homogeneous solid is being measured, this relationship would hold. In the presence of lateral homogeneity there is likely to be some variation from this equation. A percentage index of inhomogeneity, Delta, of the ground under each triad of readings can be calculated:

$$\text{Delta} = 100 * [(R_{cppc} - (R_{cpcp} + R_{ccpp})) / R_{cppc}] \tag{3}$$

where R_{cppc}, R_{cpcp}, and R_{ccpp} are the resistances read for the CPPC, CPCP, and CCPP arrays, respectively. Kirk and Rauch (1977) indicated that variation up to 2 percent is common for Delta, but that variations up to 600 percent can occur. Ackworth and Griffiths (1985) use the ratio of the CCPP and CPCP resistivities as a means of comparison of these two parameters: this method has the advantage of indicating their relative magnitude (which Delta does not). To convert tripotential resistances to resistivities, the resistances are multiplied by their respective geometric factors, K_{cppc}, K_{cpcp}, and K_{ccpp}. K_{cppc} is the same as the geometric constant for the Wenner array. The other constants are:

$$K_{cpcp} = 3 * \text{Pi} * a \tag{4}$$

$$K_{ccpp} = 6 * \text{Pi} * a \tag{5}$$

where a is the spacing between electrodes. The Tripotential method is useful because three times as much data can be collected at a single position. This method was employed in two profiles in the Kentucky Horse Park, in the study along Ironworks Pike, and in the Sinking Creek Karst Basin study.

A second commonly used array is the Schlumberger array, named for the geophysical pioneer. The Schlumberger array utilizes two current electrodes at the ends of the array and two closely spaced potential electrodes, usually at the center of the array. Close spacing of the potential electrodes allows for a small portion of the electric field to be measured and the position of any material with a distinctive resistivity signature to be located with some precision. This array lends itself particularly well to vertical electric sounding, because the equipotential lines in the center of the array are nearly vertical and there is little uncertainty about the lateral position of the subsurface interval whose resistance is being measured. Sounding with the Schlumberger array also requires moving only two electrodes (A and B, the current electrodes) until the current density has decreased enough that a potential drop can no longer be detected, at which point the current must be increased (not usually an option) or the potential-electrode (MN) spacing is increased. Figure 10 shows the Schlumberger array used for sounding. Data reduction of soundings made with the Schlumberger array can be tedious because the geometric factor, K, is calculated using Equation 6:

$$K = [\text{Pi} * (AB)^2] / MN \tag{6}$$

and must be recalculated for every change in spacing of either AB or MN. Profiling with the Schlumberger array is not usually considered practical because the reading spacing can be no greater than the spacing of the potential electrodes in order to maintain adequate subsurface coverage. Soundings using the Schlumberger array were used extensively in the Kentucky Horse Park study and less extensively in the Sinking Creek Karst Basin study. The resistivity configuration at positions other than the center of a Schlumberger array was investigated in the Sinking Creek Karst Basin study.

Data from soundings are usually plotted as apparent resistivity versus half-spacing of the current electrodes (AB / 2) on logarithmic axes. The term "apparent resistivity" is applied because, with the possible exception of data from the first one or two readings from the shallowest depths, the resistivity on a log-log sounding plot will be a composite value, influenced by the materials at the extreme depths of current penetration and by those overlying them. Figure 12 shows several sounding curves.

EQUIPMENT USED IN THIS STUDY

The instrument used to measure electrical resistivity in this research was an ABEM AC Terrameter type 5310 owned by the Department of Geological Sciences, University of Kentucky. This unit was manufactured by

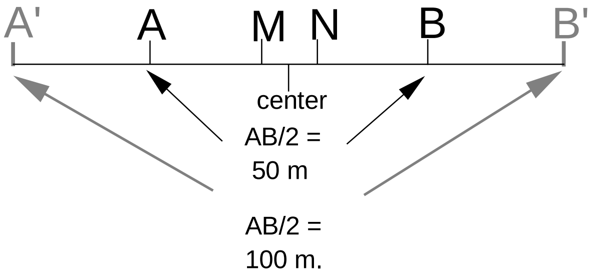


Figure 10. Expanding Schlumberger Array used for sounding. M and N, potential electrodes, are left stationary about the center of the array while A and B are expanded to create a successively larger electric field.

ABEM, of Sweden. Note that this unit utilizes alternating current; most of the theory developed for the electrical resistivity technique applies to direct current. Koefoed (1968, p. 1) noted that when alternating current is employed at very low frequencies, “the interpretation of the measurements can be based on the laws that govern direct current.” Kunetz (1966) discussed the advantages and disadvantages of alternating current, but two of the positive features are of interest in this study. First, the power requirements for alternating current are greatly reduced from those of direct current, thus making the entire apparatus very portable. Second, the unit only measures the potential of the field produced by a current alternating at the signal frequency of 4 cycles per second, effectively filtering out most of the background electrical “noise,” both man-made (from electrical transmission cables and spontaneous currents generated by buried iron objects) and natural (telluric currents and spontaneous potentials generated by contrasts in electrical properties of earth materials). Four steel electrodes with at least 100 meters (328 feet) of insulated cable apiece were supplied by the Department. A plane table, telescopic alidade, and stadia rod were used to map the immediate study area of the Sinking Creek study.

Previous Work

Many theoretical resistivity signatures of buried bodies of various sizes, shapes, and depth of burial have been published. Cook and Van Norstrand (1953) derived theoretical curves for profiling over ellipsoidal and hemispherical sinks and found that they compared favorably to field data from a carbonate terrain where the presence of filled sinks was demonstrated by drilling. Dey and others (1975) analyzed the response of various electrode arrays to a buried, conductive dike of a thickness about one-tenth of the width of the array. The differences in the results of the two studies are revealing. The sinks, a surface feature, generated a large response even when the traverse did not impinge on the perimeter of the sink, missing it tangentially (Cook and Van Norstrand, 1953, p. 170–171). The simulations conducted by Dey and others (1975, Fig. 3) indicate that for a conductive (low-resistivity) body at a depth equal to the separation of the potential electrodes, the response will be a positive (not negative, as intuitively expected) anomaly, and that for a body at greater depths the anomaly is considerably damped. Implications for the effect of depth of burial and geometric relationship of the array to the contrasting body are clear: (1) the larger and shallower the anomalous body, the more clearly it will appear in profiling, and (2) given the geometries of differing masses and their relative resistivities, the sign of the anomaly can, in theory, be opposite that of the true resistivities involved.

A large number of papers describing the use of electrical resistivity in the search for ground water have been written (e.g., Kelly, 1962; Breusse, 1963; Vincenz, 1968; Zhody, 1969). The method has seen less application in karst terrains, but some researchers have experimented with it and published the results. Denahan and

Smith (1984) conducted a series of profiles and soundings over a proposed ash-disposal site in Florida; low-resistivity anomalies they mapped were drilled into to determine if cavities existed. Correlation of cavernous rock encountered with low-resistivity zones, plus correlation of solid rock with high-resistivity zones, is judged to be very good, though by no means infallible. Fretwell and Stewart (1981) conducted soundings in a coastal karst zone in Florida; their work focused mostly on the salt-water / fresh-water interface and a layer interpreted as having a high transmissivity of groundwater due to karst processes. Dutta and others (1970) searched for cavities in a reservoir site in India, having carefully profiled the ground over known caverns prior to the survey. The use of a diagnostic profile of this sort was very helpful: it established that caverns in that terrain produced high-resistivity (positive) anomalies. Presumably, the caverns were air-filled (they had been explored and mapped underground), which accounts for the difference between Dutta and others' (1970) results and the anomalies mapped by Denahan and Smith (1984).

Extensive study was undertaken by Kirk and Rauch (1977) of the use of the Tripotential method in karst terrains. Several diagnostic profiles over known caves, filled sinks, and fractures displayed clear anomalies of several hundreds of ohm-meters. A filled sink of a diameter approximately half of the array spacing (a = 12.2 m, or 40 feet) displayed an anomaly of 500 to 600 ohm-meters, and a cave at half the a-spacing (6.1 meters, or 20 feet deep) generated an anomaly of 300 to 400 ohm-meters (Kirk and Rauch, 1977, Fig. 11). It is noteworthy that in the data presented, the response of arrays with the shorter electrode spacing (3 meters, or 10 feet; electrodes at half the spacing of the depth of the cave) to the presence of the cave is slight. An "anomaly" of less than 100 ohm-meters is generated, and this response is not above the apparent background variations in the profile (Kirk and Rauch, 1977, Fig. 11). Similar studies by Ogden and Eddy (1984) resulted in the delineation of large anomalies later found to overlie waterbearing features in Arkansas.

Electrical resistivity studies conducted in the central Kentucky area have mostly examined the faults that cut the rocks of the Inner Bluegrass. A series of theses undertaken by students of Eastern Kentucky University investigated faults of the Kentucky River Fault Zone to see if Tertiary sediments were offset. None of these theses contained any reference to the occurrence or effect of groundwater or to a water table (Paul, 1982; TenHarmsel, 1982; Cox, 1983; Dugan, 1983). Carlos Galcerán of the University of Kentucky studied faults in the Lexington Fault Zone, generated detailed resistivity pseudo-sections depicting the attitude and offset of geophysical discontinuities, and interpreted their structural significance to regional tectonic history (Galcerán, 1988).

Bonita (1993) included some vertical electrical soundings in his study of the Cane Run Groundwater Basin, in a location approximately 3 kilometers (9,800 feet) south-southeast of the Kentucky Horse Park. His cross sections and models include a laterally restricted zone or layer interpreted to be a zone of integrated conduits corresponding to the Royal Spring Groundwater Basin and feeding Royal Spring, but his methods were not designed with the objective of detecting and delineating individual conduits.

MARSHALL SPRING DIAGNOSTIC SOUNDING

A diagnostic signature of a resistivity sounding over a water-bearing conduit was obtained at the site of Marshall Spring in Scott County (Figure 11). Marshall Spring is a cave spring, where a stream issues from a conduit of 0.5 meter (1.6 feet) in height and 3 meters (10 feet) in width, and is in the Grier Member of the Lexington Limestone (Figure 3b). Three soundings using the Schlumberger array were conducted, one centered over the cave mouth and two others on centers 3 meters (10 feet) east and west of the center of the cave mouth. The centers of the soundings were approximately 3.2 meters (10.6 feet) above the level of the spring opening. Results of these three soundings are illustrated in Figure 12. The apparent-resistivity curve of the sounding centered over the cave demonstrates that a zone of lower resistivity (presumably that of groundwater) has a clear effect on the sounding curve: a drop in the apparent resistivity appears after the 6 meter current-electrode interval. The apparent-resistivity curves generated by the soundings 3 meters west and east of the cave contrast strongly with that centered directly over the cave. They show a low-resistivity zone at the surface (electrode spacings of 2 to 4 meters, or 6.5 to 13 feet) followed by a steadily rising resistivity signature (spacings of 6 to 40 meters, or 20 to 131 feet), with no apparent influence of a subsurface low-resistivity zone.

Initial conclusions drawn from these three soundings were, first, that groundwater in caves will conduct electrical current with markedly lower resistance (and hence, has a lower resistivity) than rock that does not contain water-bearing conduits, and that this contrast will be evident in electrical sounding curves. Second, the paired soundings suggest that the influence of that conduit on the electrical field was localized such that the apparent-resistivity curve of a sounding centered as little as 3 meters (10 feet) from the center of the conduit would not register a low-resistivity zone. Interpre-

Figure 11. Marshall Spring, Scott County, Kentucky. View is to the north-northeast, looking upstream. White scale to the left of the spring is 2 meters long. Diagnostic soundings were conducted on path or berm above the spring orifice.

tation of the Marshall Springs soundings is shown in Figure 13.

The resistivity values at the 2-, 3-, and 4-meter (6.5-, 10-, and 13-foot) spacings of soundings 2 and 3 are markedly lower than those for corresponding spacings in sounding 1. This is interpreted to demonstrate the effect of soil over bedrock in soundings 2 and 3; the soil has a true resistivity of 70 to 80 ohm-meters. The soil directly over the conduit at sounding 1 is very thin (less than 0.1 meter, or 0.3 foot), and the apparent-resistivity values of 900 to 1000 ohm-meters found in the 2- to 8- meter (6.5- to 26-foot) range probably reflects the resistivity of the upper part of the bedrock at that site.

KENTUCKY HORSE PARK STUDY

Introduction

The series of profiles and associated soundings in the Kentucky Horse Park was a concentrated effort intended to locate water-bearing conduits in the subsurface, and as such was conducted in a manner that differed in some respects from more conventional applications of the electrical-resistivity method. The delineation of hypothetical zones of low resistivity corresponding to the Royal Spring Conduit was attempted by profiling at a high angle (as close to perpendicular to the conduit as obstacles permitted) to the suspected trend of the conduit (Figure 14). Figure 15 illustrates the conceptual model of the configuration of Royal Spring Conduit and its resistivity signature in profile. It was assumed that the limestones of the Kentucky Horse Park area would display a relatively monotonous resistivity profile where unaffected by faulting, high joint density, or karst features. Against this background resistivity (the absolute value of which depends on the judgement and experience of the interpreter), a water-filled conduit was expected to manifest itself as a strong low-resistivity anomaly.

Traverses using the Wenner array were sometimes repeated at several electrode spacings to attempt to detect the influence of groundwater at various depths. The depth to which an electrical field will effectively pen-

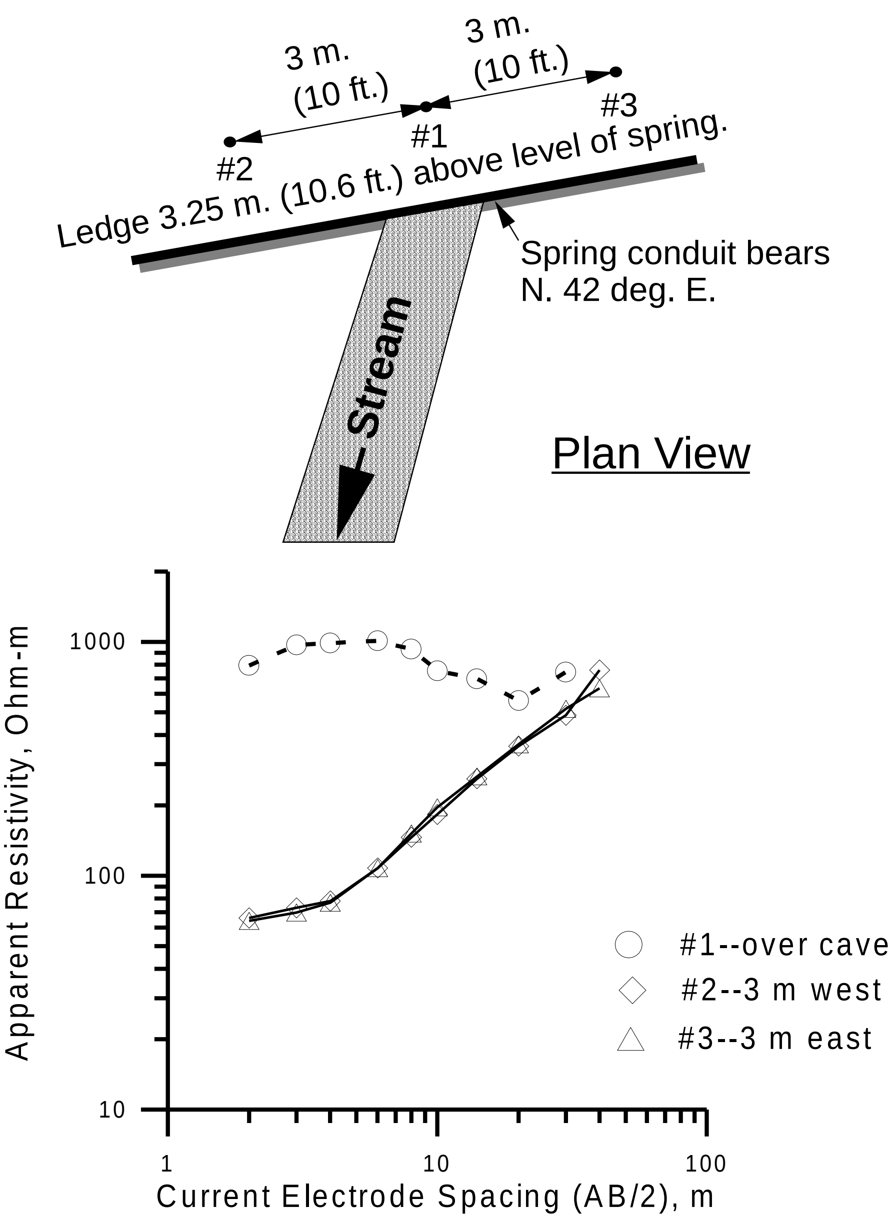


Figure 12. Marshall Spring soundings, Scott County.

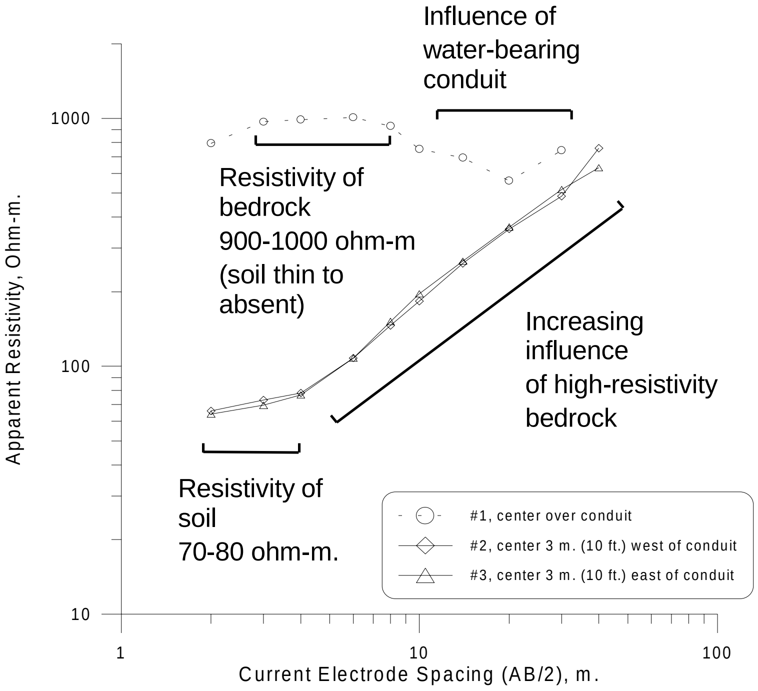


Figure 13. Interpretation of Marshall Spring soundings

etrate for purposes of exploration is a function of the distance between the current electrodes and the resistivity of the earth in that vicinity. No assumptions could be made at the inception of the project as to the most effective electrode spacing needed to detect the presence of a conduit or conduits. The maximum depth to the base-level conduit in the Royal Spring Groundwater Basin is constrained by the elevation of the spring itself. The elevation of the spring shown on the Georgetown 7.5-minute topographic quadrangle map is at or slightly below 244 meters (800 feet); in any given area the target depth can be calculated by subtracting 244 meters (800 feet) from surface elevation. Elevations of the ground surface in the Kentucky Horse Park study area ranged from around 256 meters (840 feet) to about 265 meters (870 feet); the target depth of exploration was therefore 12 to 21 meters (40 to 70 feet) The presence of conduits could be missed during profiling because the electrode spacing could be too small and hence the electrical field could not penetrate the ground deeply enough to be influenced by a water-bearing zone. Some profiles were repeated at different electrode spacings because no anomalies were detected in data gathered from the profile at the first spacing; the results are discussed under the descriptions of the profiles.

Soundings at various points on the profiles were conducted to attempt to ascertain the presence or absence of low-resistivity zones at depth. Low-resistivity anomalies in the profiles were clear targets for soundings, and in a number of cases numerous soundings within a few meters of each other were carried out in an effort to locate the low-resistivity zones in the vertical dimension (if any) that were responsible for the anomaly in horizontal profiling. The conceptual model guiding the sounding efforts was suggested by the soundings at Marshall Springs (Figure 13); the sounding over the conduit shows a relatively low resistivity, dropping from a higher resistivity at shallower depths. Soundings not centered over the conduit show a rising resistivity signature attributable to a simple soil-over-limestone geologic section.

The majority of soundings in this study consist of a series of resistance values from current electrode spacings of 8 to 10 meters (26 to 30 feet) at minimum to 40 or 60 meters (131 to 196 feet) at the maximum. Current electrode spacing is customarily reported as the distance from the electrode to the center of the array, or AB/2. If

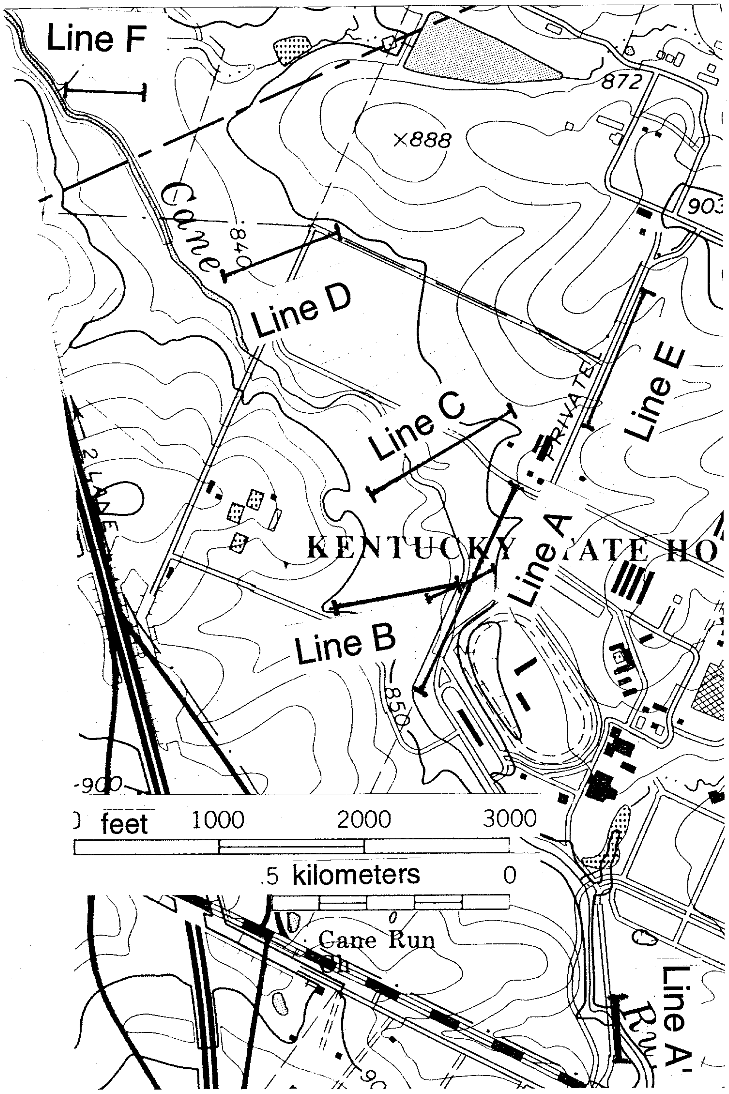


Figure 14. Profile locations, Kentucky Horse Park study area. Line T, not labled on this map, crosses Line A near the east end of Line B.

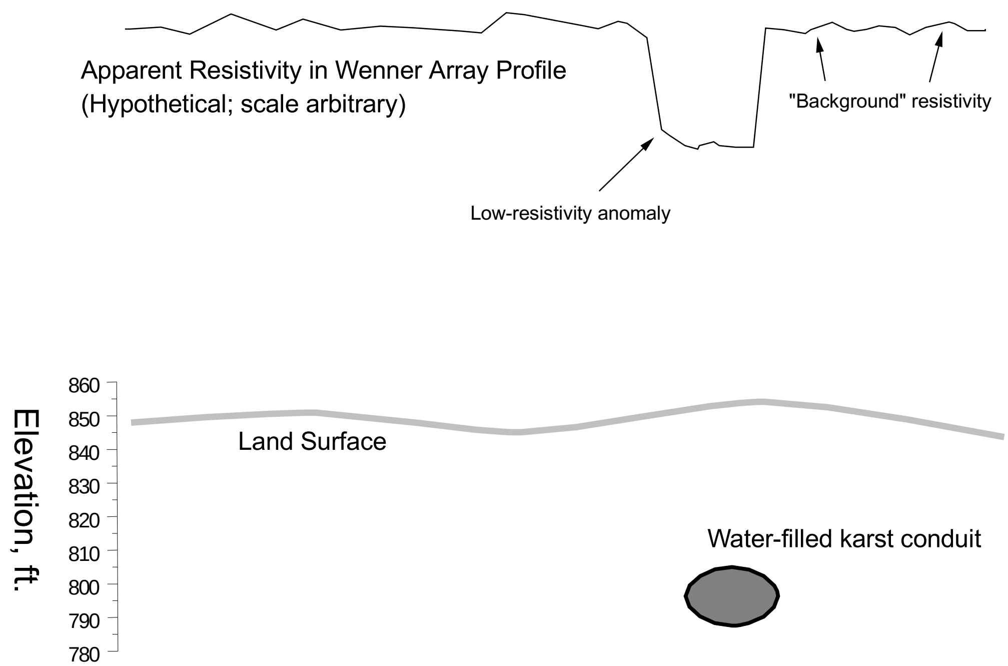


Figure 15. Conceptual basis for profiling in search of water-filled conduit

a calculated apparent-resistivity curve had not reached a maximum resistivity and then registered lower resistivity at larger electrode spacings (or, "broke downward," similar to the sounding centered over Marshall Spring, shown in Figure 13), it was judged in this interval to not be centered over a zone of low resistivity at the target depth; the likelihood of encountering a water-bearing conduit at this point is low. Points at which a sounding suggested a low-resistivity zone were often measured again by sounding with the same center point but with the electrode array oriented perpendicular to the original bearing. Zones of decreasing apparent resistivity with depth that appeared on soundings at both orientations were probably of greater lateral extent, and the point may have been marked as a possible drilling target.

A small number of large-spread soundings were taken; that is, soundings where readings were taken with the current electrodes very close to the center of the array and incrementally spread out to 80 or 100 meters (262 or 328 feet) on either side of the center. Soundings of this type, with data representing the apparent resistivities of the earth at very shallow depths as well as those of deeper zones, are the most common type employed in the investigation of near-horizontal layers, and are also the best for curve-matching or other modeling techniques that propose solutions for the thicknesses and resistivities of individual layers. The karst conduits of interest in this study are probably subhorizontal in attitude but are not of sufficient lateral extent to satisfy the demands of most modeling techniques. The data collection required to adequately perform such modeling require at least 10 or 12 resistivity measurements per sounding, a time-consuming procedure that was not routinely performed in this study.

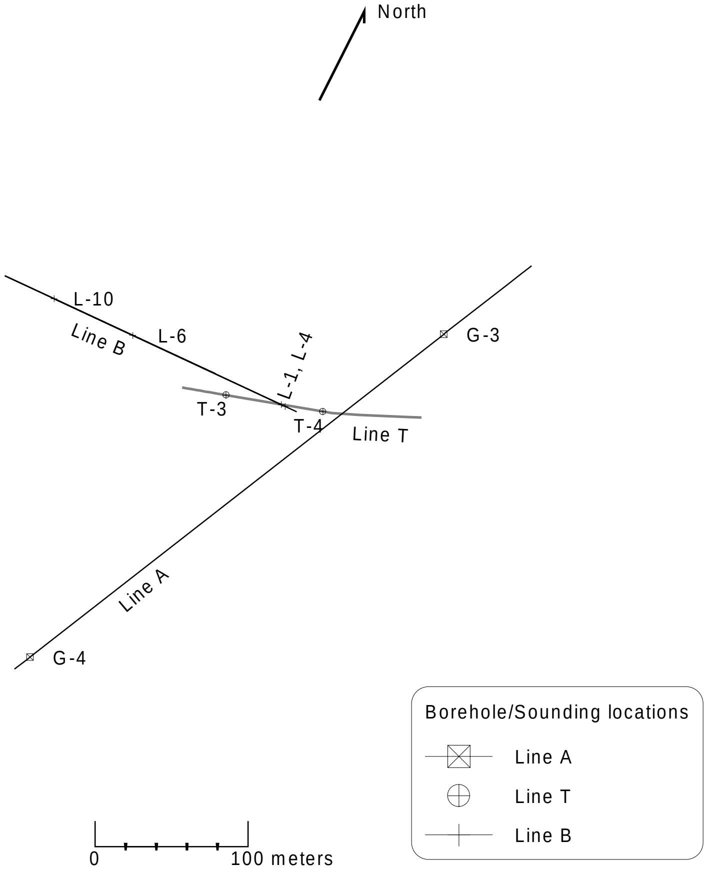
A driller, Benny Scott, was at this time working closely with geologist Tom Dugan at various locations in the Kentucky Horse Park, and a number of holes drilled by Scott were logged by Dugan. In addition, the driller completed official forms for all holes drilled and filed them with the Division of Water (Kentucky Department of Natural Resources and Environmental Protection), who assigned each hole a unique index number in the State registry (AKGWA number). The driller submitted a crude log of the wells and reported all occurrences of groundwater and an estimated yield. Many of the records are identified by sounding designations, but in all but a few cases the numbers on the DOW forms do not correspond to any known sounding from the Kentucky Horse Park project. This circumstance limits the State reports' usefulness for this study, but if the site number reported number matches a sounding it can be assumed that the hole was probably at least in the general vicinity of the sounding. Estimates of the yield of the well by the driller are considered reliable only relative to other yield estimates by that driller. Locations of the drilled holes used in the interpretation of the resistivity data are shown in Figure 16.

Interpretation

Preliminary interpretation of the results of the profiles in the Kentucky Horse Park and vicinity was carried out in the field. Profile data were examined and the points were noted where the apparent resistivity deviated strongly from a presumptive background resistivity, which was assumed to be the resistivity of soil over resistive limestone unbroken by dense fracturing or large karst features. The assessment of what resistivity threshold constituted background is usually based on the interpreter's knowledge of the average resistivities in an area and in that particular profile, and can be somewhat subjective, but generally a series of resistivities varying less than 20 percent was considered a background range. The range of background resistivity thresholds is from about 400 ohm-meters to 650 ohm-meters; backgrounds on the floodplain of Cane Run generally are at the lower end of that range and backgrounds for upland sites away from the main drainage are considered to be higher. Figure 17 shows the ranges of resistivities encountered at the Kentucky Horse Park and the background values assumed for each profile. Individual or clumped values deviating from background were considered anomalies and may have been investigated by electrical sounding. Soundings in which the apparent resistivity rose to a maximum value at electrode spacings of 40 or 60 meters (197 or 262 feet) and decreased at larger spacings were believed to be sited over zones of low resistivity, suggesting the nearby presence of a water-bearing karst conduit. Often a second sounding was taken over sounding centers that had shown low resistivity at depth, with the array turned perpendicular to the first sounding; a second low-resistivity signature was assumed to indicate a laterally extensive zone of low resistivity. Where a perpendicular sounding failed to demonstrate similarly low resistivity, the zone was not considered to be of large extent. Final interpretation utilized the comparison of profiles and sounding curves, diagnostic soundings, data from wells drilled in the sounding sites, and the presence of karst topographic features. The following interpretations were held to be most valid and applicable to the geophysical results of all of the lines in the Kentucky Horse Park study area.

- **Sounding curves that rise smoothly, or with minor cusps, from low resistivity at short electrode spacings to high resistivity at the widest spacings are over earth with few water-bearing fea-**

Figure 16. Boreholes in the central part of the Kentucky Horse Park used in the interpretation of resistivity results.



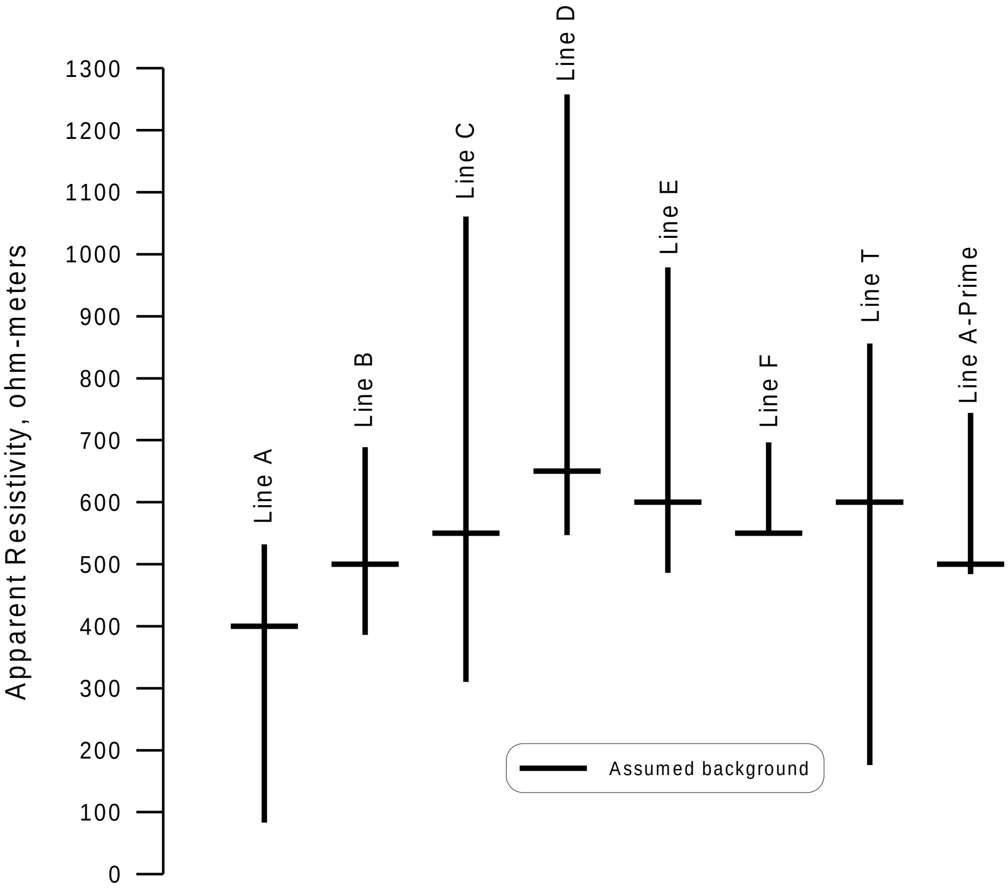


Figure 17. Comparison of apparent resistivity ranges and the assumed background resistivity thresholds, Kentucky Horse Park profiles. Resistivity values which fell below background were considered to be negative anomalies.

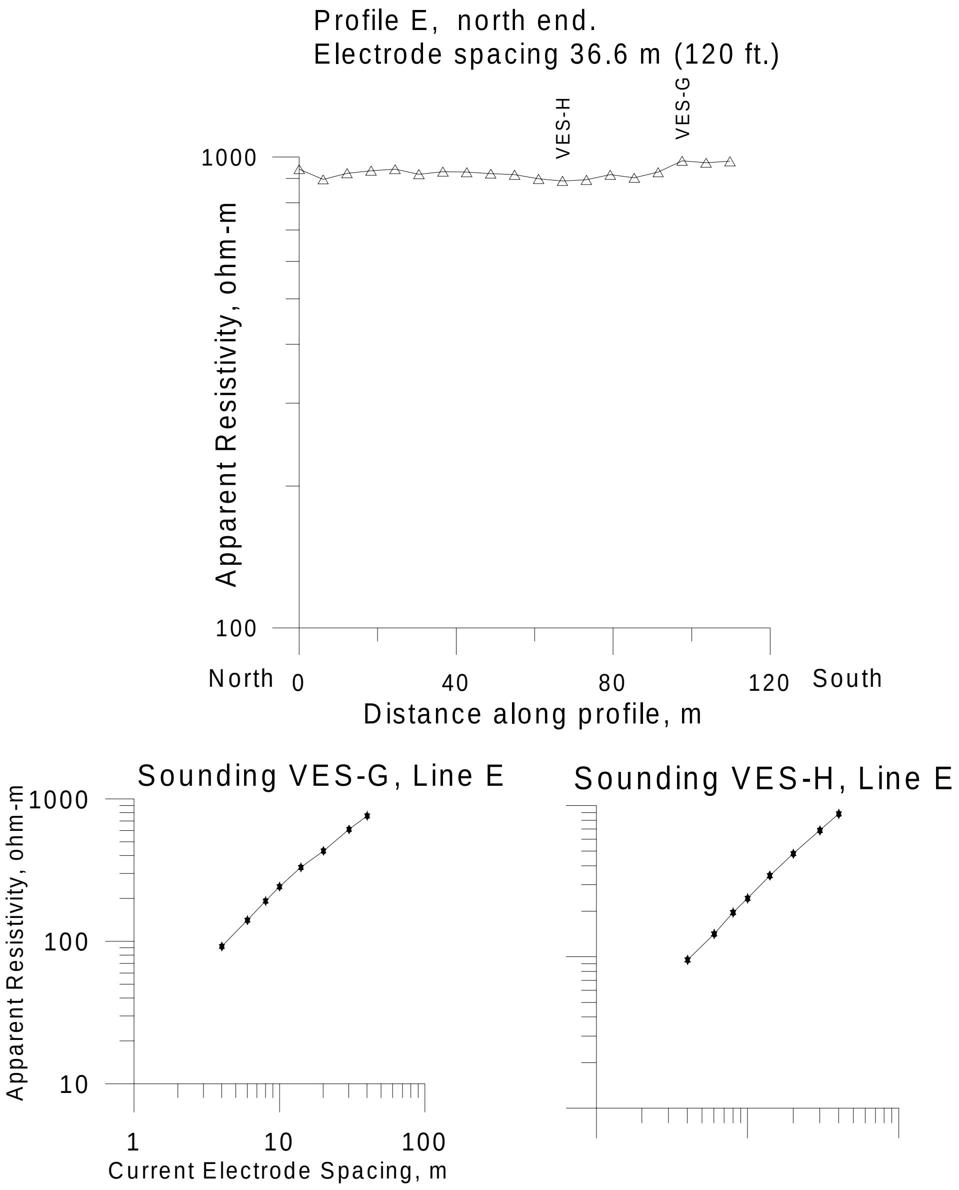


Figure 18. No karst or water-bearing features apparent in resistivity signature of profile or soundings.

tures. Combined with consistent, high background profile values (500 to 600 ohm-meters, varying from profile to profile), the segment of the study area is interpreted to be outside of zones of karst development or other avenues of significant groundwater flow. The soundings from Marshall Spring that were offset from the conduit were taken over solid limestone; their shape is distinctive (Figure 13). Profile data with consistent, monotonous trends or narrow ranges of resistivity values characterize profile data from areas distant from visible karst features. Figure 18 shows the profile data and two soundings from the north end of Line E. The apparent resistivity of the profile taken with a Wenner array has no remarkable variations in this interval; the sounding curves trend smoothly to a maximum. Co-occurrence of these two resistivity signatures is believed sufficient to dismiss the presence of major low-resistivity zones, water-bearing fractures, or voids. In the interpretation of sounding data, the presence of minor changes in slope or of single points that do not follow the trend of a sounding curve are often attributable to inhomogeneities of the ground, or are the result of errors in electrode spacing or data manipulation (Zhody, 1974, p. 39) and are not significant in the interpretation of the sounding. Generally, topographic features indicating major subsurface solution activity are absent in these areas.

- **Erratic or spiky profile data combined with sounding curves reaching nearly 10^3 ohm-meters before stabilizing asymptotically with the X-axis (and in some cases, dropping slightly) indicate that numerous water-bearing cavities or zones of small vertical extent exist in the profile.** Figure 19a illustrates typical profile data of this sort, the central part of Line B. Different background ranges for data from Profile B can be suggested, but application of a single threshold is problematic, as the profile data vary widely and electrode spacing was changed in the middle of the profile. The existence of several water-bearing voids was clearly established by drilling on this profile. A localized background range of data up to 45 meters (150 feet) east of L-6 stays within a range of 386 to 447 ohm-meters, and three of the boreholes with the largest voids (L-6, L-6A, and L-6B with voids 0.9 meter, or 3 feet) were drilled in that part of the profile. Of the sounding curves from Line B, sounding L-6 had the greatest reduction in resistivity at wide electrode spacing (Figure 19c).

  Flanking the zone of lowest resistivity, wells logged at soundings L-10 (Figure 19b) and others encountered some small voids (0.1 meter, or 0.33 foot), some of which yielded water, but not in usable quantity. The profile resistivities range from 500 to 660 ohm-meters, and the soundings at L-1, L-4, and L-10 do not show a large resistivity decrease at larger electrode spacings. A semi-quantitative analysis seems to fit the data: soundings with slight drops in resistivity at large electrode spacings were probably influenced by small water-bearing zones 0.1 meter (0.3 foot) or less. Soundings that display a resistivity drop of 50 percent or more at wide electrode spacings can indicate the presence of voids approaching 1 meter (3.3 feet) in vertical extent encountered in drill holes.

- **A sharp drop in profile resistivity to less than 100 ohm-meters combined with a sounding curve that does not exceed 200 ohm-meters is located over a major water-bearing conduit.** Figure 20 shows the combined resistivity signature obtained at the site of sounding G-4. The consistently low resistivities between soundings run perpendicular to the profile bearing (G-4perp) and the sounding taken 2 meters (6.6 feet) to the north are unequaled by other soundings taken in the Kentucky Horse Park study. Drilling at this site encountered the Royal Spring Conduit.

- **Consistently low background resistivity in profiles near Cane Run indicates shallow groundwater.** The presence of a shallow water-bearing zone at the soil-bedrock interface is documented in holes L-4 and G-3, both of which are in close proximity to Cane Run. Occurrence of water at this interface has been documented in other studies in the Inner Bluegrass Karst Region (Keagy and others, 1993; Hampson, 1994). The influence of a shallow water-bearing zone is believed to create segments of low resistivity in profiles taken in sites where it was not confirmed by drilling. In profiles, shallow groundwater is interpreted to produce very low background resistivity, yielding a signature that is relatively uniform over a number of profile positions (Figures 21a and b). The signature of shallow groundwater in soundings is problematic: not all occurrences of groundwater at the soil-bedrock interface were manifested as a low-resistivity signature in soundings. Soundings such as G-1, 1.5 meters (5 feet) from hole G-1, taken over a zone of shallow groundwater, usually display resistivities well under 100 ohm-meters at the short electrode spacings (less than 8 meters, or 26 feet)

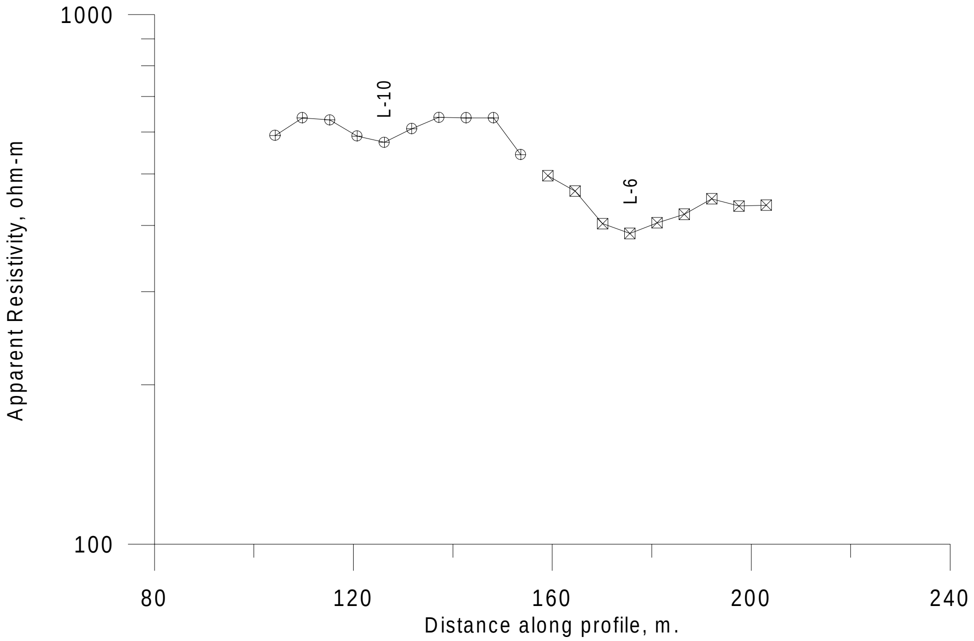


Figure 19a. Profiles over small- and medium-sized conduits, Line B, Kentucky Horse Park

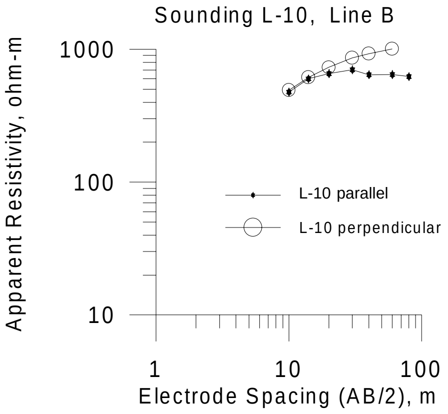


Figure 19b. Sounding over small-sized conduits (<0.1 m)

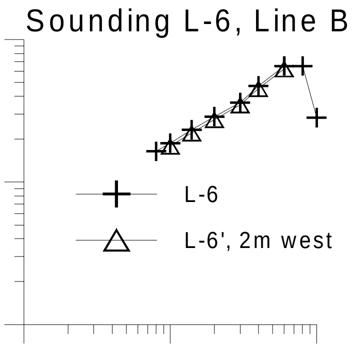


Figure 19c. Sounding over medium-sized conduits (<1 m.)

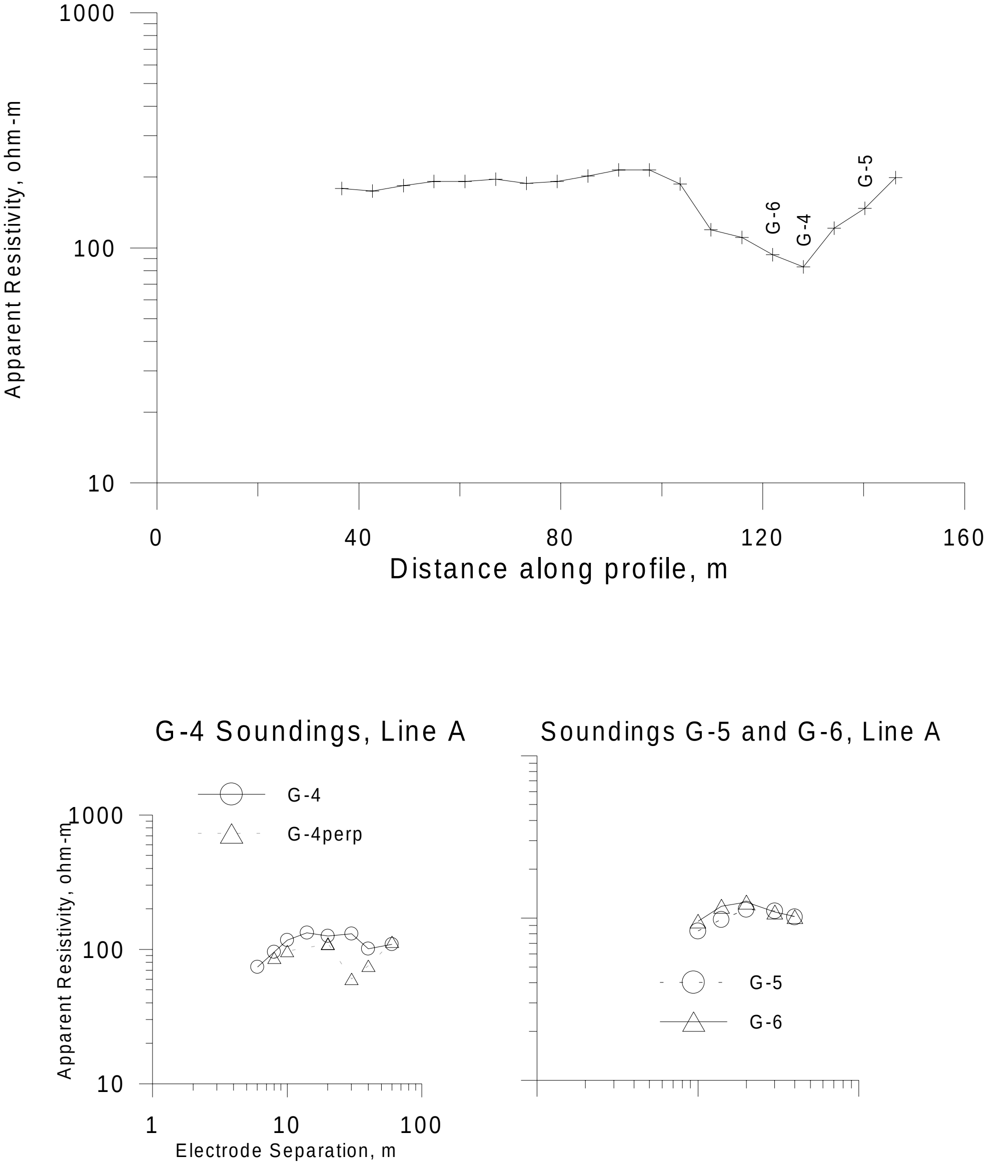


Figure 20. Profile and soundings over Royal Spring Conduit, Line A, Kentucky Horse Park.

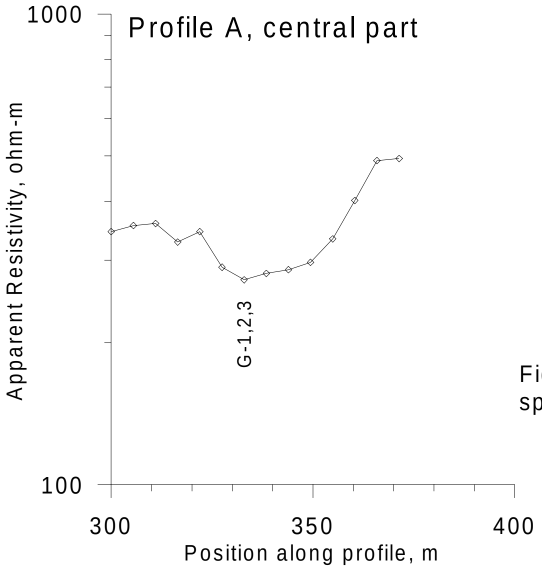


Figure 21a. Influence of water at soil-bedrock interface on Profile A, central segment.

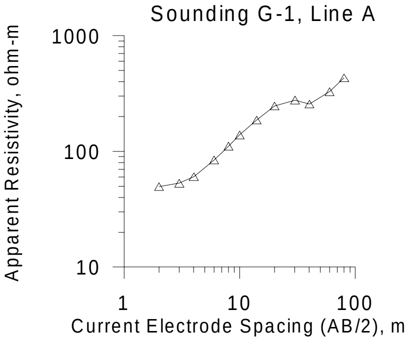


Figure 21c. Low resistivity in short-spacing (<8 m.) readings in soundings.

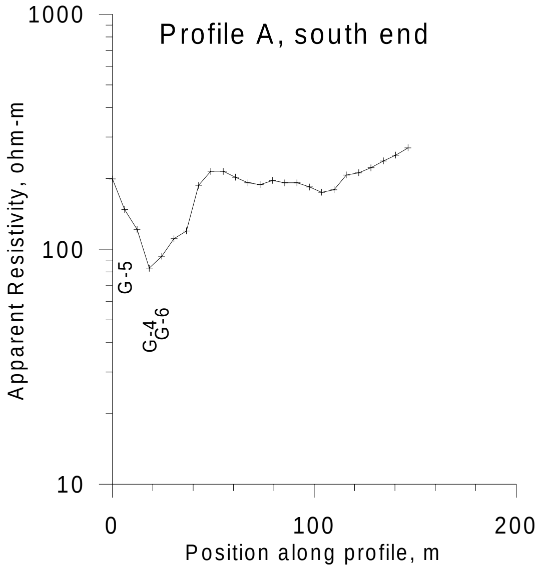


Figure 21b. Low "background" of profile resistivity, G-4 vicinity, probably due to shallow groundwater.

(Figure 21c), but the presence of water at the soil-bedrock interface apparently did not affect all soundings near Cane Run (see sounding L-4, Figure 44). The interpretation that an initial drop in resistivity in a sounding, followed by a large rise, is due to shallow groundwater is applied conservatively and only in proximity to Cane Run or other surface water. Sounding resistivities that drop to a low in the 4- to 10-meter (13- to 33-foot) range of electrode spacing, sometimes even falling below the shallowest (2-meter, or 6.6-foot) readings, as is visible in the sounding curves of HP-7, HP-7', HS-5, and HS-6 (Figure 37), may be due to groundwater at the soil-bedrock interface.

Layered-Earth Modeling

The profile of Line A' was complemented with a number of full-spread soundings (that is, soundings in which the electrode-spacing range starts at 2 to 4 meters [6.6 to 13 feet] and extends to 80 or 100 meters [262 to 328 meters]). This line was modeled, and a resistivity section was constructed using RESIX, a commercial resistivity modeling program (Interpex, 1990). The modeling routine consists of both forward modeling and inverse modeling steps. In forward modeling, the modeler conceives of a model of various layers and resistivities based on the shape of the curve, and the program converts this into an apparent-resistivity curve, simulating the measurements that would be registered if a sounding was conducted at the surface over that layer configuration. By comparing the result of forward modeling with field curves, the modeler can adjust the number of layers and their resistivities and thicknesses so that the model simulates the field data. Theoretical solutions to sounding curves are not unique, however. There always exists a family of model configurations capable of generating any single field curve, and it is best to constrain the model with as much physical data as is available. RESIX can "fix" any of the modeled layer thicknesses or resistivities to known values, according to the judgement of the modeler. A configuration of layers is selected for inverse modeling, and the computer program iteratively modifies the thicknesses and resistivities of some or all of the layers to more closely mimic the field data for a given curve until the modeler is satisfied that the model cannot be further modified to significantly improve the fit with respect to the field data. Residual error between inverse-modeled resistivities and field data is presented as a percentage error for each model. In this study, models were constructed, tested, and inverted only for Line A', where there was sufficient lithologic and hydrogeologic data to suggest a model and which model parameters should remain fixed during inverse modeling.

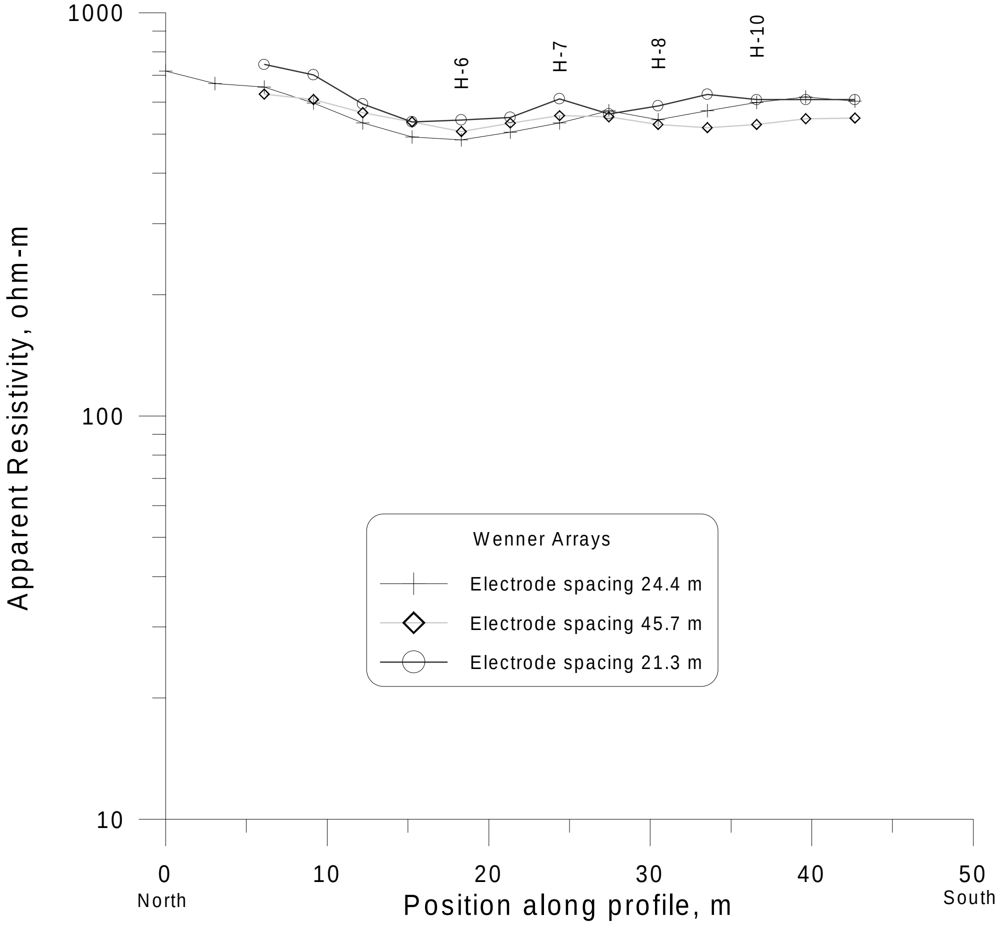
Studies Peripheral to the Royal Spring Conduit System

Figure 14 shows locations of the lines profiled in the Kentucky Horse Park study. Lines A', D, E, and F were close to the polo fields that were to receive irrigation. Line A' is in the southern part of the Kentucky Horse Park. Lines D, E, and F are around the northern polo field. Interpretation of the data from these lines indicates that these profiles do not impinge upon the Royal Spring Conduit system, or do so only peripherally.

Line A'. Line A' is located in the southern part of the park near a proposed polo field. Profiling with the Wenner array was conducted at three different electrode spacings. Steep low-resistivity anomalies were not found in this profile at any electrode spacing (Figure 22), and it is probable that the broad, shallow anomaly in which sounding H-7 was conducted may have more to do with the influence of surface topography than configuration of subsurface layers, because H-7 is located in the bed of Cane Run. Sounding H-7 (Figure 23) does show a decrease in resistivity at current-electrode spacing greater than 20 meters (66 feet), and this drop is more evident in the sounding curve for this site than in the soundings of other points on this profile. The spot was drilled, and some water had been encountered at 27.1 meters (89 feet) and 38 meters (125 feet) (Tom Dugan, pers. commun., 1986). Neither zone produced enough water for irrigation, and probably does not originate from conduit flow because the water was encountered considerably deeper than the target range of 12 meters (39 feet). The soundings of Line A' were modeled using RESIX (Interpex, 1990). The model consisted of a soil layer of moderately low resistivity, a high-resistivity layer of a fixed thickness of 25 meters (82 feet) representing limestone bedrock, a very low-resistivity layer representing the upper water-bearing horizon, and the bottom high-resistivity layer, again representing limestone bedrock (Figure 24). Agreement between models for the different soundings is fairly good, with the exception of H-7. Sounding H-7 could not be inversely modeled with that layer configuration to an error of less than 15 percent. This anomaly is interpreted to arise from lateral inhomogeneities beneath the sounding array at H-7, and is possibly related to the topography or surface materials of the creek bed.

Line D. Existing polo grounds were located at the north end of the park. Several small sinkholes in the vicinity suggested that the Royal Spring Conduit might

Figure 22. Profile A-Prime, with sounding points indicated.
Kentucky Horse Park



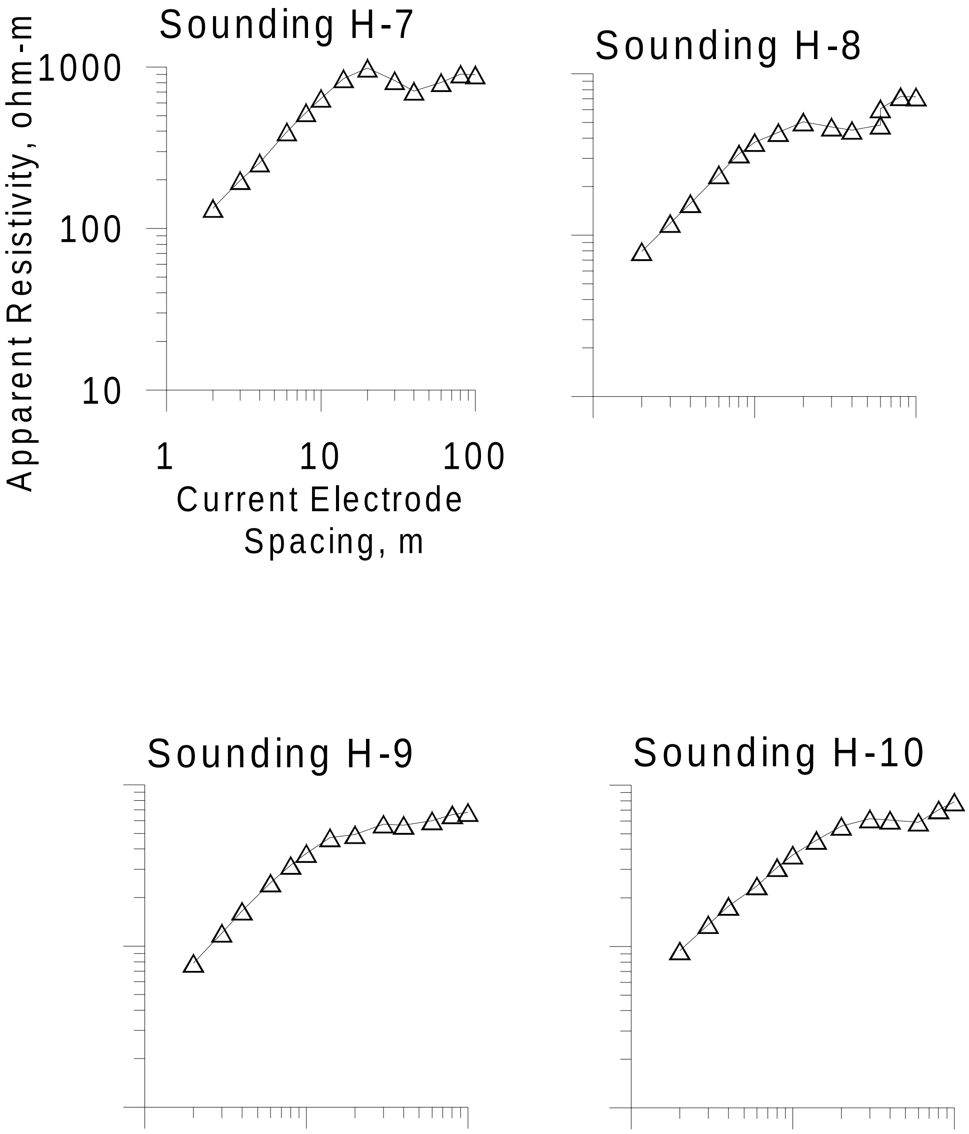
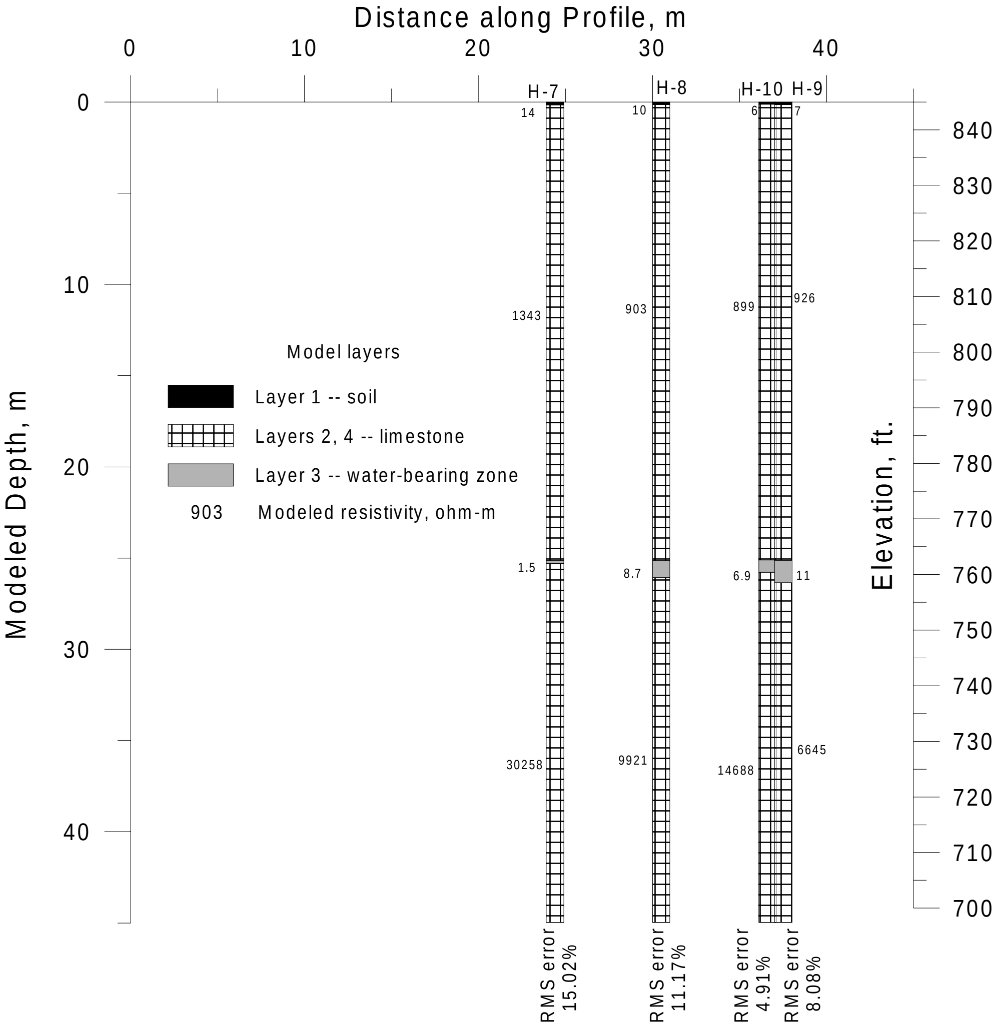


Figure 23. Soundings, Line A', Kentucky Horse Park

Figure 24. Modeled resistivities from soundings, Line A'. Layer 2 thickness fixed at 25 meters. Layer 4 thickness is infinity. Kentucky Horse Park.



run beneath the area. A traverse later designated Profile D was run through the vicinity of the sinkholes, first with an electrode spacing of 24.4 meters (80 feet) and later at a spacing of 45.7 meters (150 feet). At the time the minimum necessary electrode spacing required to penetrate to the depth of the conduit was not known and it was thought that an electrode separation of 45.7 meters (150 feet) might delineate more anomalies than the profile at 24.4 meters (80 feet). The results of this experiment are clearly that the 24.4-meter (80-foot) spacing is more sensitive to variations in resistivity, though it is probable that those variations are in the near-surface materials (Figure 25). A zone of lowered resistivity at the east end of the line was tested with soundings HS-12, HS-21, and HS-20 (Figure 26). None of the soundings at the east end of the line showed evidence of a large zone of low resistivity at depth, though the plot of HS-21 shows markedly higher resistivities overall and has a slight inflection in the 20- to 40-meter (66- to 131-foot) electrode spacings. A sharp drop in the profile data from around 1,000 ohm-meters to 600 ohm-meters starting west of 175 meters was explored with soundings HS-13 and HS-17. Data from these two soundings did not indicate a low-resistivity zone at depth (Figure 27).

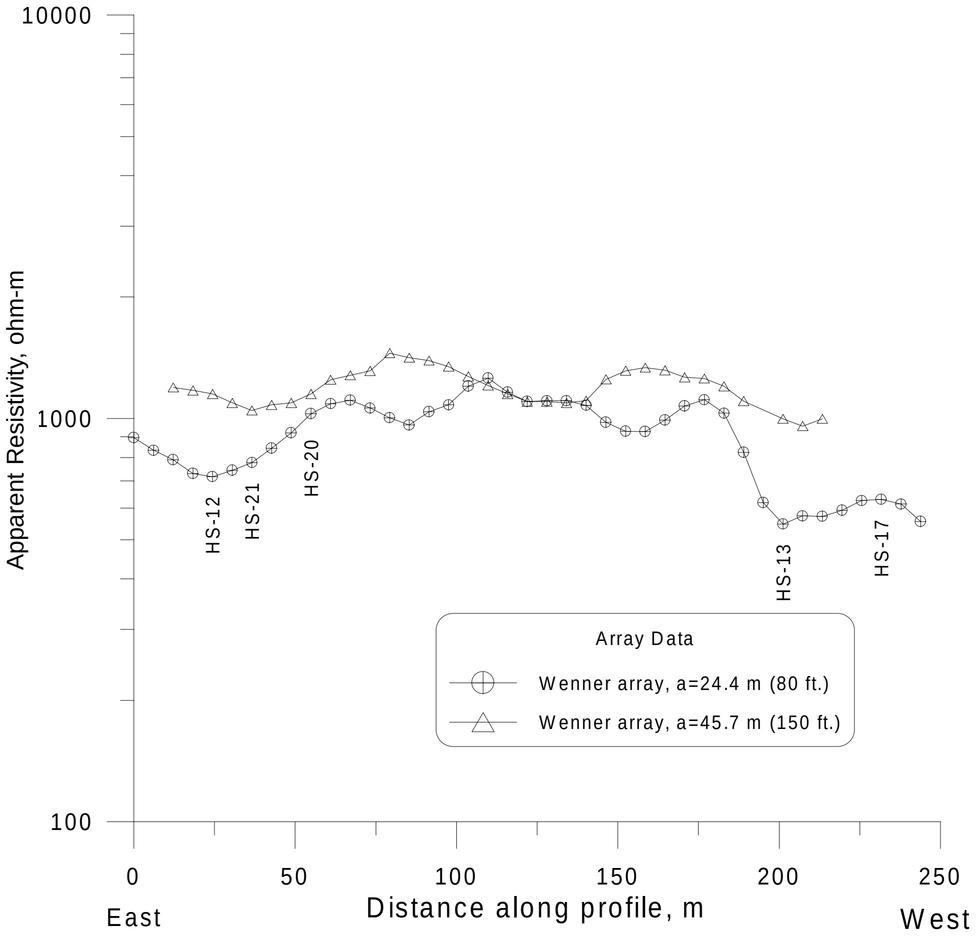
Interpretation of the data obtained at Line D is summarized in Figure 28. The presence of sinkholes, the overall lowered resistivity around HS-12 and HS-21 on the profile data, and the slight inflection of the sounding curve of HS-21 suggest that a zone of small distributaries, perhaps with some slight groundwater flow in the lower part, may exist in this area. The resistivity decline of 400 ohm-meters at the west end of the line probably reflects the influence of Cane Run, which was bank-full on that date, and was probably backflooding the soil and the soil-rock interface with surface water.

Line E. Profile E was conducted along a road leading out of the immediate valley of Cane Run and toward the road to the polo field studied in Line D above. Although the plot of the profile data (Figure 29) shows several sharp contrasts of resistivity over 10 meters (33 feet) or less, low-resistivity zones were not discernible in sounding data to electrode separations of 40 meters (131 feet). In order to bracket one of the largest of these contrasts in the profile data, four soundings, VES-A, VES-B, VES-C, and VES-D (Figure 30), were carried out within 18.3 meters (60 feet). The resulting curves were quite similar in shape. Overlaying the resistivities from the sounding curves on the plot of the profile data for these points (Figure 31) indicates that the slope of the profile data is not mimicked by that of the sounding data, and indeed the irregularity of the sounding data suggests lateral changes in resistivity. The southern part of the profile showed an anomaly that was tested further with VES-E (Figure 30), the curve of which, while not having a discernible drop in apparent resistivity, nonetheless became asymptotic with the X-axis at a resistivity value considerably lower (around 500 ohm-meters) than that of the other soundings of this line (700 to 800 ohm-meters).

Interpretation of Line E will be in general terms. Soundings along this profile were not full-spread soundings; lack of data, particularly at spacings greater than 40 meters (131 feet) or of any subsurface geologic data from drilling, preclude the modeling of these soundings and the construction of a resistivity section for this profile. The northern 100 meters (328) of the profile are free of any anomaly, but as the array was carried southward and downhill, there is an overall drop in the profile's apparent resistivity. The decrease is greatest between VES-F (115.8 meters, or 380 feet) and VES-A (140.2 meters, or 460 feet), where it dropped to 78 percent of the resistivity at VES-F. The noise in the curve to either side of this interval suggests the rises and dips in apparent resistivity that are encountered near vertical contacts between materials of markedly different resistivities, according to the theory of images discussed by Van Norstrand and Cook (1966). Or, the profile could have crossed a contact between sedimentary layers of different geoelectric properties during the descent of the sloping road. The geologic map of the area does not indicate either vertical (fault) or horizontal (stratigraphic) contacts in the vicinity of Line E (Cressman, 1967). The interpretation proposed herein is that the northern segment of the line crossed ground relatively unaffected by karst processes, while the influence of minor tributary and distributary conduits associated with the Royal Spring Conduit is noticeable in the southern part of the line.

Line F. A well had been drilled on property adjacent to the park that had intersected a major karst conduit of the area (Barton's well) (Figure 2a). On a line between the well (a point known to intersect the conduit system) and the sinkholes along Profile D was a plowed field of low relief. Profile F (Figure 32) was conducted near this line on a day when the ground was moist with rain. The Tripotential method was employed for this profile, to maximize the detection of lateral inhomogeneities of resistivity. A plot of the Wenner-array resistivity of the profile showed no significant anomalies. The CPCP and CCPP resistivities were more erratic, probably due in part to variations in soil moisture. Sounding F-1 (Figure 32), at a low point in the Wenner resistivity profile, showed no sign of a low-resistivity zone at depth. Line F is interpreted to have encountered no discernible karst features.

Figure 25. Profile D, with sounding points indicated.
Kentucky Horse Park



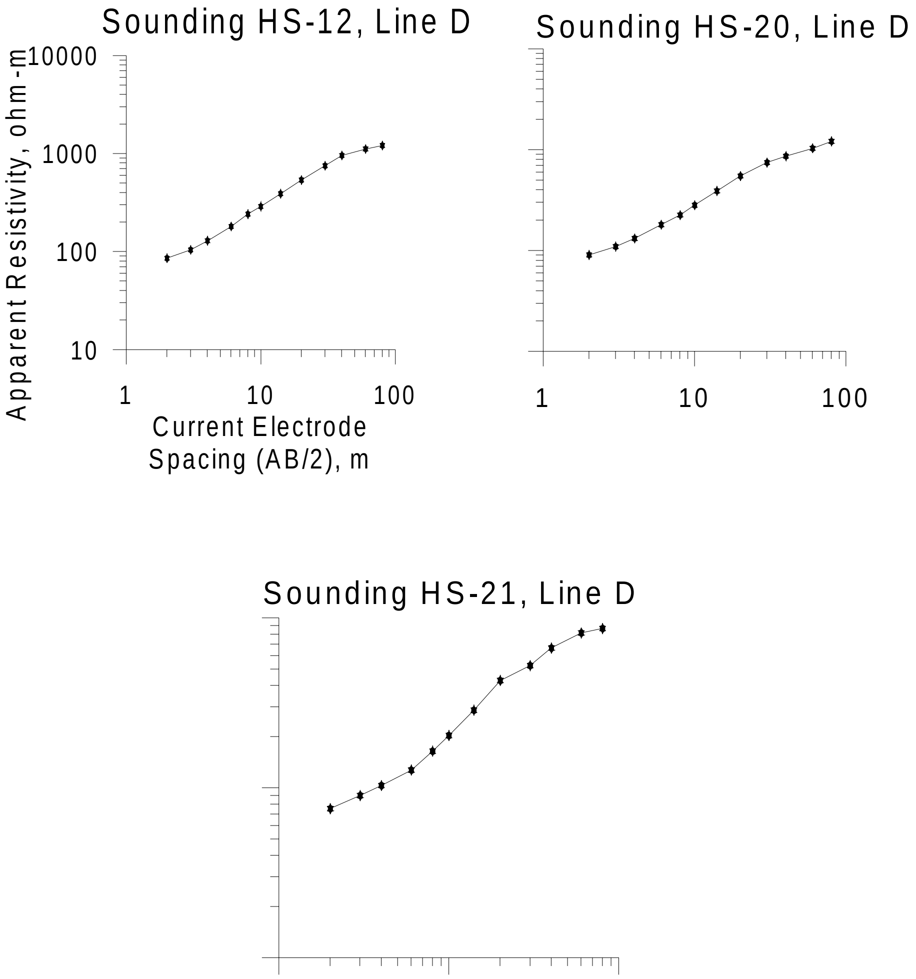
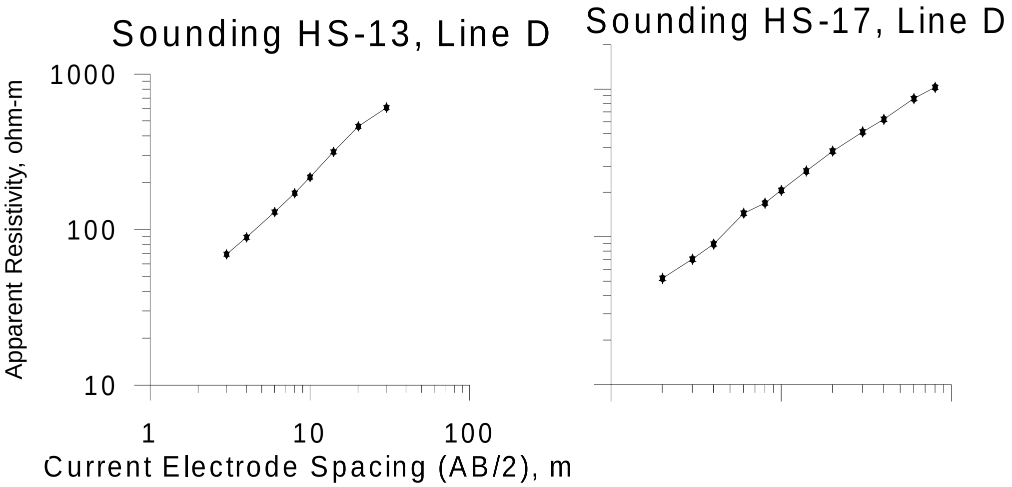


Figure 26. Soundings, east end Line D, Kentucky Horse Park.



Sounding HS-13, Line D

Sounding HS-17, Line D

Figure 27. Soundings, west end Line D, Kentucky Horse Park.

Figure 28. Profile D, with interpretation.
Kentucky Horse Park

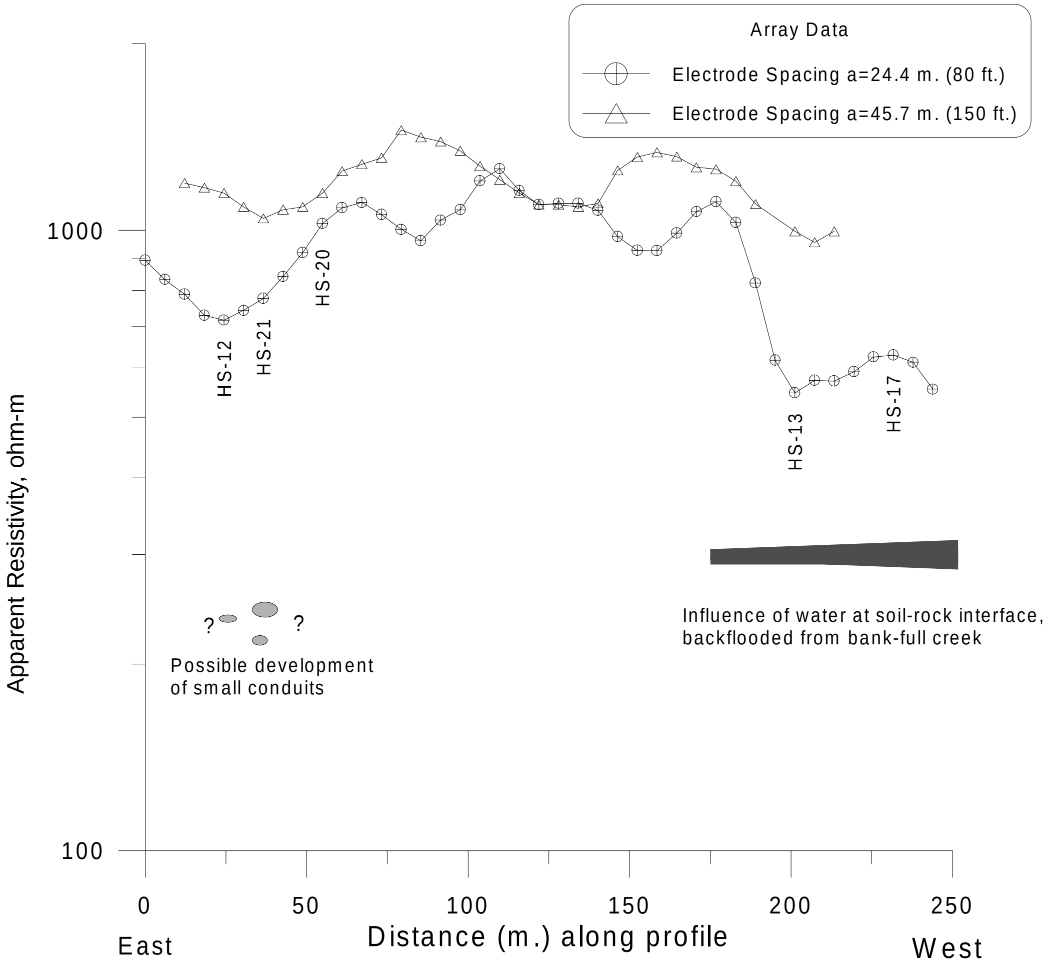
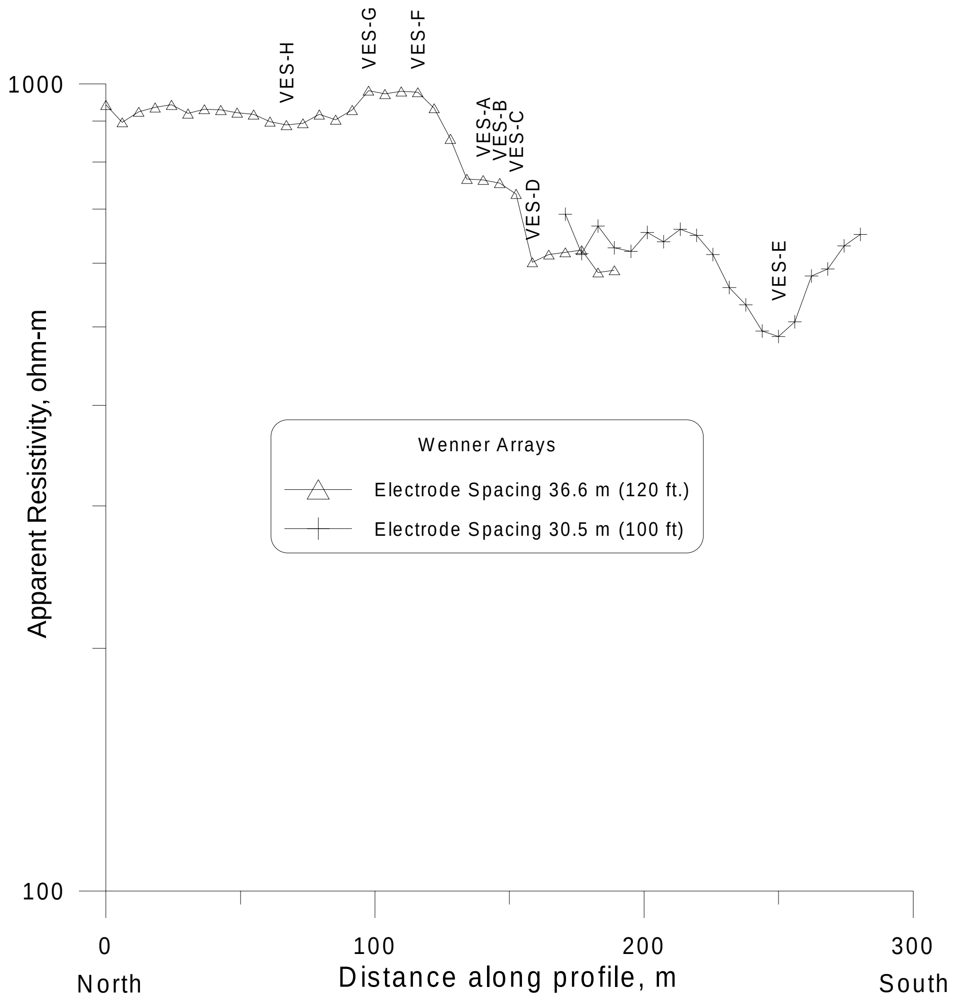


Figure 29. Profile E, with soundings indicated.
Kentucky Horse Park



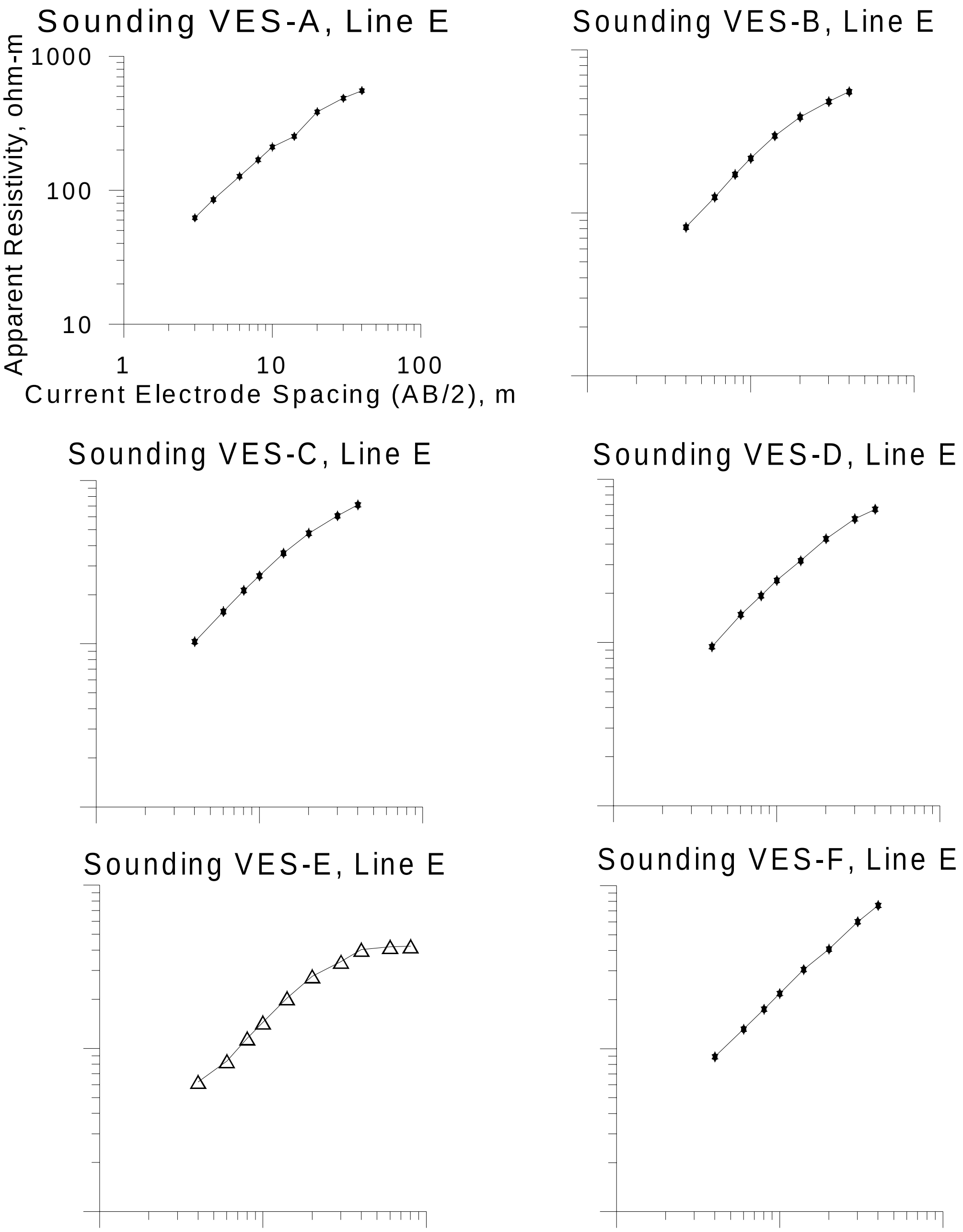


Figure 30. Line E soundings, Kentucky Horse Park

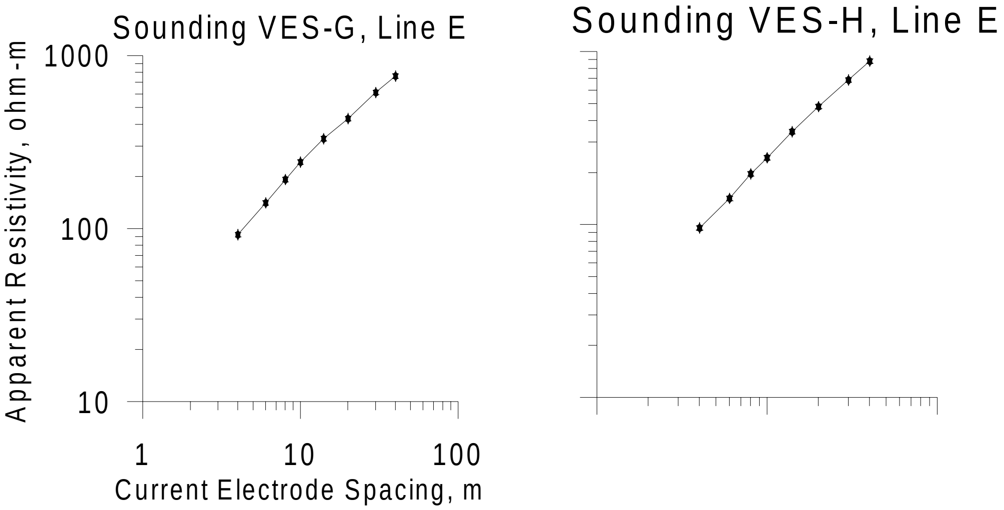


Figure 30, cont. Soundings, Line E. Kentucky Horse Park

Figure 31. Profile E, central part, with sounding data overlain. Kentucky Horse Park

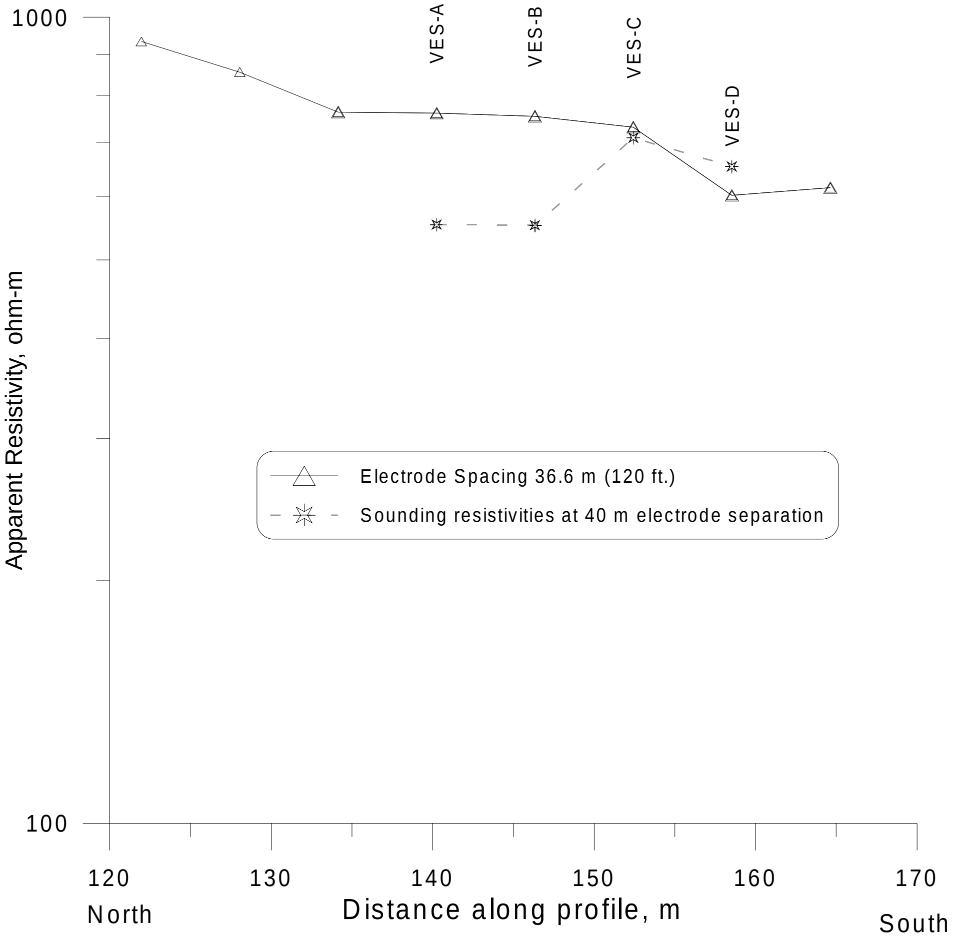
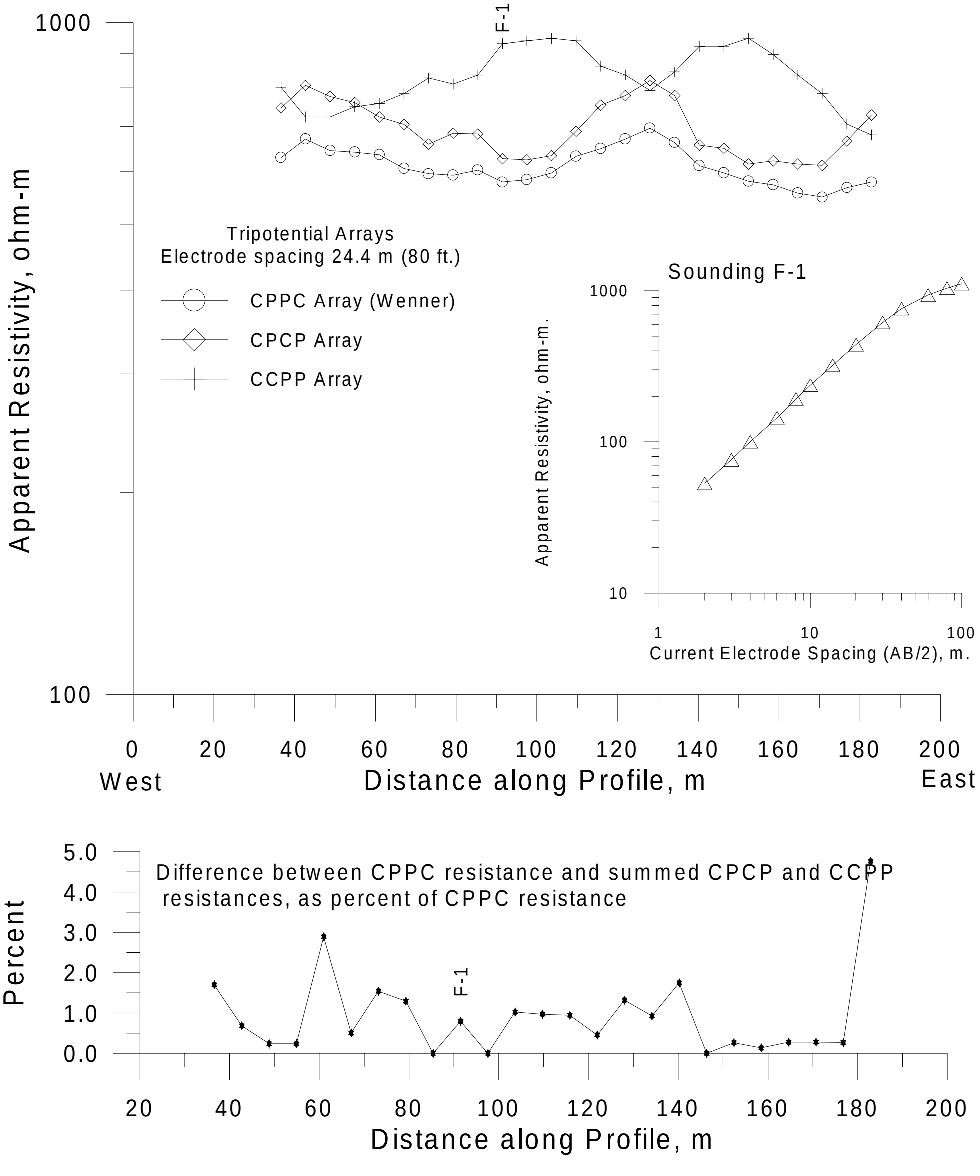


Figure 32. Line F, Tripotential Profile
with sounding indicated, Kentucky Horse Park area.



Studies in the Central Kentucky Horse Park

The central part of the park became the locale for intensive study when it was judged that no resistivity signature of the Royal Spring Conduit was found near the polo fields in the northern part of the park (Figure 14). Old topographic maps of the central Kentucky Horse Park area show a large, curving sinkhole, later filled during park development and now occupied by an oval track used for equine events, visible in Figure 14, east of Line A and southeast of Line T. In addition, Cane Run was frequently dry below that area; a series of swallow holes approximately 150 meters (500 feet) along that reach of the channel effectively diverted all water from upstream underground during low to moderately low flow. The area was also along the main road through the park, and to the east of Cane Run was somewhat congested with barns, driveways, maintenance sheds, buried utilities, and paddocks occupied by horses. The setting provided a number of challenges to operating geophysical apparatus using long cables in straight-line arrays, but the density of features associated with the modern karst-flow system strongly suggested close proximity to the Royal Spring Conduit or a major tributary of it. Interpretation of the geophysical data for this locality was greatly aided by drilling results at various sounding sites, the locations of which are shown in Figure 16.

In this section of the study, measurements were repeated on days when there was reason to believe that there had been change in the electrical properties of the ground. Of greatest concern was the effect of soil moisture on near-surface resistivity. When profiles were continued on different days, the last point measurement in a profile was repeated on the day that the profile was extended. Line A profile values did not differ greatly, only about 6 ohm-meters or 2.3 percent of the previous measurement. Tripotential values from Line T were more divergent, and in the case of the CPCP array the difference was 86 ohm-meters, or 10.3 percent of the previous value.

To make a more thorough investigation of differing conditions, the array was set up over a sounding point, and some or all measurements for a vertical electric sounding were taken. Figure 33 shows the repeated measurements taken at L-10 for purposes of monitoring changes at that site. The greatest change was a decrease of 45 ohm-meters, or 6.4 percent, hardly significant to the interpretation methods employed in this study.

Repeated soundings at HP-1A (Figure 34) show a systematic difference that cannot be seen in the relatively frugal series of re-measurements at L-10; the resistivities measured later (on December 14, 1986), shortly after rainfall, were considerably lower than those that had been taken a month earlier, and the differences were most apparent in the measurements taken at spacings less than 60 meters (197 feet). Smaller spacings correspond to shallower depths; the effect of antecedent moisture conditions on electrical resistivity measured in the soil zone is very strong. The shape of the original sounding curve and that of the repeat curve are similar, and the steep decrease in resistivity at electrode spacings greater than 30 meters (98 feet) is still noteworthy, but the 50 percent decline in the resistivities of the short spacings between original and repeat curves is a cautionary sign that detailed analysis of sounding data, and especially the comparison to other soundings, must be approached with due attention to antecedent moisture conditions.

The repeat sounding at L-1, Line B, was taken after a borehole 8 centimeters (0.25 feet) in diameter had been drilled at the sounding center. Water in the hole had been encountered at 13.4 meters (44 feet) depth during drilling, and the water level in the borehole had risen and was measured at 8 meters (26.3 feet) depth on the day that the sounding was re-run. Figure 35 shows a 5 percent difference, which is slight, in the readings from 14 meters (46 feet) to 40 meters (131 feet). The final reading on the later date is of interest: resistivity measured at 60 meters (197 feet) current-electrode spread is 180 ohm-meters less than the original, a 26.5 percent difference. This change cannot be explained by changes in the near-surface layers due to rainfall or soil moisture, as the readings for the two surveys converge at the shorter spacings corresponding to shallow layers. The second sounding may reflect the effect of the water rising in the borehole and entering permeable zones, reducing the resistivity of the rock at a higher level than had been possible prior to drilling.

Line C. Profile C was run from the west across Cane Run across a tributary waterway or ditch and up the slope to the east of Cane Run. A negative anomaly was encountered extending from Cane Run east across the tributary, while several low-resistivity anomalies of lesser magnitude were encountered toward the east and west ends of the profile (Figure 36). The resistivity drop in the middle part of the profile was covered by closely spaced soundings (from the west, soundings HS-4, HS-2, HS-1, HS-5, HP-7, HP-7', HP-7'perp, and HS-6) (Figure 37); only HP-7 and HP-7' showed reduced resistivity at depth, and it is noted that the cable to the easternmost current electrode for readings at 60, 80, and 100 meters (197, 262, and 328 feet) lay across a buried power line. In theory, the ABEM instrument will only be minimally influenced by the sort of electrical interference

Figure 33. Sounding L-10, Line B, repeated on 3/15, 3/27, and 4/4/87. Kentucky Horse Park

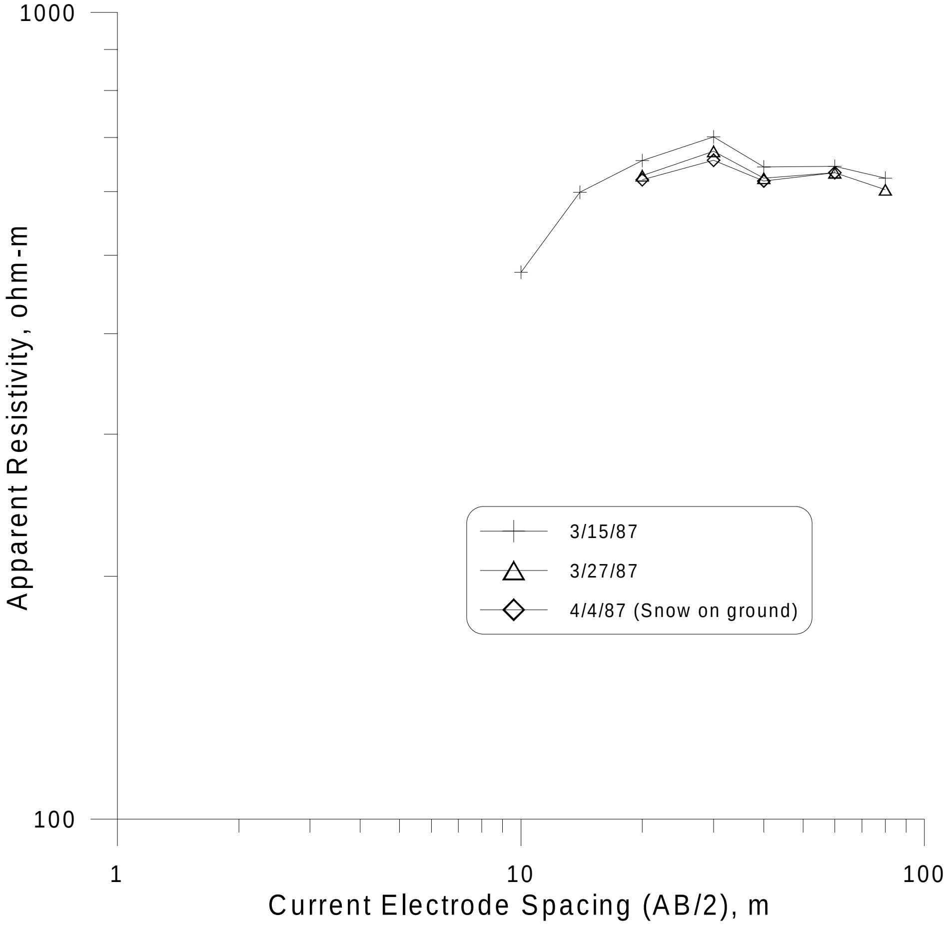


Figure 34. Sounding HP-1A, Line A,
repeated 11/13/86 and 12/14/86
Kentucky Horse Park

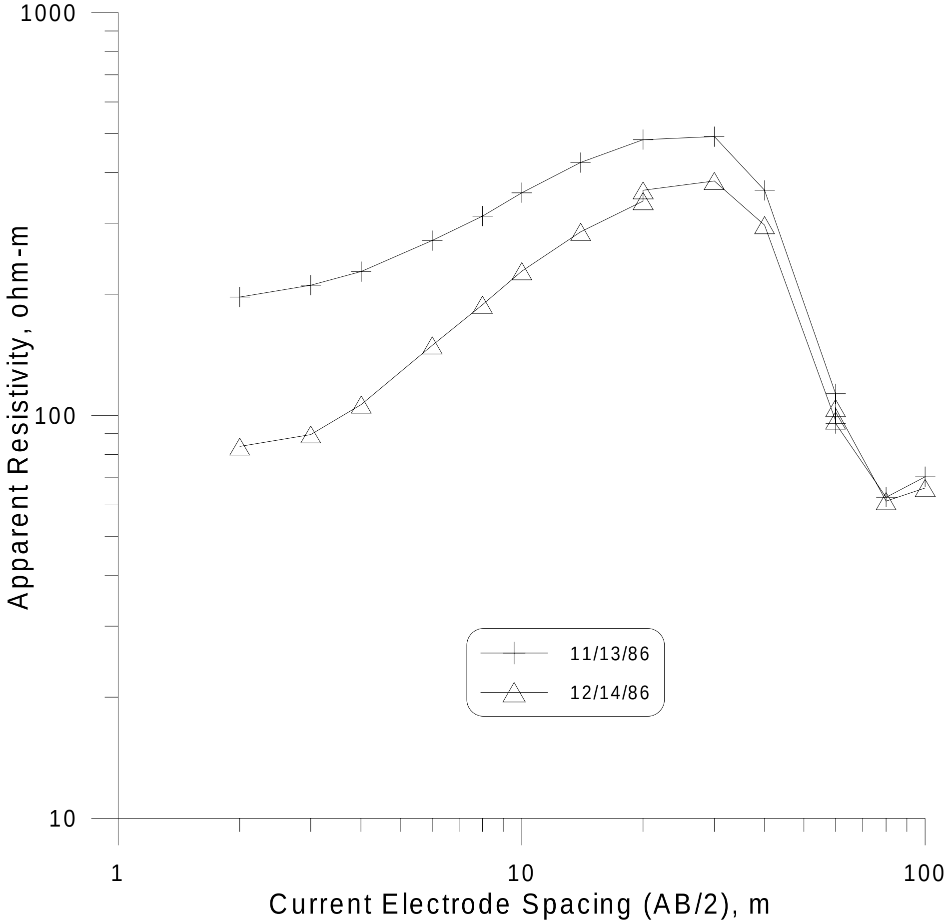


Figure 35. Sounding L-1 (Line B) and L-1 redone after 8-centimeter (0.25-foot) drill hole to water at 13.4 meters (44 feet). Kentucky Horse Park.

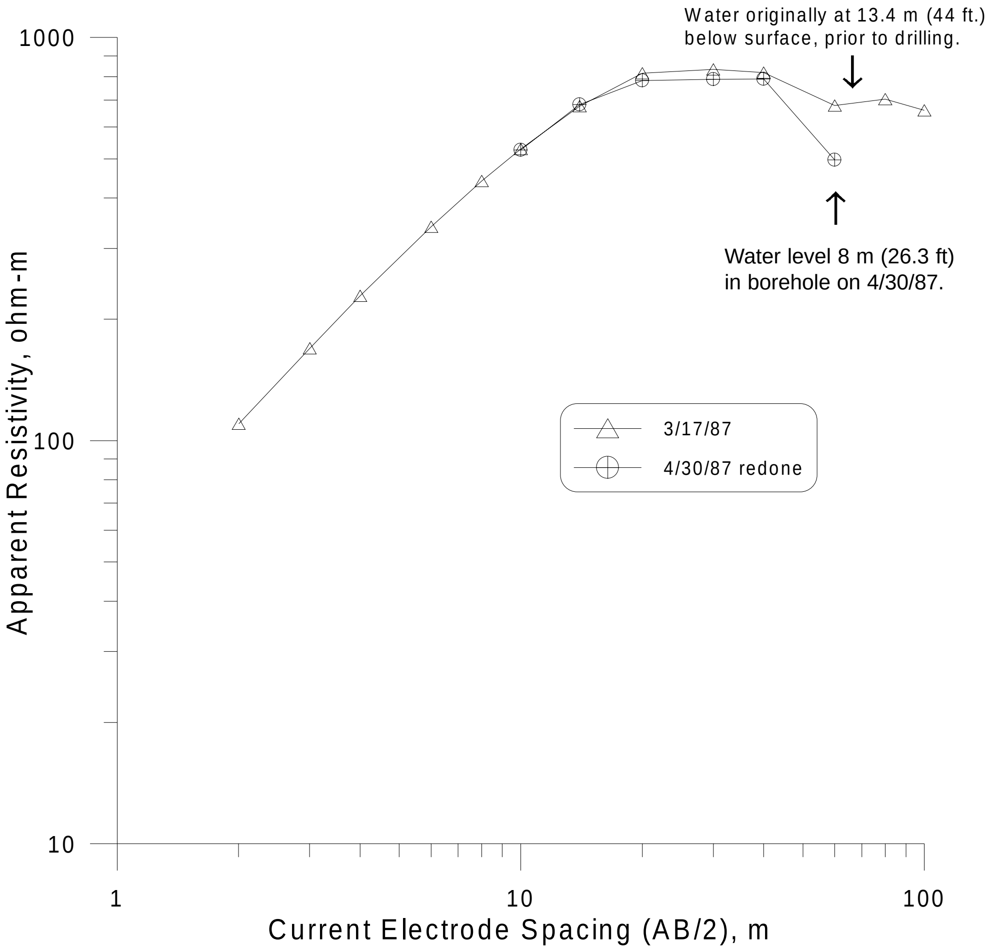
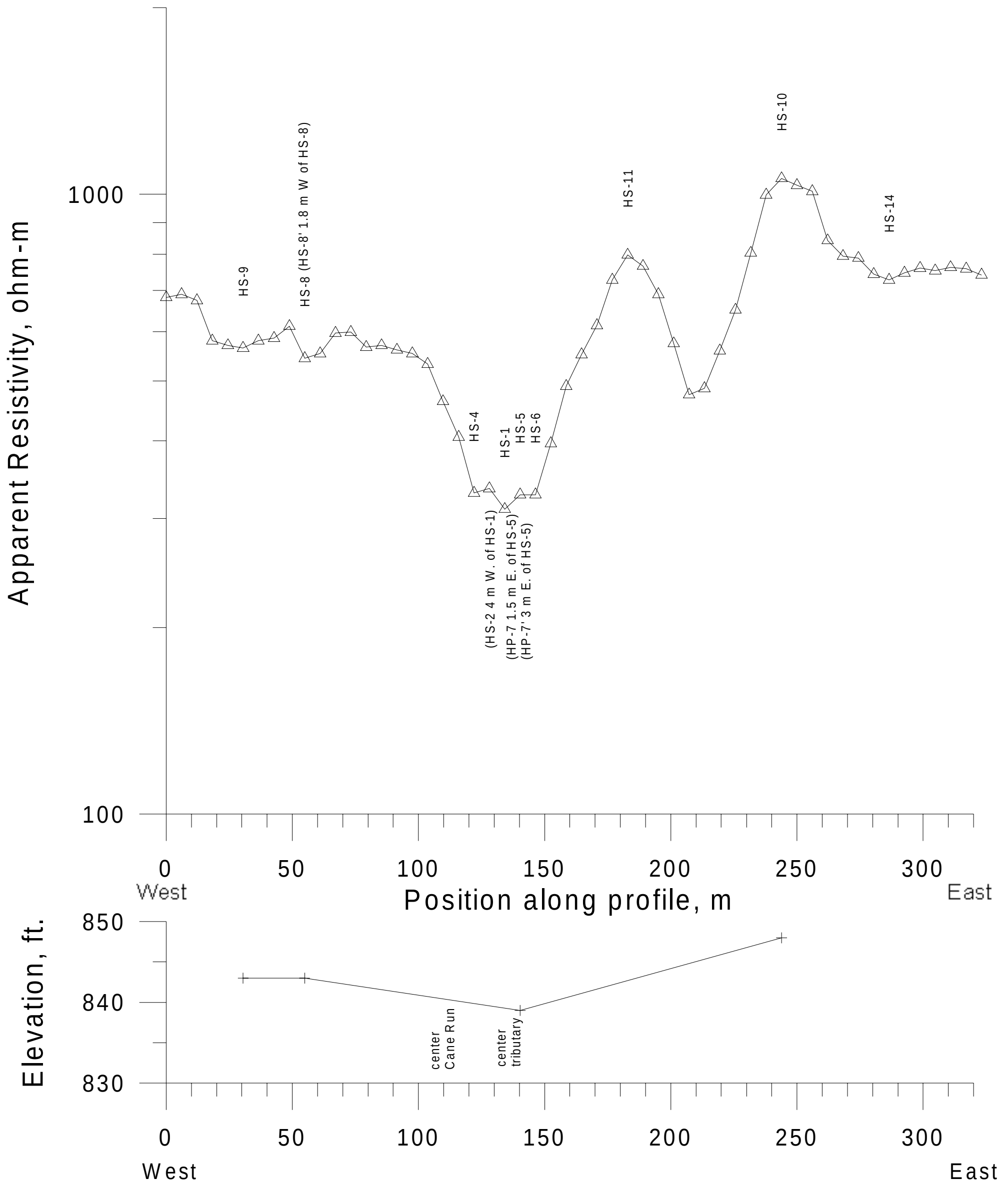


Figure 36. Profile C, with sounding points indicated. Wenner array, electrode spacing 30.4 m (100 ft). Kentucky Horse Park.



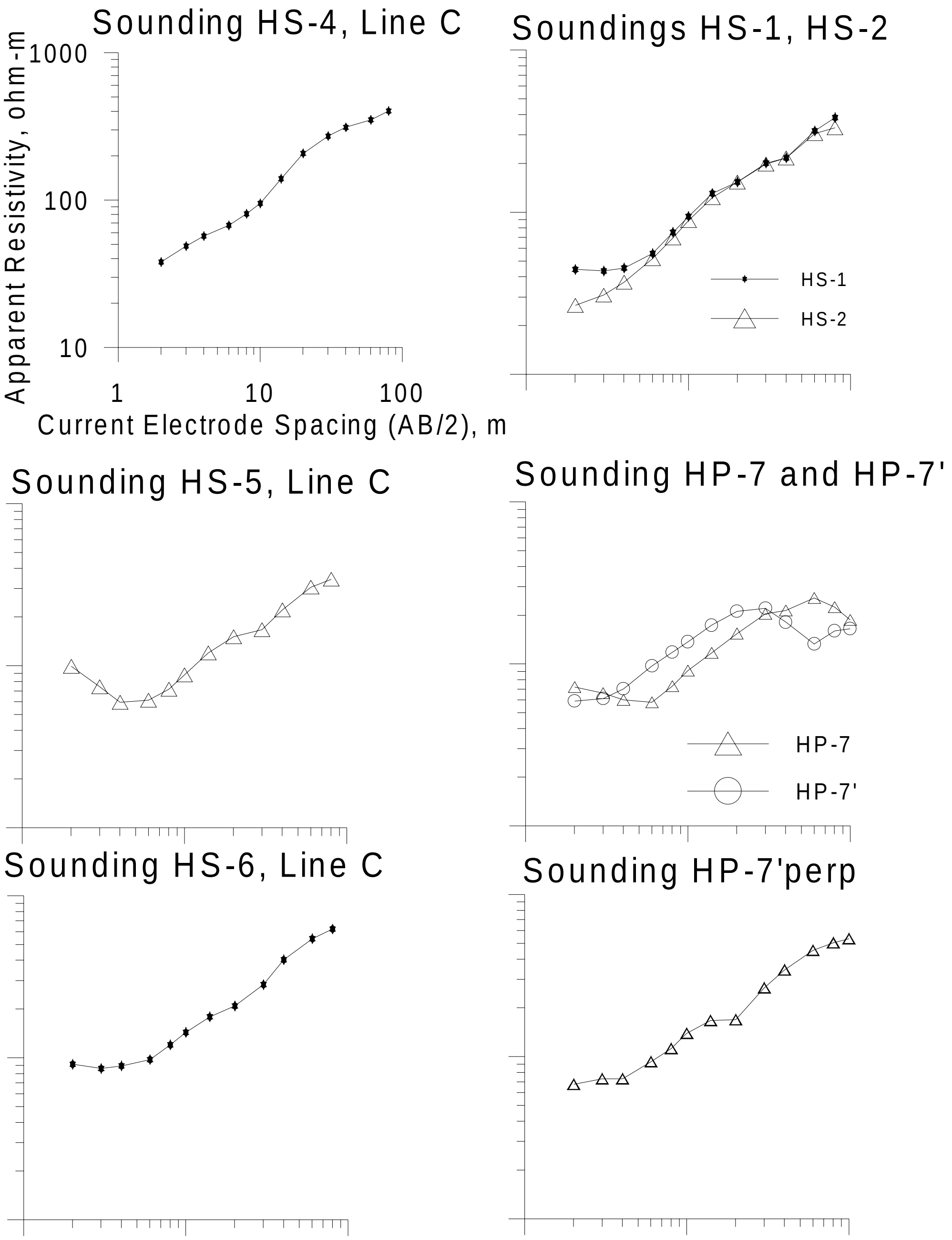


Figure 37. Soundings, central part of Line C, Kentucky Horse Park.

possible from buried power lines (R. Street, pers. commun., 1993). HP-7'perp was carried out over the same center as HP-7' at an orientation that did not intersect the power line and shows no low anomaly on the resistivity curve, suggesting that even if the low anomalies displayed by HP-7 and HP-7' are not noise but do in fact represent zones of low resistivity, the lateral effects or extent of that zone is relatively small.

Soundings HS-9, HS-8, and HS-8' (Figure 38a), taken from the western end of the profile, yielded apparent-resistivity curves showing no low-resistivity zones down to depths corresponding to electrode separations of 100, 100, and 80 meters (328, 328, and 262 feet), respectively. High-resistivity anomalies east of Cane Run were targets of soundings (HS-11 and HS-10) (Figure 38b) which indicated no resistivity lows at depth. Profile C displayed a large range of resistivity values, with relatively low resistivities in the proximity of Cane Run and its tributary and resistivities in excess of 1,000 ohm-meters at the east end; these high values were not consistent as background levels but were anomalous features and may reflect edge effects (image effects) of the low-resistivity area between them. Sounding HS-14 was located in a low-resistivity interval in the eastern segment of the profile, and up to electrode separation of 30 meters (98 feet) did not suggest the presence of a low-resistivity zone beneath that point.

Interpretation of Line C and the soundings taken on it is largely speculative, as no subsurface geologic data are available for this traverse (Figure 39). The clearest anomaly on the profile is the central low anomaly tested by the soundings between 122 and 146 meters east of the starting point, where the profile crossed the creek and tributary. Only two of the seven soundings in this central low demonstrated any potential for low-resistivity materials at depth. Five of the seven soundings show significant low resistivity at electrode spacings of 6 meters (19.7 feet) or less, corresponding to shallow depths. The strong conductor of electricity in this area is probably shallow groundwater associated with the creek and the soil-bedrock interface. The other area of interest (given the position of anomalies later encountered on other lines) is the low anomaly between the high-resistivity peaks at HS-11 and HS-10 (Figure 36). These peaks may represent image effects around a low-resistivity mass (see Figure 8). No sounding data were taken in that interval.

Line B. Profile B started at the western edge of the Cane Run floodplain in the mouth of a small swale or rill that was issuing a stream of water from an upper-level spring into a series of swallow holes at the edge of the floodplain (Figure 14), and the line terminated eastward in the bed of the stream. Numerous abrupt changes in resistivity are visible in the profile that owe nothing to the surface topography, although one apparent contrast is an artifact of a change in electrode spacing in the array. Anomalies both high and low were targets for soundings in this traverse (Figure 40).

Relatively low (400 ohm-meters) background resistivity at the west end of Profile B is probably attributable to shallow groundwater, which was visibly sinking into soil pipes from the upper-level spring. Soundings L-13 and L-11 were taken at two high-resistivity intervals on the western segment of the line (Figure 41). The apparent-resistivity curve of L-13 showed no resistivity drop to a depth corresponding to current-electrode spacing of 60 meters (197 feet). Two soundings (parallel and perpendicular to the profile) were conducted at the point of high resistivity labeled L-11 (Figure 41), and whereas there is a slight reduction in resistivity in L-11, the dissimilar curve for sounding L-11perp suggests that the anomaly is not areally extensive. Soundings L-12 and L-12perp (Figure 41) are also from the western segment of profile B, situated in the middle of a low-resistivity interval. Shape of these curves strongly resembles those of the L-11 set, though the actual resistivity values are several hundred ohm-meters lower. The difference may correspond to differences in lower subsurface resistivity due to greater water content of the bedrock, or differences in resistivity in the soil zones between the two sites. Sounding data for electrode spacings between 2 and 10 meters (6.6 and 33 feet) were not collected for either site, so the effect of the near-surface resistivity on the sounding curves cannot be estimated.

Sounding L-10 (Figure 41) showed a slight drop in resistivity at the 40- to 80-meter (131 to 262 feet) interval. Drilling at that spot encountered water-bearing voids at 10.4 meters (34 feet) and 15.2 meters (50 feet), less than 0.1 meter (0.33 foot) in diameter, at elevations between 241.9 and 246.9 meters (793 and 810 feet; Dugan, unpub. data). Figures 42 and 43 show the results of drilling on Line B, and relate them to features on the resistivity profile and to soundings, respectively. The voids encountered at L-10 probably represent incipient conduits developing peripherally to a larger conduit system.

The electrode spacing of the Wenner array was reduced to 24.2 meters (80 feet) after 154 meters (505 feet) along the profile (Figure 40). The most significant resistivity low on the profile was the target of soundings L-6 and L-6'. The apparent-resistivity curve for L-6 has a marked drop after 80-meter (262-foot) electrode spacing (Figure 41). Logs of three holes (L-6, L-6A, and L-6B) covering an interval of 11.3 meters (37 feet) east of L-6 indicated that a zone of intense karst development extends from 5.5 meters (18 feet) to as deep as 19.4 meters (63 feet), including several water-bearing voids

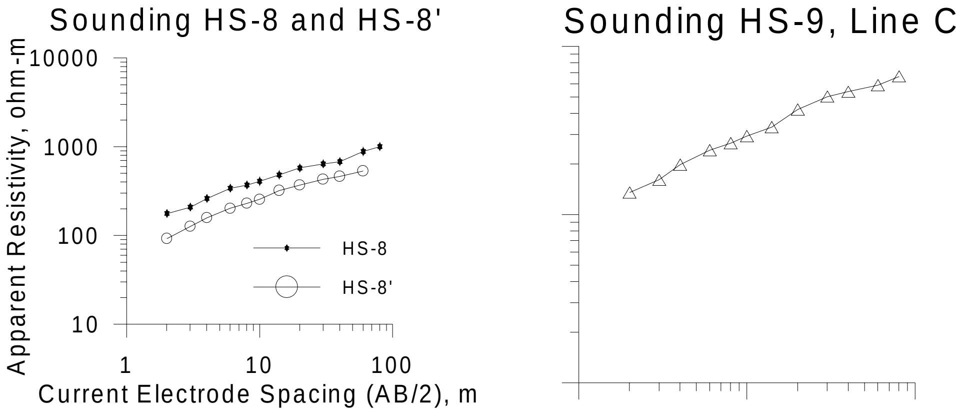


Figure 38a. Soundings from the west segment of Line C

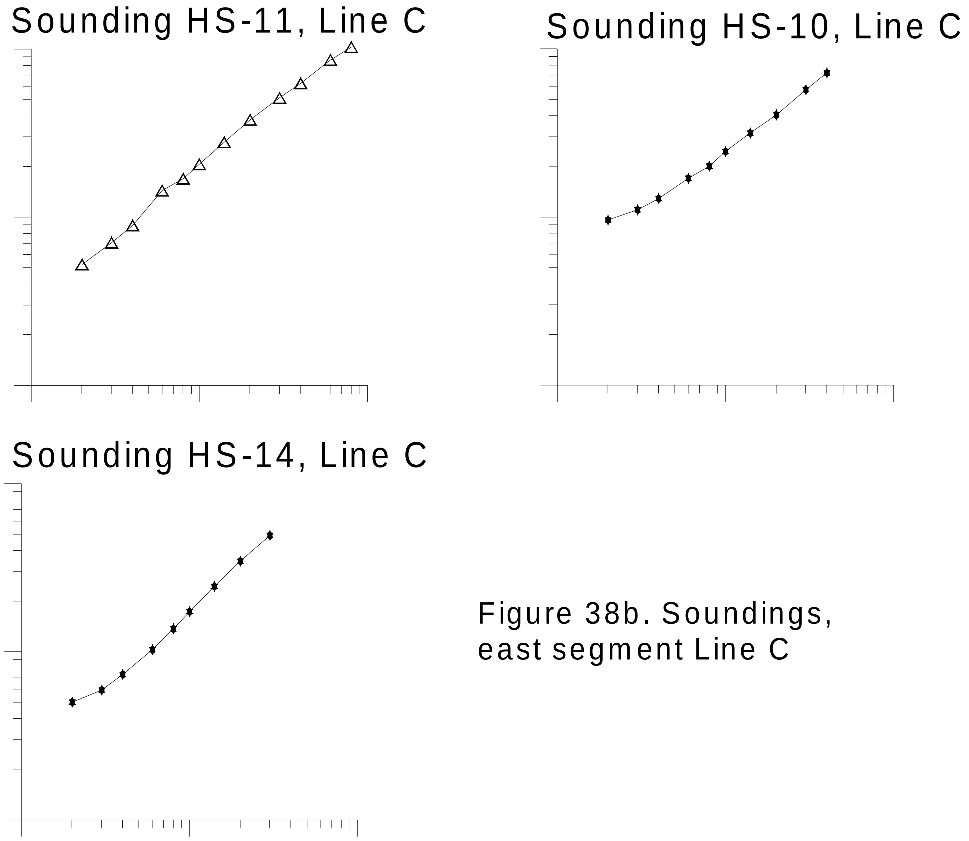


Figure 38b. Soundings, east segment Line C

Figure 39. Profile C, with interpretation. Wenner array, electrode spacing 30.4 m (100 ft). Kentucky Horse Park.

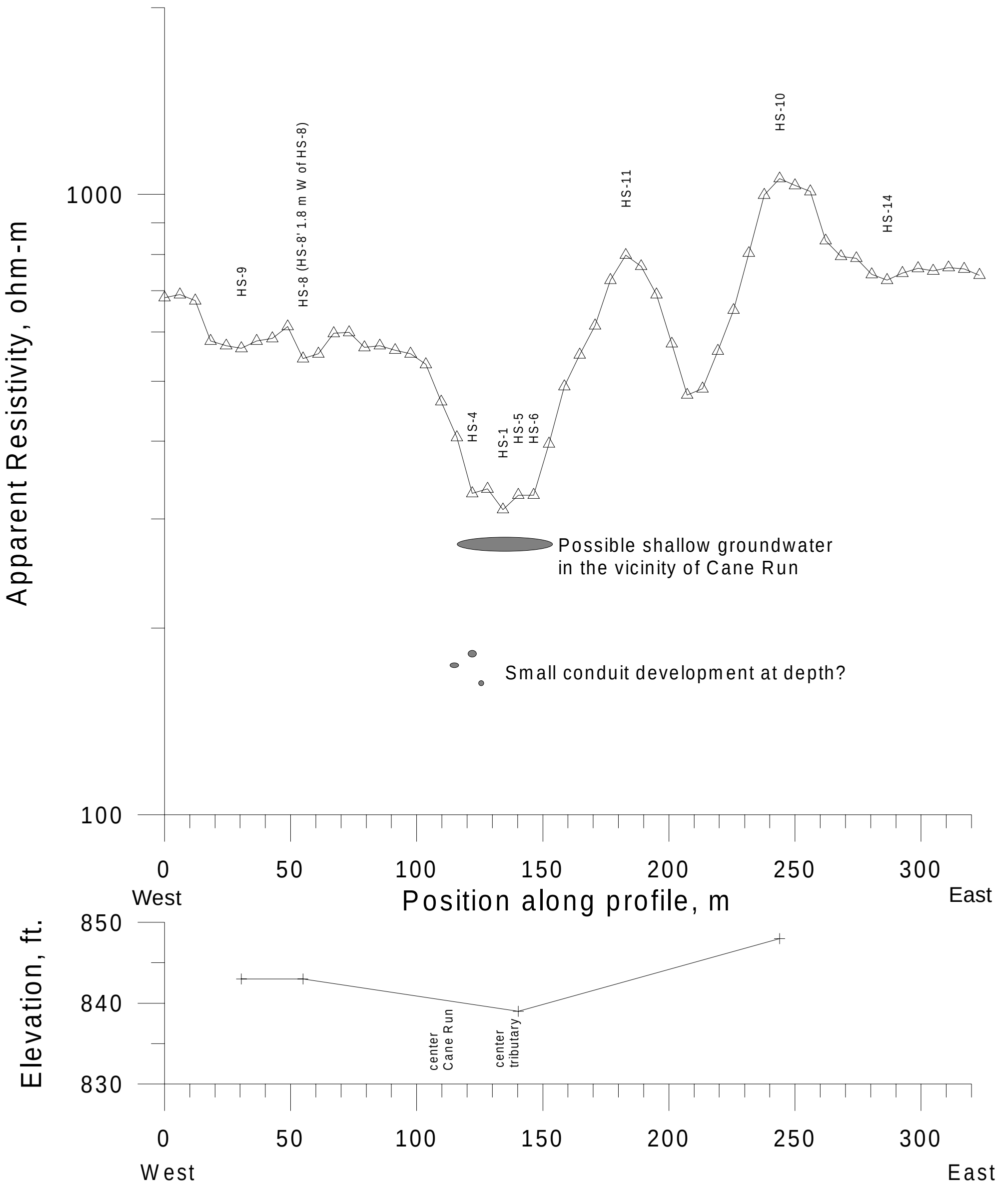
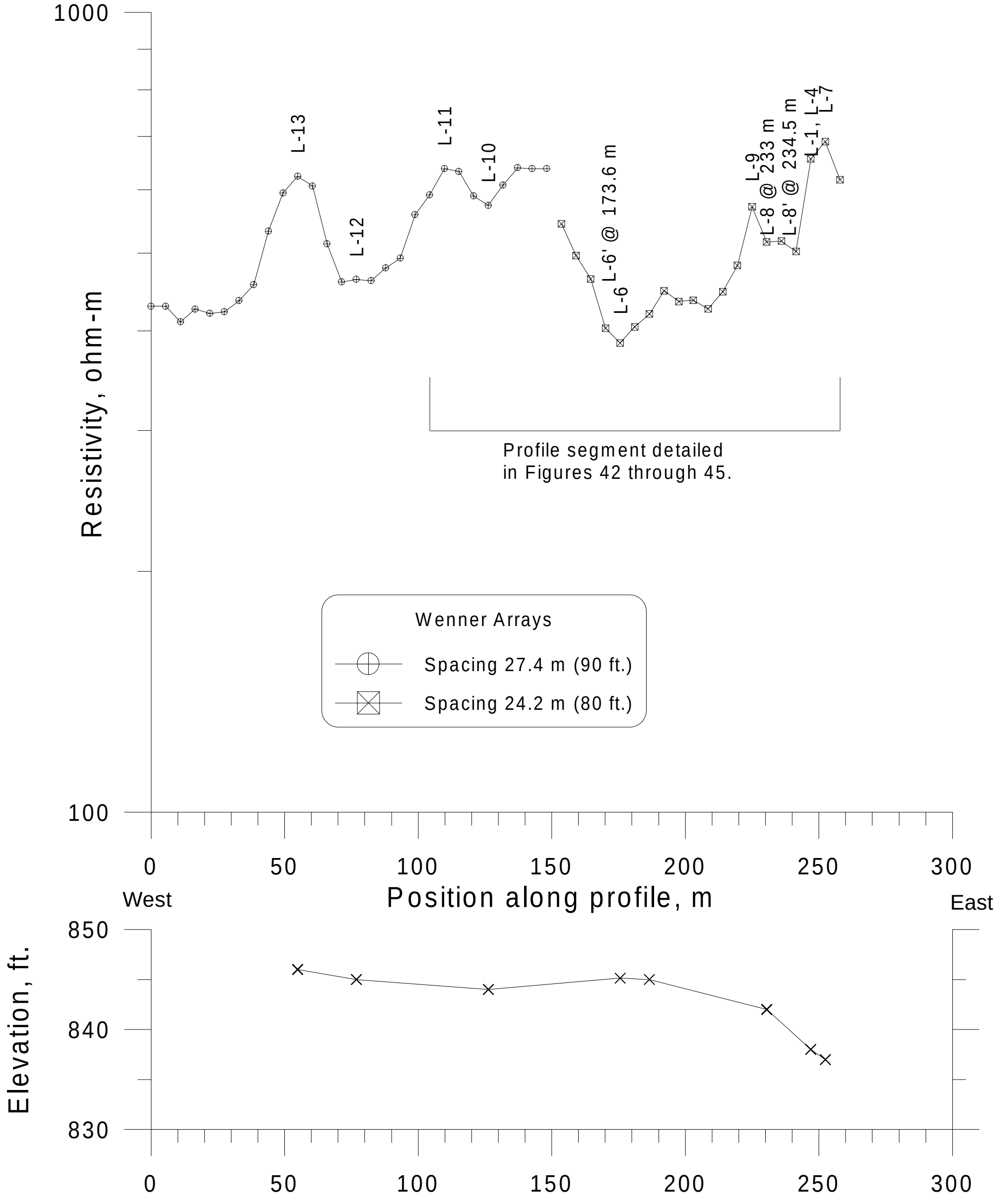


Figure 40. Profile B, with sounding points indicated.
Kentucky Horse Park



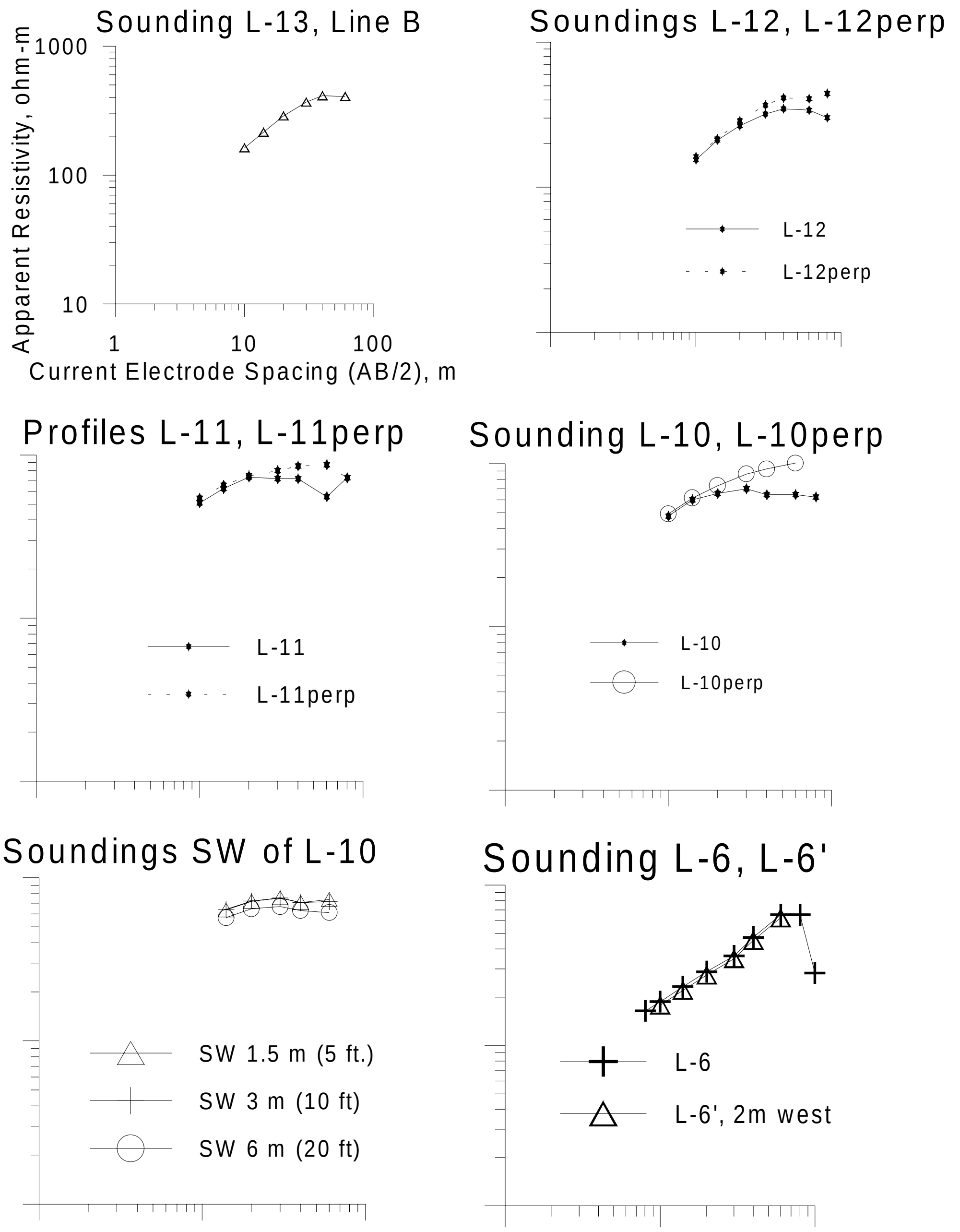


Figure 41. Soundings, west and central segments, Line B, Kentucky Horse Park.

Figure 42. East end, Line B. Resistivity profile and drilling results. Kentucky Horse Park.

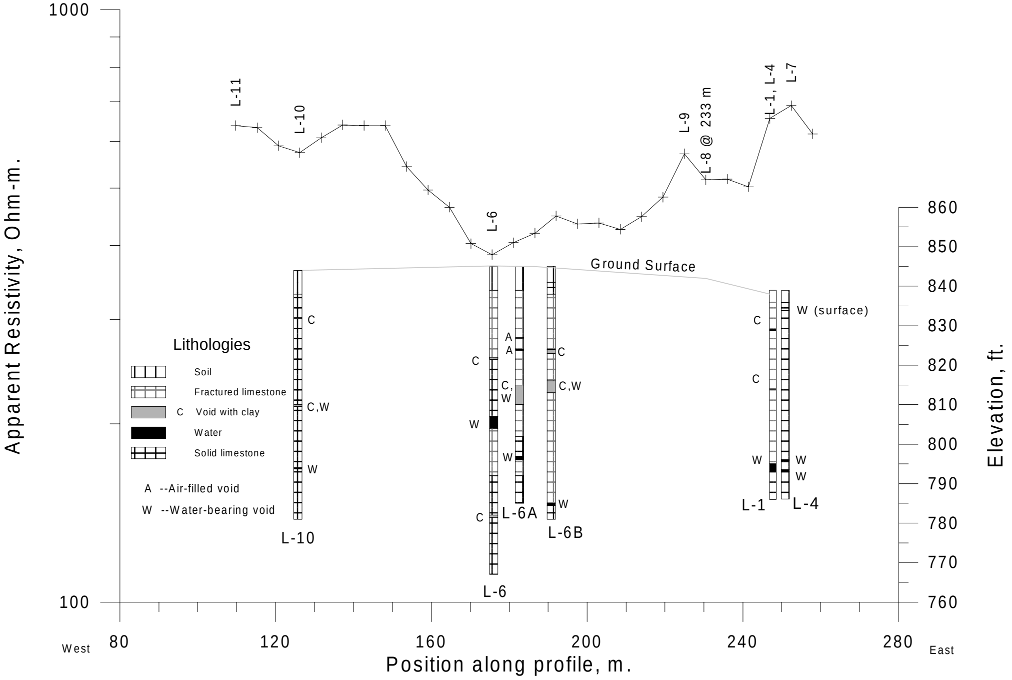
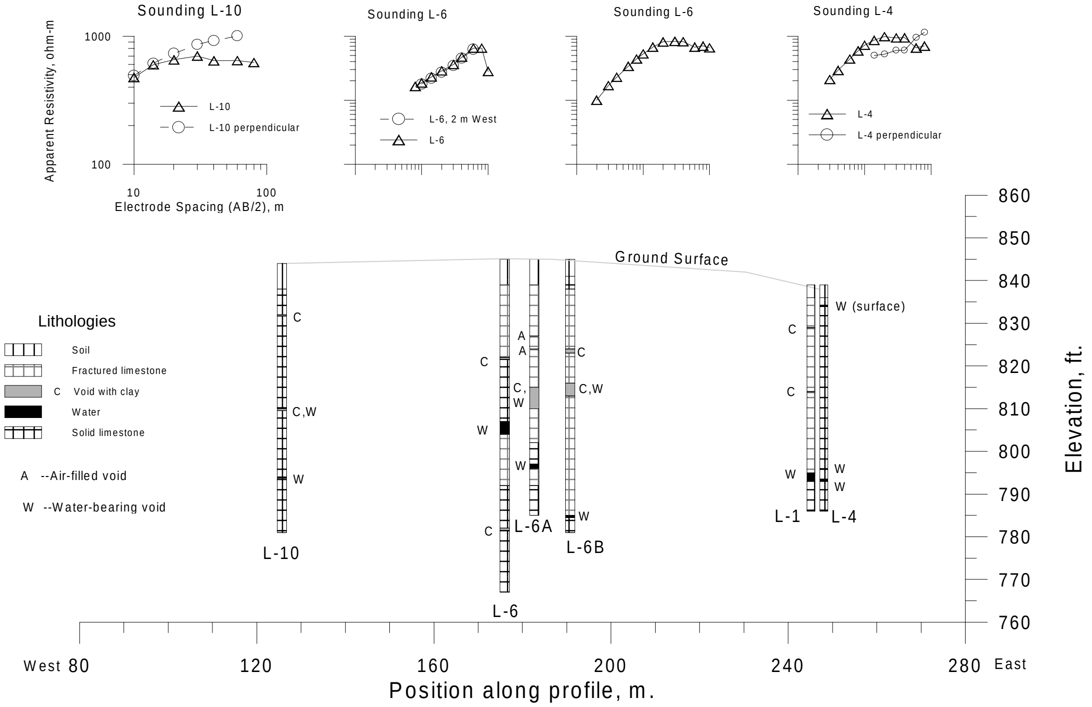


Figure 43. East end, Line B. Resistivity sounding and drilling results.



between 8.8 meters and 14.6 meters (29 to 48 feet) that were up to 0.9 meter (3 feet) in diameter (Dugan, unpub. data). Indeed, the log of L-6A notes that when the driller hit the air-filled voids there was “air and mud spouting out of L-6....” This segment of the profile is interpreted to have crossed a zone of abandoned and active tributary or distributary conduits of the Royal Spring Conduit, with water-bearing voids between 239 meters (784 feet) and 247.8 meters (813 feet) elevation. Figures 42 and 43 juxtapose lithologic logs and the resistivity data for the east end of Line B.

Sounding L-8 was conducted in a segment of low resistivity on the profile between the resistivity highs at L-9 and L-1 (Figure 40), and the apparent-resistivity curve shows a resistivity drop at depths penetrated by the electrical field at electrode spacing greater than 25 meters (82 feet, Figure 44). Signatures from sounding at that point with the array perpendicular to the line of the profile showed no drop in resistivity, suggesting that the measurable electrical field created by the original sounding encompassed a greater volume of low-resistivity material than did the sounding from a perpendicular array. Soundings L-8’ (1.8 meters, or 6 feet, east of L-8) and L-9 (8 meters, or 26 feet, west of L-8) do not show evidence of low resistivity in the subsurface (Figure 44).

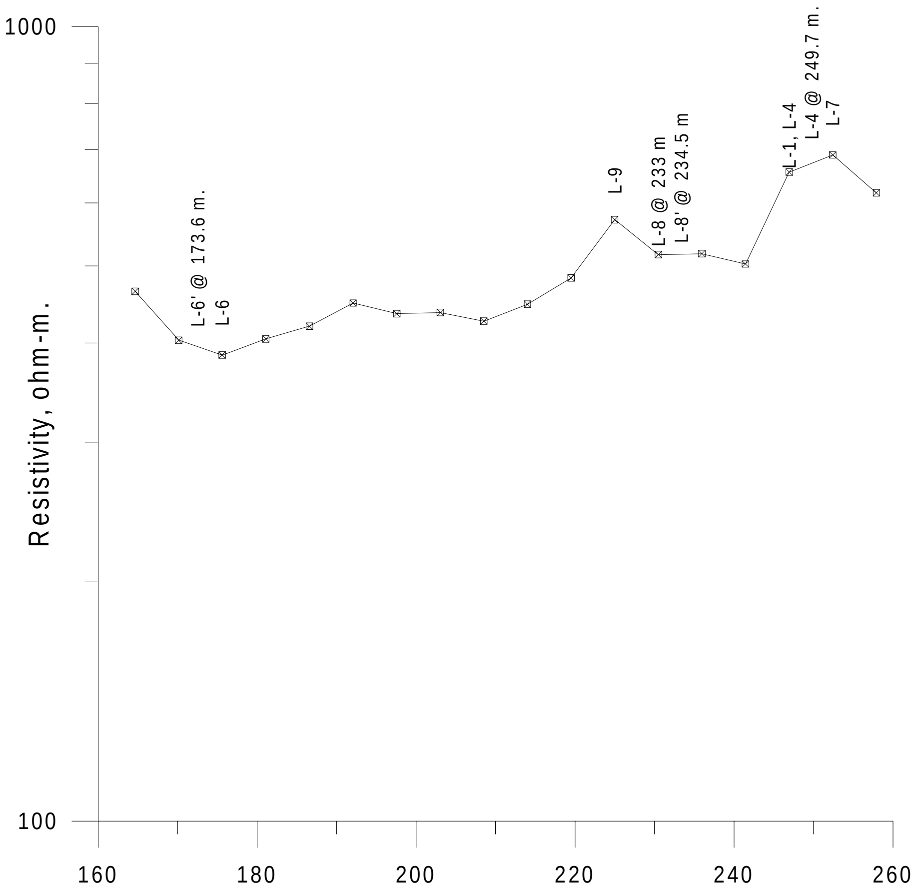
A rise in apparent resistivity at the eastern end of Profile B was explored intensively (Figure 45). Sounding L-1 was conducted perpendicular to the profile line (to avoid the creek 12.2 meters [40 feet] to the east), and the apparent-resistivity curve at electrode separation greater than 30 meters (98 feet) shows a consistent, though not large, decrease (Figure 44). Sounding L-4 was sited 2.8 meters (9 feet) east of L-1 and also was oriented parallel to the creek. The sounding curve (Figure 44) is very similar to that of L-1, but the sounding L-4perp (run parallel to the profile line) shows no drop in apparent resistivity, and the resistivity rises steeply in the curve L-4perp for precisely the electrode spacings at which the curve L-4 dropped. A hole drilled at L-1 (Figure 42 and Figure 43, from Dugan, unpub. data) indicates water was encountered between 13.4 and 14 meters (44 and 46 feet), at an elevation of approximately 242.4 meters (795 feet), and that the water was brown and muddy and the driller was losing circulation. The latter two points are strong indicators that the water encountered was part of a karst system. Brown mud is unusual below the soil zone in the Inner Bluegrass except in karst conduits and caves, where it is commonly deposited by slow illuviation or as sediment deposited by running water. Lost circulation indicates that flow of fluid under pressure from the drill stem and up the borehole (by which drill cuttings and liquid are carried to the ground surface) has been interrupted, probably because a subsurface void has been encountered. A borehole at L-4 (Figure 42 and Figure 43, from Dugan, unpub. data) encountered groundwater at the soil-bedrock interface, and at 13.1 to 13. 4 meters (43 to 44 feet, elevation approximately 242.4 meters, or 795 feet) in two small breaks; estimated yield was approximately 158 liters per second (10 gallons per minute).

The sounding conducted 2.8 meters (9 feet) east of L-4 was designated L-7 (Figure 44), and no decrease in apparent resistivity was detected from resistivities taken from 20 to 80 meters (66 to 262 feet) of electrode separation (Figure 45). Two other soundings were taken at close spacing off the profile line to the north near L-1 and L-4 (designated L-4 offsets 1 and 2; not figured in this study due to uncertain location), which indicated only increasing resistivity with depth in those locations.

Interpretation of anomalies of the electrical resistivity of Line B is considerably aided by the abundance of drilled and logged holes on the traverse line or in the immediate vicinity. Figure 46 illustrates the hydrogeologic interpretation of Line B. The water-bearing zone detected in resistivity sounding and encountered in drill holes in the vicinity of L-10 is at approximately the same elevation as the water-bearing zones of the L-1 and L-4 wells. The L-1 and L-4 wells clearly were drilled into karst conduits, and, like L-10, the voids are probably incipient conduits or minor openings developing on or parallel to the bedding planes of the limestone and feeders to the larger tributaries and distributaries of the Royal Spring Conduit. Figure 47 is a photograph of bedding-plane openings exposed in a roadcut on Ironworks Pike west of the Kentucky Horse Park, and illustrates the type of openings interpreted to exist under both L-10 and L-1 / L-4. The signatures of soundings at L-11, L-12, and L-13 suggest the existence of similar small conduits across much of the western end of Line B, and the influence of shallow groundwater on the profile resistivity is clear. Features at L-6 and vicinity are clearly karst-related, and are interpreted as representing tributaries or distributaries to the trunk conduit of the Royal Spring Conduit. Water at the soil-bedrock interface discovered at L-4 is believed to be shallow-subsurface flow or backflooding from surface water in Cane Run.

Line A. The line of Profile A was run on the east side of Cane Run. The usual surveying method for discovering linear anomalies in the subsurface is to traverse at an angle approaching 90 degrees to the trend of the anomaly; numerous obstacles dictated that Line A must run sub-parallel to the suspected trend of the Royal Spring Conduit if the area east of Cane Run was to be covered in the survey (Figure 14). The profile was carried out in segments at three different electrode spacings (Figure 48).

Figure 44. Profile B (eastern end), with sounding points indicated.
Kentucky Horse Park



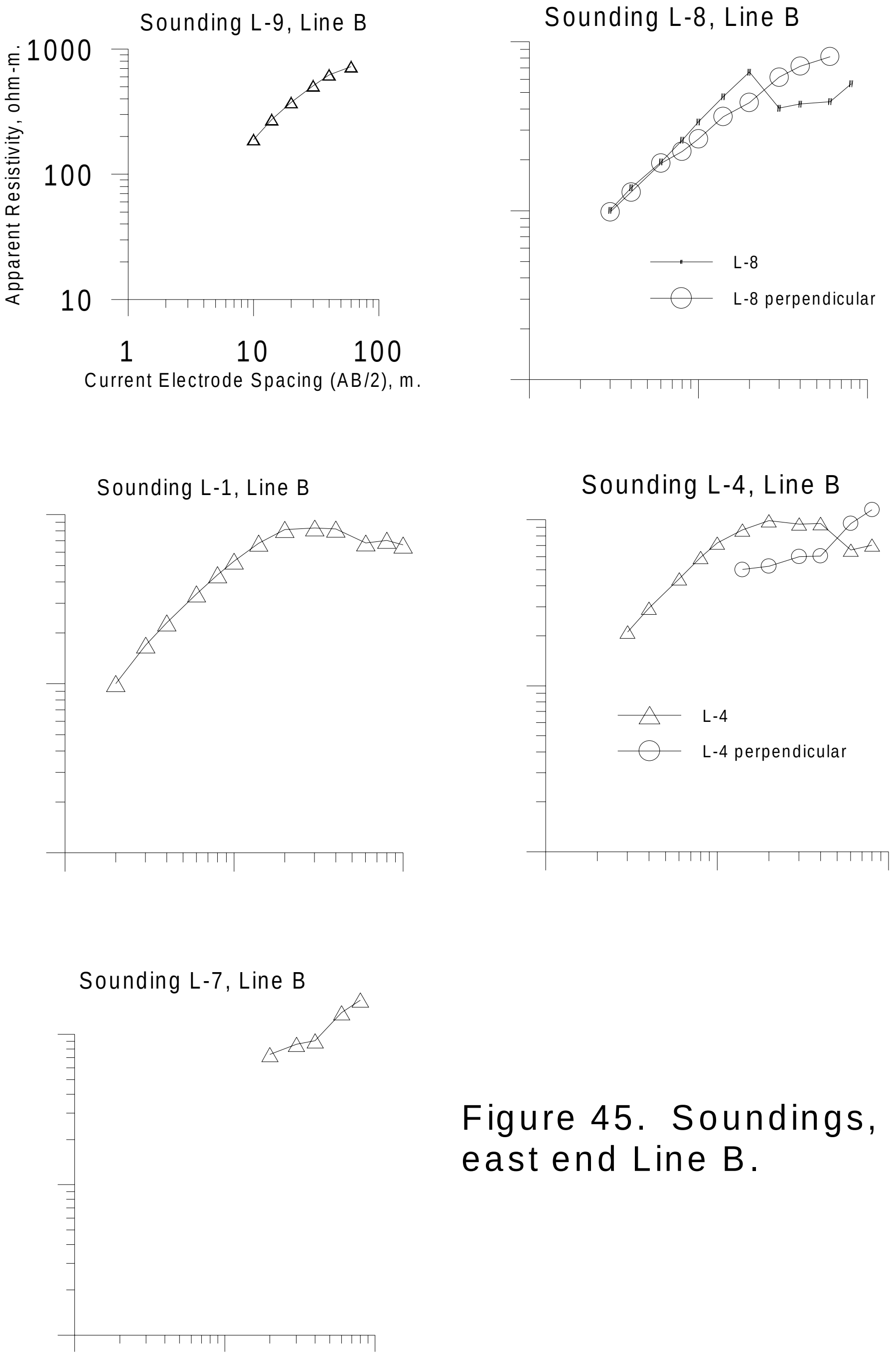


Figure 45. Soundings, east end Line B.

Figure 46. Profile B, with interpretation.
Kentucky Horse Park

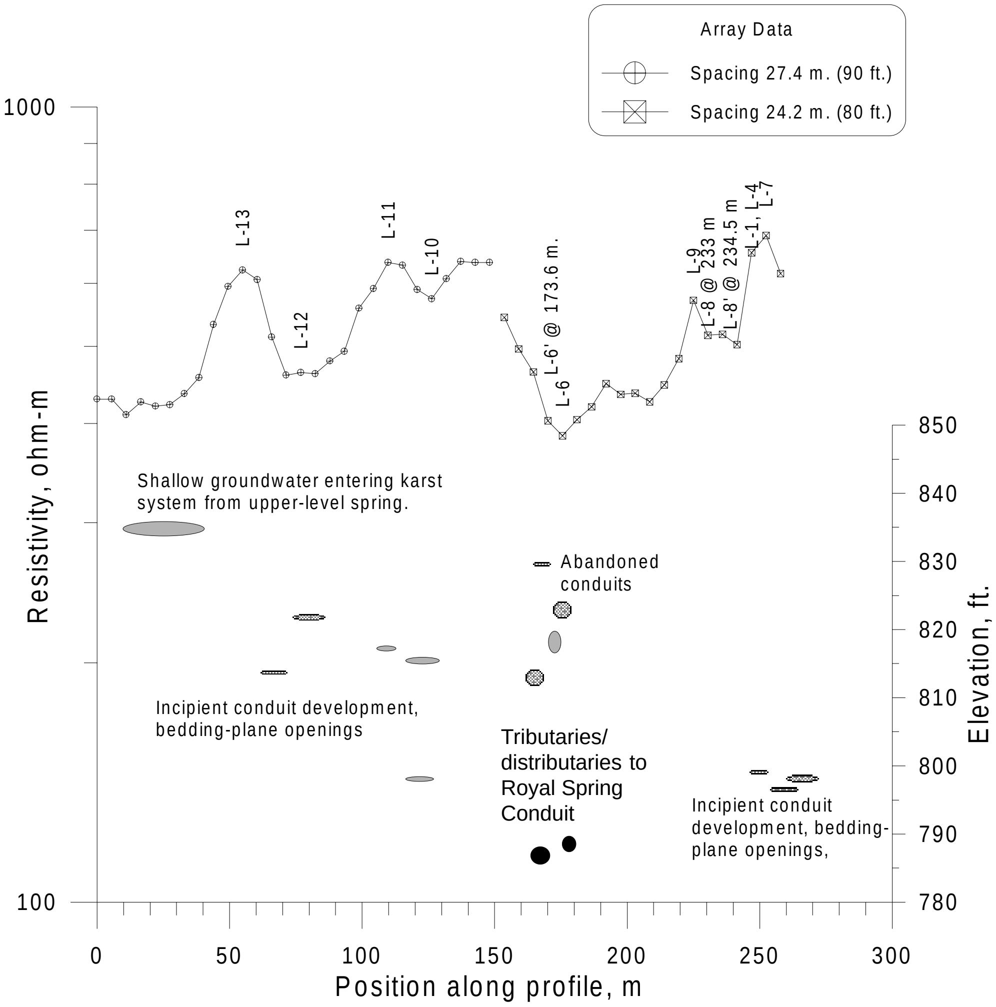


Figure 47. Stream of water running from a solutionally enlarged bedding plane along Ironworks Pike, Fayette County, Kentucky.

At the northern end of the profile, a section of low-resistivity anomalies was the target of soundings HP-1A through HP-1E (Figure 49). The centers of sounding HP-1A and HP-1B are the same, but the arrays are perpendicular. The apparent-resistivity curve of HP-1A shows a very strong decrease in resistivity at depth, while HP-1B shows only weak effect of a low-resistivity zone under that point. Soundings HP-1C, HP-1D, and HP-1E all have large decreases in resistivity at electrode spacing greater than 30 meters (98 feet). South of segment A1, the discontinuity on the resistivity profile is probably attributable to the decrease from 30.5 meters (100 feet) to 27.4 meters (90 feet) in electrode spacing of the Wenner array, although differences in soil moisture content might have had some effect (Figure 48).

A low-resistivity anomaly at the 333-meter position was explored in soundings G-1, G-2, and G-3 (Figure 50). Decreasing slope and a slight drop in apparent resistivity at 40 meters (131 feet) of electrode separation is apparent in all three sounding curves, though comparison of G-3perp with G-3 indicates that the low-resistivity zone underlying that point is not laterally extensive. A log of G-3 noted that water was encountered at a number of depths (Figures 51 and 52, from Dugan, unpub. data). Water was encountered at the soil-rock interface at 3 meters (10 feet), at a "crevasse" (the driller's term) at 9.1 meters (30 feet), and at three water-bearing zones between 15.2 and 18.3 meters (50 and 60 feet). The total yield was estimated to be approximately 6.3 liters per second (20 gallons per minute), but it is noted in the log that some fraction of the total is surface water, probably arriving from Cane Run through shallow conduits and via the soil-bedrock interface.

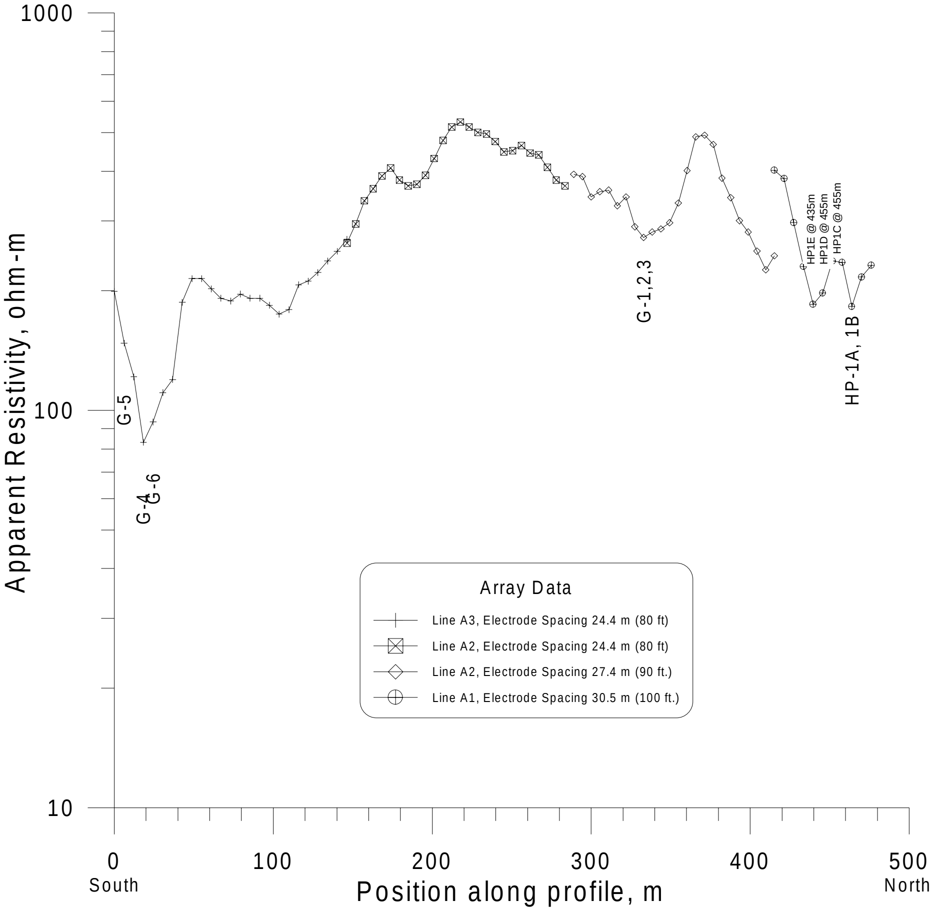
At the southern end of Profile A, a steep negative anomaly was encountered approximately 30 meters (100 feet) north of the segment of Cane Run that commonly loses water to swallow holes in the stream bed (Figure 48). From soundings run at or near the lowest resistivity point on the profile, apparent-resistivity curves for soundings G-4 and G-4' (positions 18.3 and 20.3 meters on the profile) are nearly identical, showing strong low anomalies (Figure 53). The curve from sounding G-4perp was more profoundly deflected downward than those from G-4 and G-4', and all three soundings collectively suggest that the low-resistivity zone causing the anomaly is relatively extensive. Soundings G-5 and G-6, on either side of G-4 (7 and 28.4 meters [23 and 93 feet], respectively), showed a slight drop at the 30- and 40-meter (98- and 131- foot) electrode positions, but not nearly as profound as the one in G-4perp. A log of the hole drilled at this spot (Figure 51 and 52, from Dugan, unpub. data) reports major water-bearing voids encountered at 11.7 to 12.7 meters (38 to 41 feet, bottom at elevation 245.8 m or 806.25 feet approximately) and 14.6 to 15.2 meters (48 to 50 feet, bottom at elevation 242.8 meters or 796.25 feet approximately). Though the driller reported "small water" in the upper void, he estimated the yield of the lower void at 31.5 liters per second (500 gallons per minute). Dugan was more conservative, placing the yield in excess of 6.3 liters per second (100 gallons per minute).

Line A can be interpreted in terms of three magnitudes of karst features. The smallest are the incipient conduits presently forming along joints and bedding planes (Thrailkill and others, 1982); they bear water, but not a great deal, and their effect on the sounding curve is not great. The incipient conduits and the soil-bedrock interface cannot be tapped for large-capacity water supplies, rarely even for a domestic well. Incipient conduits form a network described as a "complexly-branching dendritic pattern" (Thrailkill and others, 1982, p. 93), which is widespread and throughgoing, and both the soil-rock interface and the networks of anastamosing channels at bedding planes act as collector systems for flow that moves by both horizontal and vertical pathways to ultimately join larger conduits or emerge as a spring (Keagy and others, 1993; Hampson, 1994). A signature typical of bedding-plane flow, or at least wet conditions, is that of the 2- to 3-meter (6.6- to 9.8-foot) segment of sounding G-1 (Figure 50); the inflection or reversal of slope centered at the 30-meter (98-foot) position is indicative of a small zone of low resistivity at depth, which could be a system of incipient conduits. Medium-sized tributaries and distributaries, such as those encountered in Line B at L-6 (Figure 43), have a more pronounced signature, such as that shown by the north end of Line A (HP-1A, 1B, 1C, 1D, and 1E) (Figure 49). Major trunk conduits of a large karst groundwater system have a low, wide-crested signature such as that found under the G-4 family of soundings (Figure 53).

Line T. A profile was conducted roughly parallel to Line B that ran from the center of the floodplain and across Cane Run to intersect Line A, with the objective of detecting the conduit that was encountered in Line A at G-4 (Figure 14). The Tripotential method was employed, using the multiple electrode configurations to calculate the index of lateral inhomogeneity, Delta. Electrode spacing of 30.5 meters (100 feet) was chosen, larger than that used in Line A in the profile at G-4, because it was believed that the differing arrays employed by the Tripotential method would be sensitive to shallow anomalies as well as deep ones.

The western segment of the profile registered resistivity consistently less than 100 ohm-meters in the CPCP configuration, and several points were the targets of soundings (Figure 54). Soundings T-2 and T-3

Figure 48. Profile A, with sounding points indicated
Kentucky Horse Park



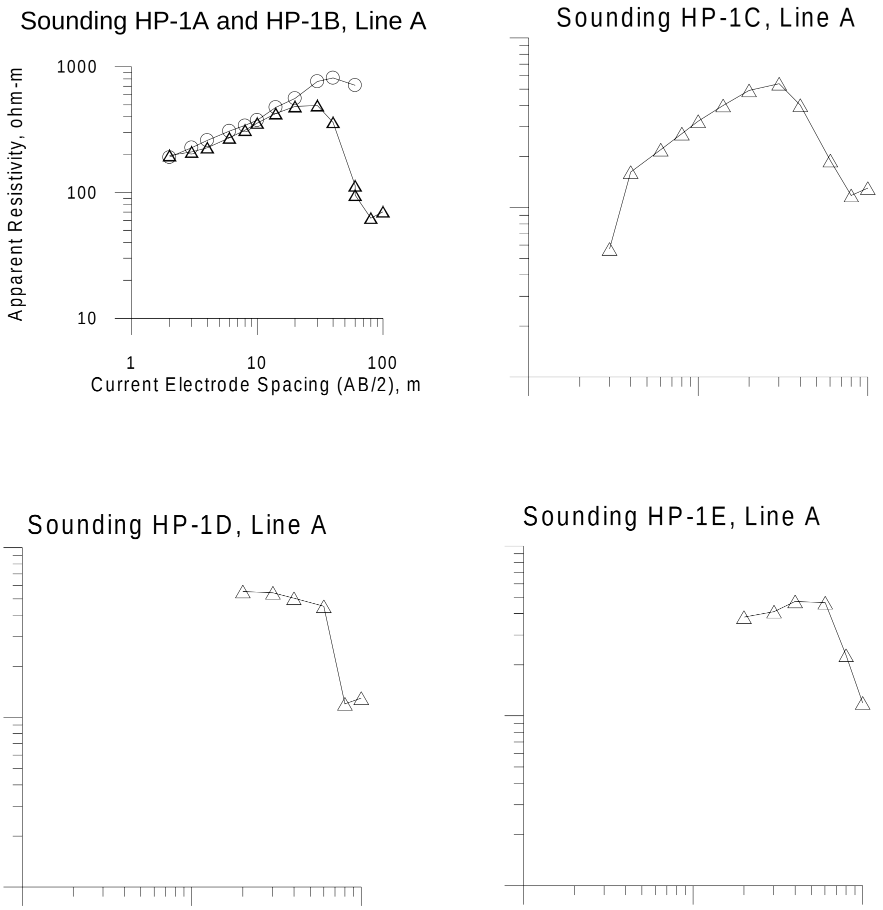


Figure 49. Soundings, north end Line A

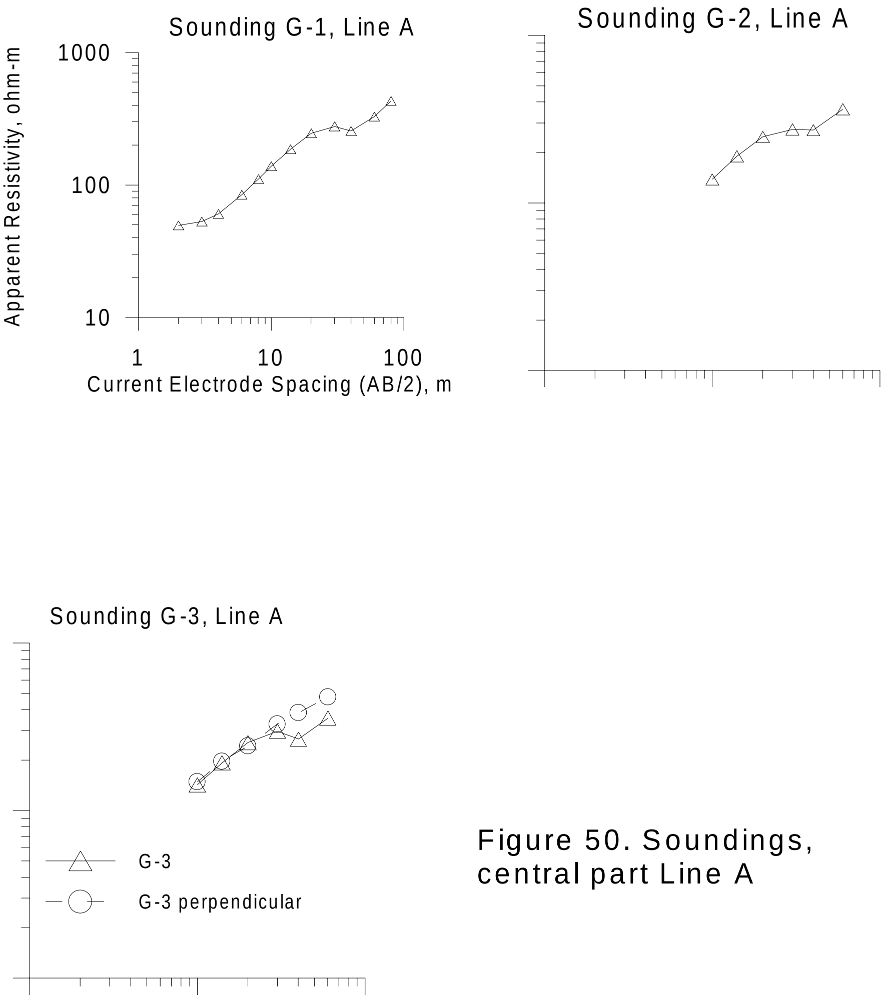


Figure 50. Soundings, central part Line A

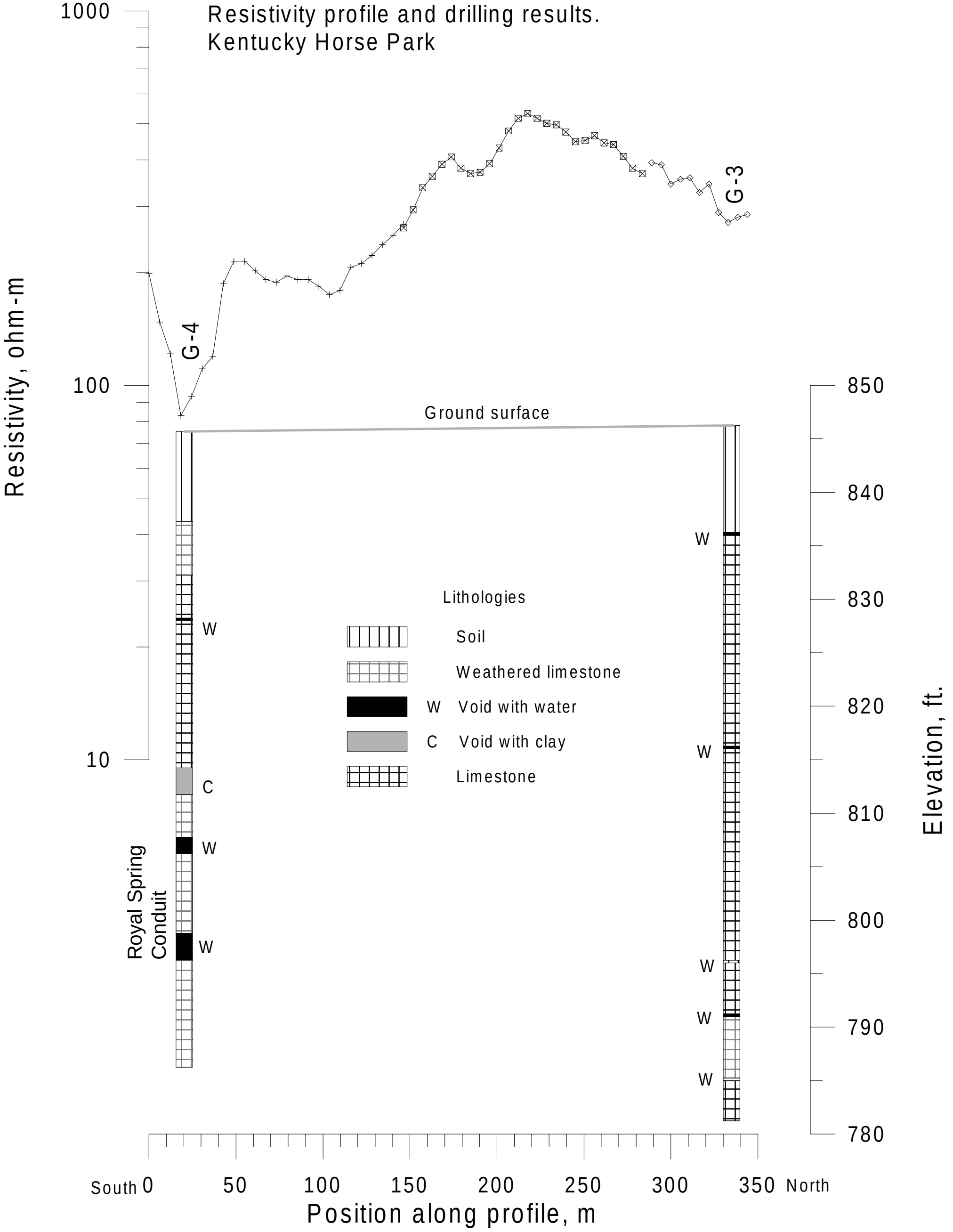
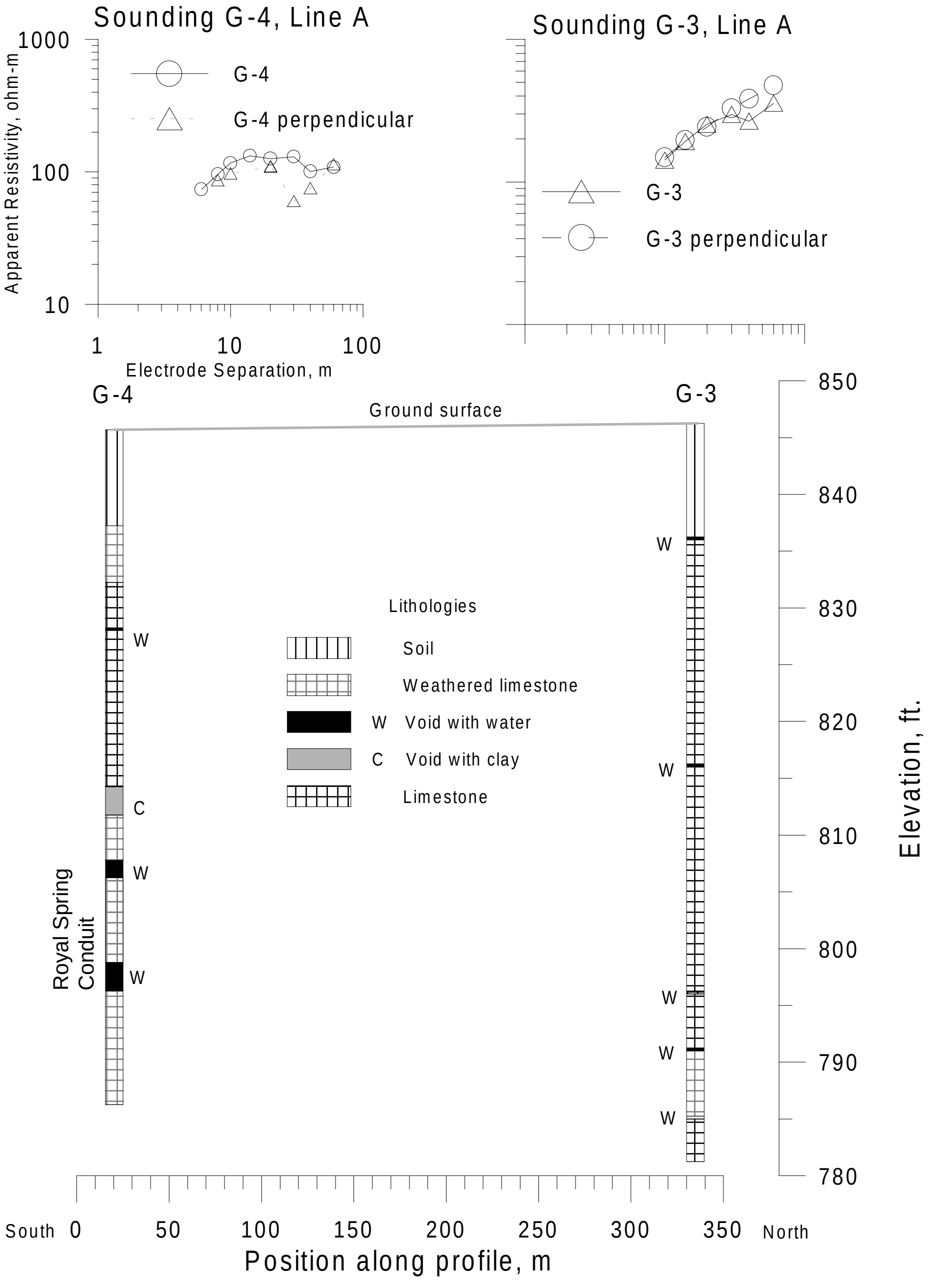


Figure 51. Line A, southern and central segments.
Resistivity profile and drilling results.
Kentucky Horse Park

Figure 52. Line A, southern and central segments.
Resistivity soundings and drilling results.
Kentucky Horse Park



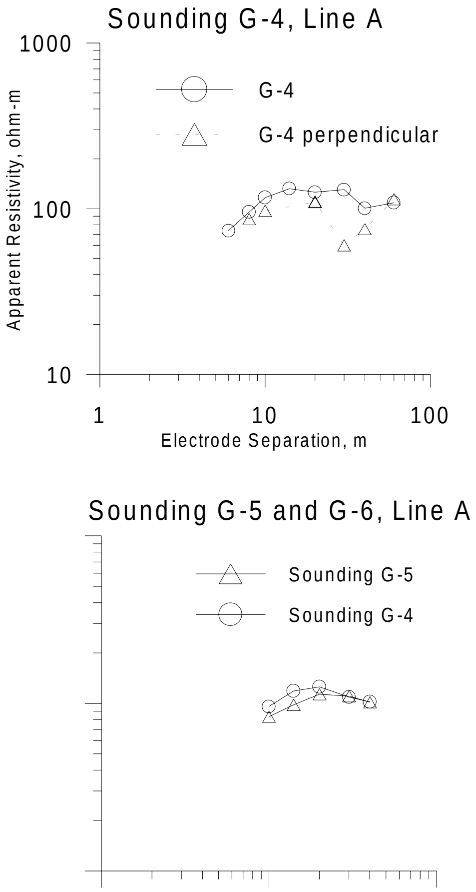


Figure 53. Soundings, south end Line A

(Figure 55) showed reduced resistivity at depth, and though the drops in resistivity were not as great as had been encountered at G-4 (Line A), the anomaly at T-3 was considered to be possibly indicative of a major water-bearing zone. Three boreholes in the vicinity of T-3 encountered water between depths of 14.6 and 15.6 meters (48 and 51 feet), at an elevation of around 242 meters (between 795 and 792 feet, Figures 56 and 57, from Dugan, unpub. data), but the yield was not significant. The plot of sounding T-6 had no resistivity drop at wide electrode separations (Figure 55).

The central segment of Line T shows a fairly constant relationship between the apparent resistivities measured at different array configurations (Figure 54). Low values of Delta indicate little lateral change in the resistivity in this segment (Kirk and Rauch, 1977). The CCPP array is the exception, but may be sensitive to differences in soil moisture or may be reacting to the presence of a buried sewer line in the vicinity of the 154-meter position of the line. East of the 154-meter position another series of anomalies was encountered that was explored by soundings T-1, T-4, and T-5. Figure 55 illustrates the paired curves, corresponding to soundings carried out with the array parallel and perpendicular to the line of the profile. Sounding T-1 has a persistent resistivity low past the 30-meter (98 feet) electrode spacing, but T-1perp did not detect low resistivity, indicating that the anomaly at that site was not laterally extensive. Soundings T-4 and T-4perp both indicated low resistivity at depth (Figure 55). A well drilled here encountered a small break from 17.7 to 17.8 meters (58 to 59 feet) but did not yield water (Figures 56 and 57, from Dugan, unpub. data). Sounding T-5 (Figure 55) displayed a precipitous drop in resistivity to nearly 100 ohm-meters from a high of 243 ohm-meters, but T-5perp did not match the low resistivities of T-5, though it did drop from 487 to 351 ohm-meters between 40 and 60 meters (131 and 197 feet) electrode separation. A detailed log of a well drilled at T-5 was not kept, but water-level records (Dugan, unpub. data) indicate that it encountered water sufficient to fill it to within 2.35 meters (7.7 feet) of ground level in 3 days; the source may have been ephemeral groundwater or leakage from the channel of Cane Run moving along the soil-bedrock interface.

Line T failed to encounter low-resistivity anomalies that, when sounded with a Schlumberger array, produced the apparent resistivities of less than 130 ohm-meters encountered at G-4 (Line A). Soundings taken in the low-resistivity zone at the west end of the profile (T-2, T-6, T-3) (Figure 55) show low resistivity at considerable depth, and are physically close to the anomalies at L-8 and L-9. They are probably related to the low-resistivity anomaly at L-1 and represent the effect of moderate-sized conduits at depth (Figure 46). The east end of the line is close to the anomalies explored by G-1, G-2, and G-3 of Line A, and the results of the drilling were similar (Figure 56 and 57, from Dugan, unpub. data), but the shape of the sounding curves from this end of Line T resemble more closely the curves corresponding to karst conduits of moderate size encountered in sounding and drilling at L-1 and L-4 (Figure 44). These results weaken the argument that a correlation can be inferred between the magnitude of the resistivity decrease encountered while sounding and the size of the conduit producing the anomaly. Interpretation of the geology of Line T is presented in Figure 58, which shows incipient conduit development at T-3 and T-4.

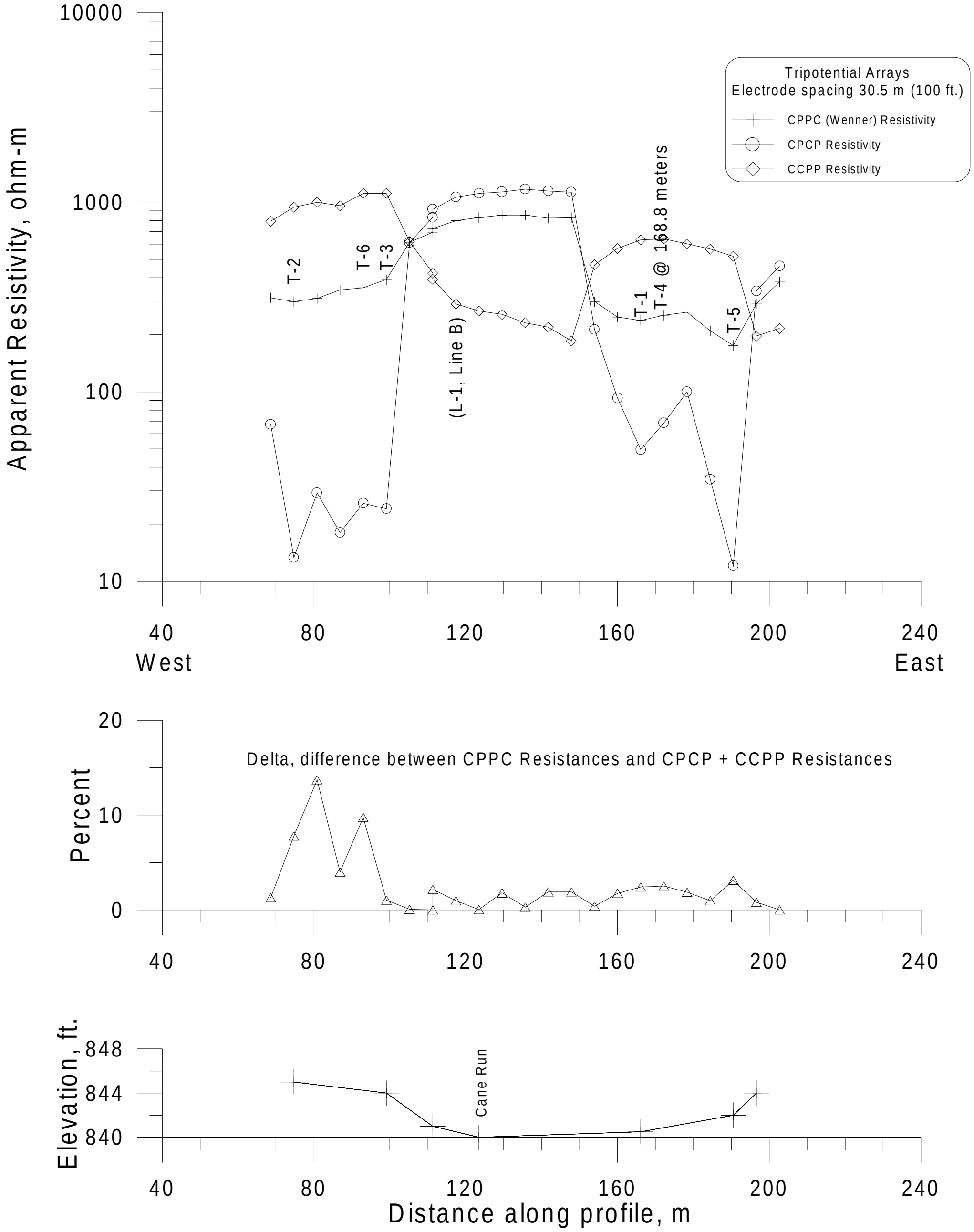
Kentucky Horse Park Study—Discussion

Figure 59 shows the sounding curves of various points that were drilled in the course of the study, arranged according to the size of the water-bearing voids encountered versus the depths at which they were encountered. The figure shows a trend toward curves with low-resistivity crests and decreasing resistivities in the wide electrode spacings that seems to be most pronounced in the 0.1 to 1.0 meter (0.3 to 3.3 feet) sector of the size axis (soundings L-1, L-4, and G-4). In contrast, the presence of shallow groundwater seems to effect a slight decline in resistivity, often followed by continued rise in apparent resistivity at large electrode spacings. The largest voids were encountered under the site of the G-4 family of soundings, which also registered most of the lowest resistivities encountered at depth in the Kentucky Horse Park study. It must be noted, however, that the resistivity signatures of the holes that drilled into conduits around 0.1 meter (0.3 foot) are not unique; similar sounding curves were found at sounding T-4 (Figure 57), and the site was drilled but no significant water-bearing voids were encountered.

The geophysical data gathered were not of a consistent overall quality to allow a definitive series of geophysical signatures to be related to unique geologic situations. The exception was the sounding taken at G-4, which produced the lowest resistivity values at depth in the Kentucky Horse Park study area; it was sited over the conduit that was the target of exploration.

The sounding at G-4 and the profile data around it were unique, and the drilling of other low anomalies as “false positives” can, in retrospect, be considered a failure of field interpretation of the geophysical records rather than a failure of the method. Less pronounced low-resistivity anomalies predict the existence, size, and depth of smaller (less than 1 meter in diameter [3.3 feet]) conduits only approximately. This rough form of curve-matching does not yield consistent correlation of geo-

Figure 54. Profile T (Tripotential profiling) with soundings indicated
Kentucky Horse Park



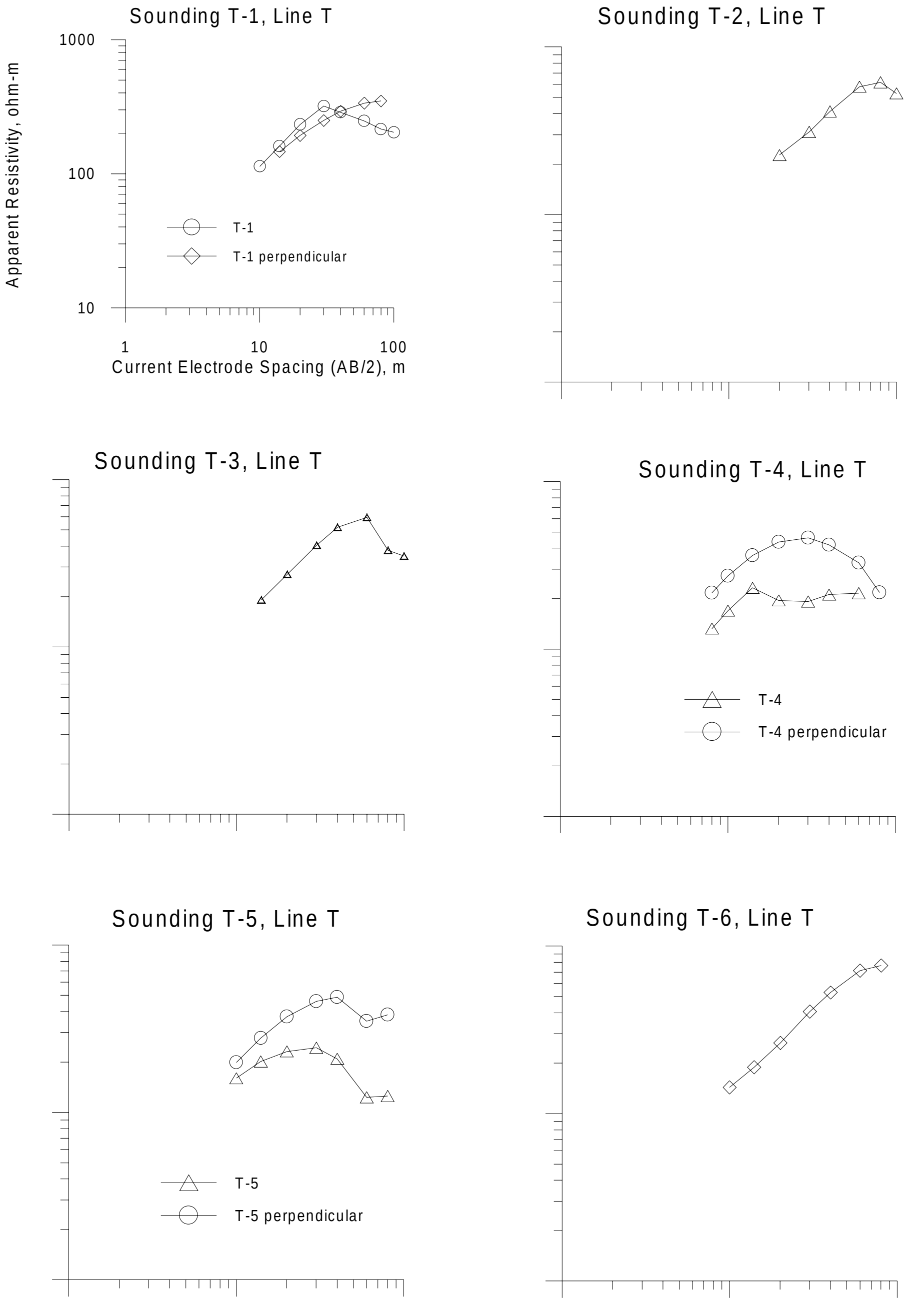
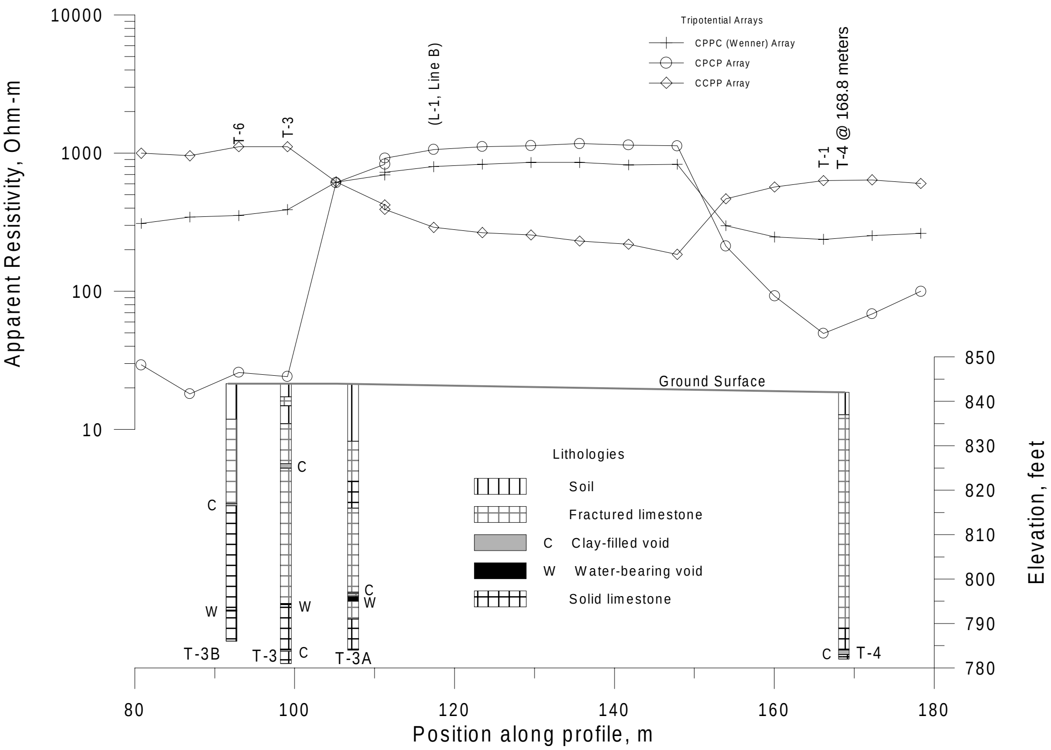


Figure 55. Soundings, Line T

Figure 56. Central segment, Line T. Resistivity profile and drilling results.



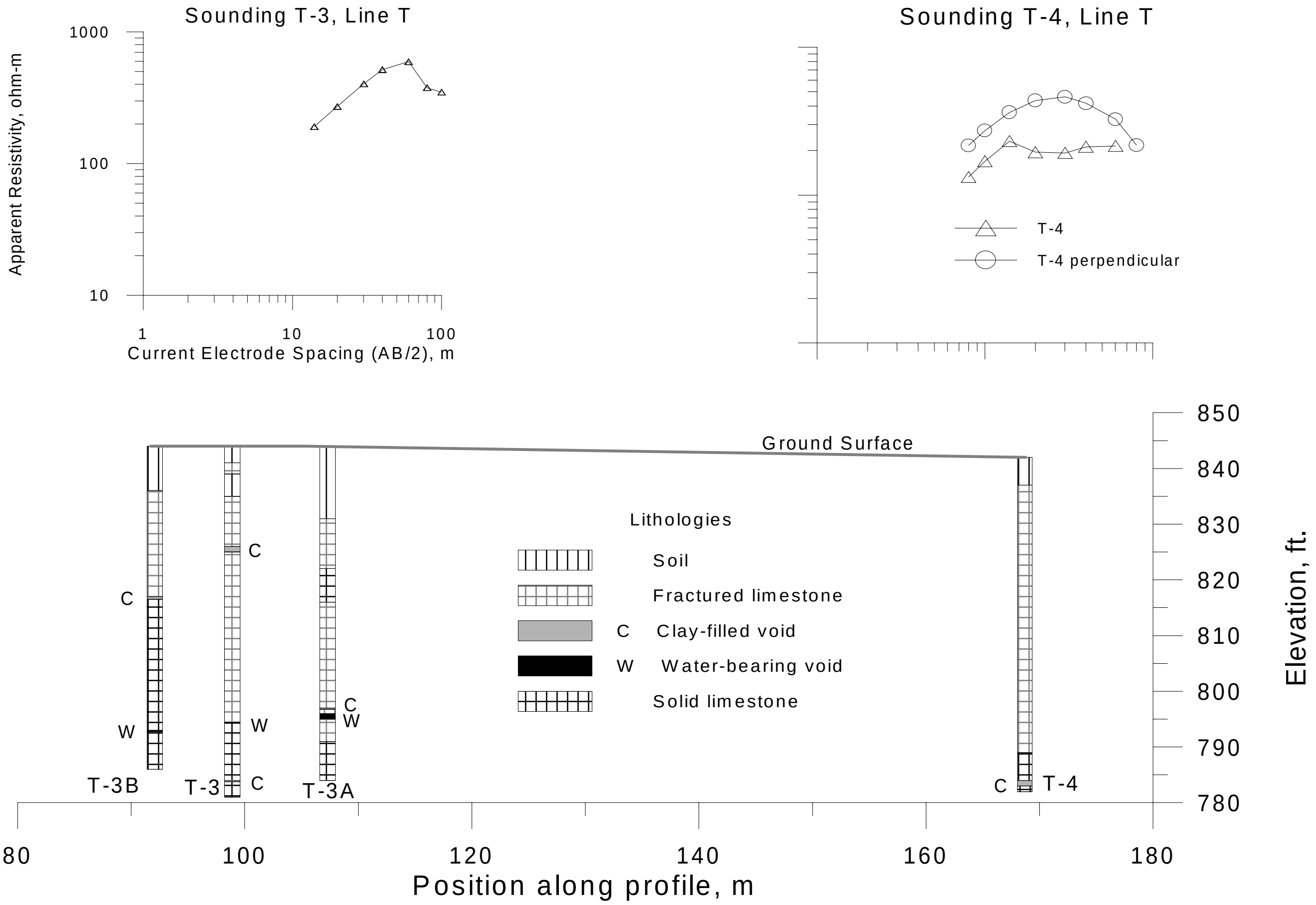
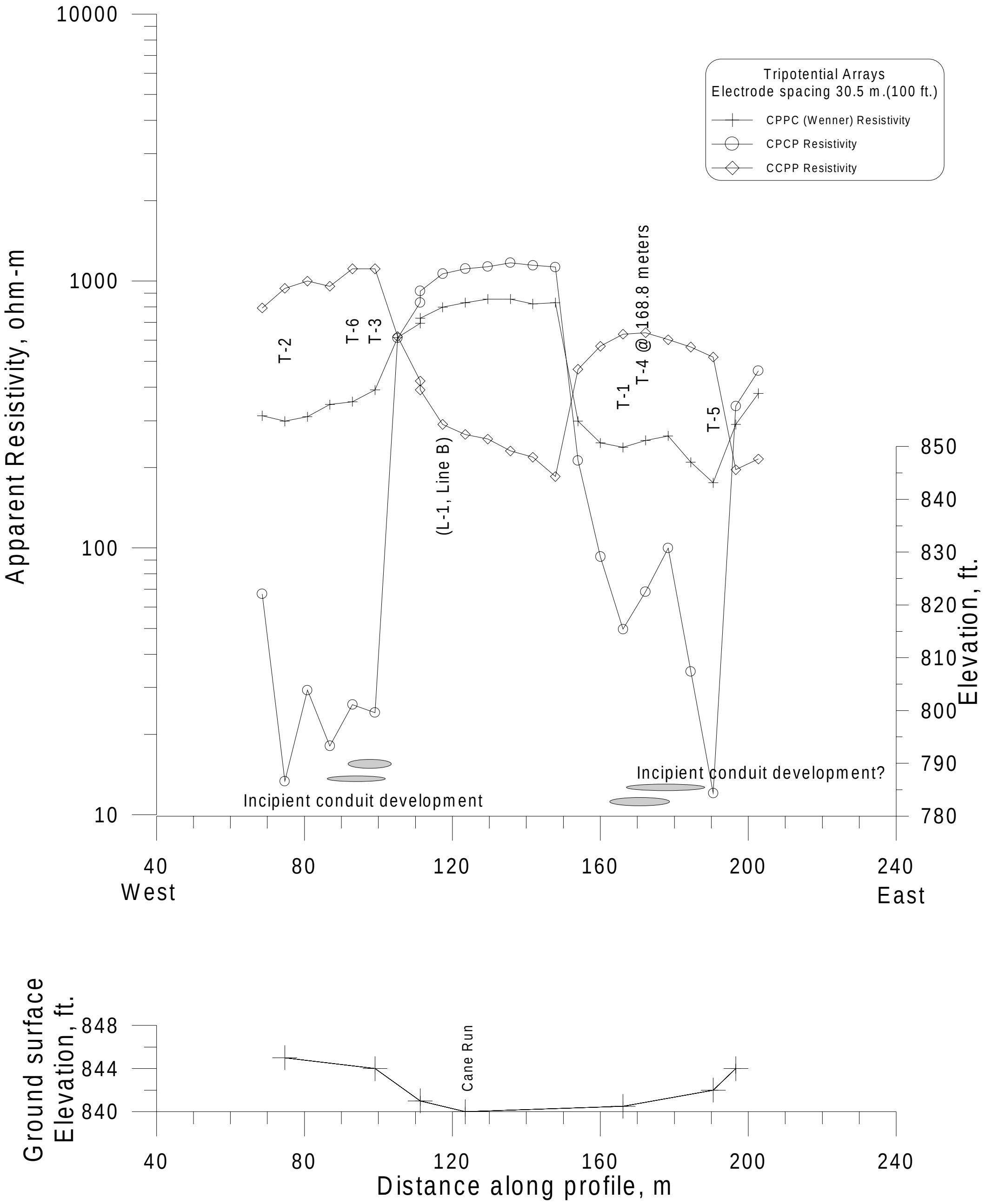


Figure 57. Central segment, Line T. Resistivity sounding and drilling results.

Figure 58. Profile T (Tripotential profiling) with interpretation
Kentucky Horse Park



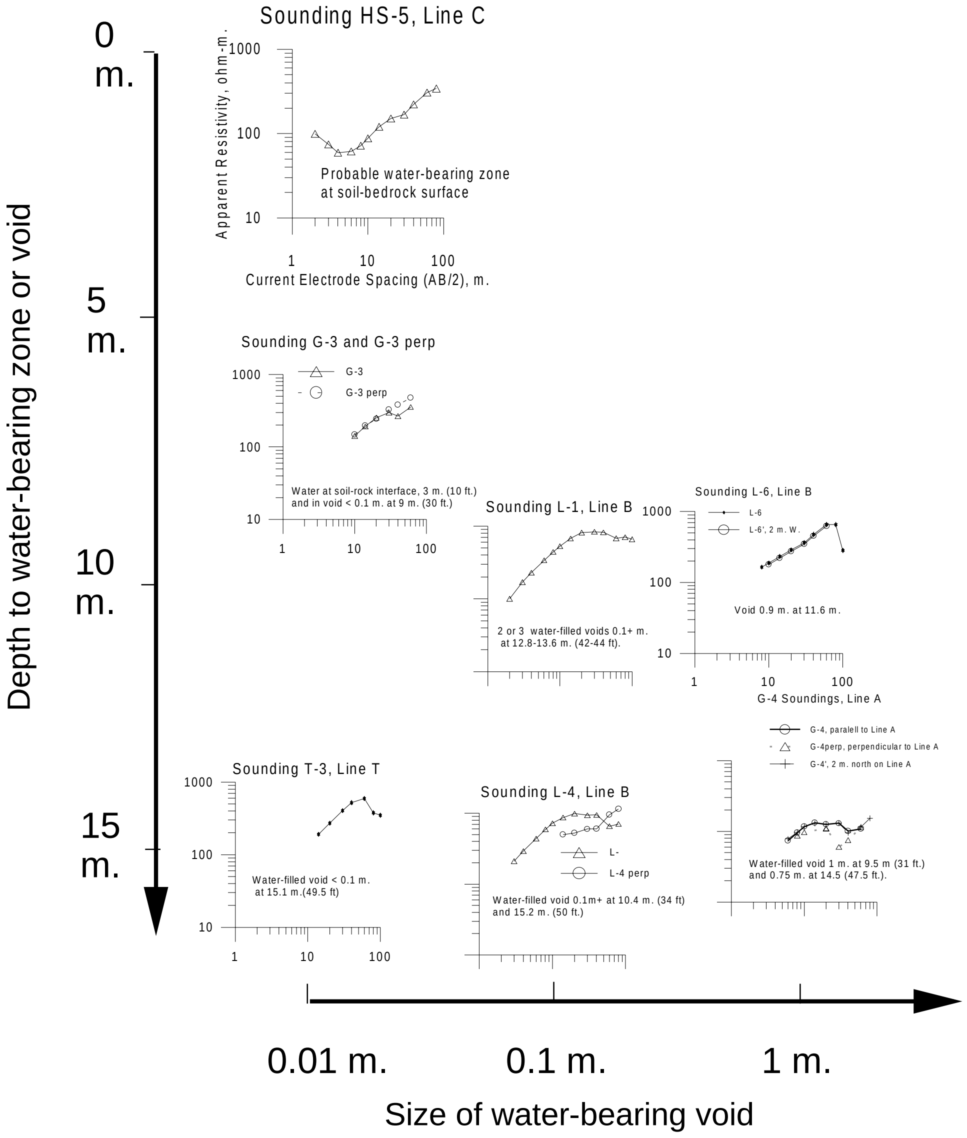


Figure 59. Comparison of sounding signatures of water-bearing zones, arranged by size and depth, Kentucky Horse Park. The presence of water at HS-5 is speculative.

physical data to observed geology. A more thorough examination of the method of electrical resistivity is in order, to determine if changes in application or interpretation would make it more practical for prospecting water in karst terrains.

Figure 60 is a comparison of the ranges of apparent resistivity of profile data from the Kentucky Horse Park. Background thresholds were interpreted loosely and in the field, and are considered unique to each profile. Not all deviations were considered anomalies, and thus were not targets for sounding. Lowest resistivities were encountered in Line A (at G-4, over the Royal Spring Conduit) and Line T, both of which are known from drilling data to be over water-bearing conduits. Highest resistivities were encountered in Lines C, D, and E. Line E is situated in an upland area, away from waterways and observable karst features. By contrast, Line D was run in an area of karst features, and one end was close to Cane Run, while Line C crossed Cane Run and did not extend up onto high ground. A consistent interpretation of the ranges of apparent resistivity in the Kentucky Horse Park is further complicated because profiling with the Wenner arrays was not carried out at a consistent electrode spacing, which ranged from 21.2 meters (70 feet) to 45.7 meters (150 feet).

Profiling with the Wenner array in its simplest form is suitable more for the delineation of large-scale, high-angle, throughgoing discontinuities than the detection of small, isolated zones of contrasting resistivity. The Wenner array is easily adaptable to Tripotential profiling, a method that is considered to be highly sensitive to lateral changes in earth resistivity, and the Tripotential method was employed in Lines F and T. In Line T, the index of inhomogeneity, Delta, was noticeably elevated in the vicinity of L-3, where water-bearing conduits were located by drilling (Figures 54 and 57).

The Schlumberger array is probably the best array for vertical electric sounding, but the effect of discontinuities and isolated anomalous bodies at a scale less than the electrode spacing creates irregularities in the curves that either must be ignored in interpretation or modeled by the use of layers of slight thickness and often alarmingly contrasting resistivity (Zhody and others, 1974). Vertical electric sounding with the Schlumberger array, and sounding generally, must be undertaken where the layering can be considered consistent, or where the effects of lateral inhomogeneity will be minimized. Bonita (1993) conducted his soundings using the Wenner array where the Royal Spring Conduit is known to exist, and in terrain very similar to that of the Kentucky Horse Park; his sounding curves were much smoother than those produced in this study.

A problem shared by both profiling and sounding as carried out in this study is a changing electrical field. At each successive position of the potential electrodes, the electrical field is different because the current electrodes have been moved as well. This makes objects difficult to distinguish on a scale smaller than the increment between measurements, especially in cases where the maximum distortion of the electrical field caused by a more- or less-resistive object is registered at the potential electrodes in only one array position. Tripotential profiling takes three resistivity measurements at each position, and increases the sensitivity of the survey to lateral changes in subsurface geology. Numerous other arrays not used in the Kentucky Horse Park can be found in the literature for profiling and sounding (Lee and Hemberger, 1946; Van Norstrand and Cook, 1966; Dey and others, 1975; Smith, 1986). Some less commonly used arrays can be used or adapted for use with a stationary, and presumably stable, electrical field.

The effectiveness of the electrical-resistivity method in the detection of water-filled conduits seems clear, as illustrated by sounding G-4, where a well intersected the Royal Spring Conduit that can produce water in excess of 4.7 liters per second (75 gallons per minute). The discovery of the conduit signature at sounding G-4, diagnostic of the Royal Spring Conduit in that location, was late in the project. Notes indicate that Tom Dugan was in the field frequently for the space of 5 months taking resistivity and other measurements. Twenty-seven water-well records submitted to the Kentucky Division of Water for drilling done in the Kentucky Horse Park are associated with a number believed to represent a sounding or profile position. A few of these records indicate that the optimistic but experienced driller believed that the well would produce 0.3 to 0.6 liter per second (5 to 10 gallons per minute). This estimate is nearly meaningless for its vagueness and considering its source, but probably indicates that the driller believed the hole would make an adequate well for domestic use but would not deliver constant, large volumes of water for irrigation. The success rate of the electrical-resistivity method, then, for discovering the conduit is less than 4 percent (one successful well out of 27 holes drilled on the basis of electrical-resistivity data). The driller's records also indicate that 43 holes were drilled in the Kentucky Horse Park over a 10-month period and of the 16 wells drilled apparently without resistivity signature to prompt their siting (being placed on the basis of geology, terrain, convenience, or other reasons), none were successful in encountering the conduit. It is significant, therefore, that the use of geophysical methods provided the final piece of information that

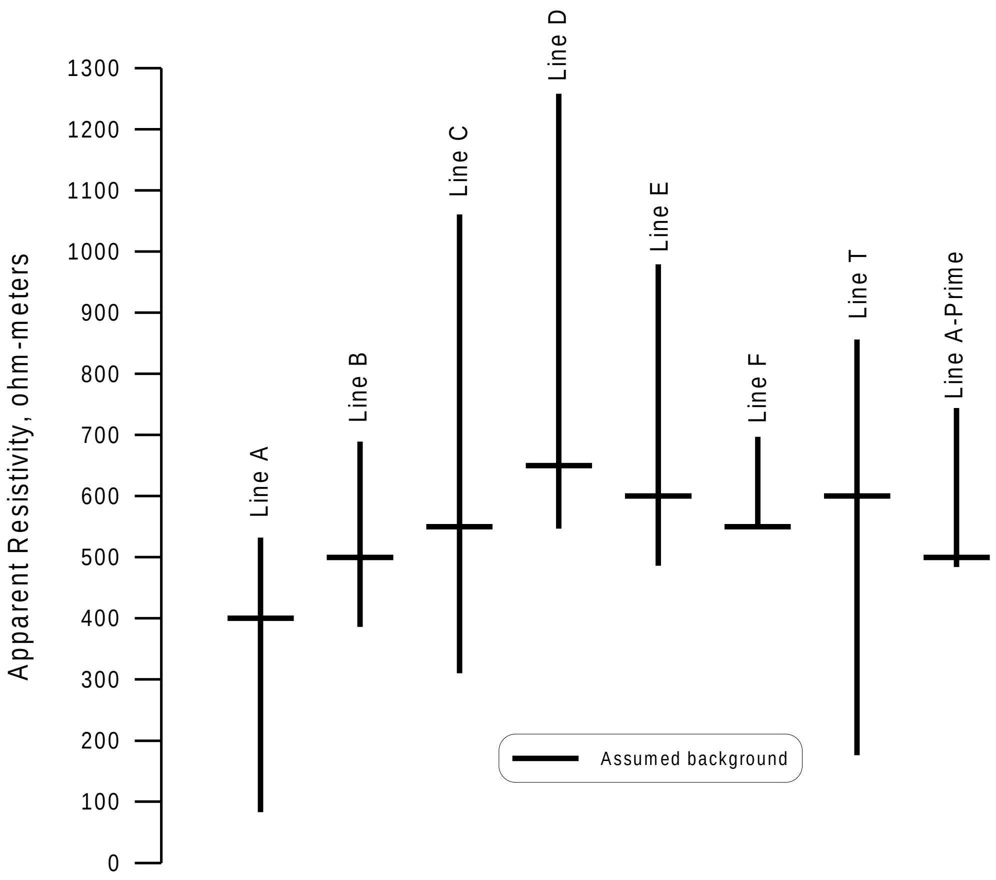


Figure 60. Comparison of apparent-resistivity ranges and the assumed background resistivity thresholds, Kentucky Horse Park profiles. Resistivity values which fell below background were considered to be negative anomalies.

complemented the geologic investigation to locate the conduit and drill into it.

DIAGNOSTIC PROFILES FROM IRONWORKS PIKE

A roadcut on Ironworks Pike approximately 1.1 kilometers (3,600 feet) west of the central part of the Kentucky Horse Park, immediately west of the Southern Railroad right-of-way, was selected for additional study (Figure 2a). Three large solutionally enlarged joints cut the limestone subvertically in the south wall of the roadcut, and were filled with illuviated clay from the overlying soil (Figure 61). These features are common in roadcuts in the Inner Bluegrass and are encountered during excavation for construction. The largest of the joints with the least eroded soil cover was selected for diagnostic profiling in order to determine the electrical-resistivity signature, if any, that could be attributed to the feature. The joint averaged approximately 0.8 meter (2.6 feet) in width at the roadcut. Figure 62 shows the results of Tripotential profiling at the Ironworks Pike study area. The resistivities rise to more than 63 percent and 98 percent from the lowest values for the CPPC and CPCP arrays, respectively. Data from the CCPP array are the most affected, with resistivities dropping significantly as the array begins to cross the joint and then doubling as the array moves completely off of the joint.

The resistivity signature of jointed rocks has been studied by other workers, usually by the use of azimuthal surveying; that is, rotating the array about a fixed center by fixed azimuthal increments (Leonard-Mayer, 1985; Taylor and Fleming 1988). In order to investigate the resistivity signature of the joint, the array was set so that electrode C1 was fixed in the earth above the joint and a succession of readings was taken at 5- to 10-degree increments as the array was pivoted on that fixed point. Fan profiling (Figure 63) of the Ironworks Pike exposure shows the effect of the “paradox of anisotropy,” the apparent reversal of the anomaly produced by electrical anisotropy such that an elongated high-resistivity body or feature will have a low-resistivity signature when the array is aligned parallel to it (Kunetz, 1966).

SINKING CREEK KARST BASIN STUDY

A system of surface streams and karst conduits in Jessamine and Woodford Counties, culminating in Garretts Spring, was under study by the Kentucky Geological Survey (Currens and Graham, 1993). Electrical-resistivity techniques were employed in a part of the basin to investigate the feasibility of siting monitoring wells in the conduit system connecting Sinking Creek to Owens Karst Window, on the Denver Dillingham farm (Figure 64). The study area is underlain by the Tanglewood and Grier Members of the Lexington Limestone, though it is possible that as much as 50 meters (164 feet) of the northeast and southwest ends of the line of survey are in the Brannon Member (Cressman, 1965). Numerous large and small sinkholes lie between the swallow-hole system of Sinking Creek and the springs of Owens Karst Window, but one area was found where a profile could be run perpendicular to the trace of the conduit that would not encounter too much topographic relief. Figure 65 illustrates the position of the features with respect to the resistivity surveys discussed below.

A combination of arrays was used in an effort to simultaneously test the methods and clearly delineate the position of anomalies encountered. A symmetrical Schlumberger array was used to conduct a sounding to a current-electrode spacing of 100 meters (328 feet). Figure 66 shows the results of sounding P1. A resistivity low between electrode separations 1 and 6.8 meters (3.3 and 22 feet) is probably a reflection of increased soil moisture in the lower part of the soil profile or at the soil-bedrock contact. The plot of the apparent resistivity levels off after electrode spacing 46.4 meters (152 feet) at approximately 1,300 to 1,400 ohm-meters; the slight dip at 68.1 meters (223 feet) is probably not significant. Sounding P-1 was redone the following day after a rain of approximately 0.3 centimeters (0.1 inch), and there was no significant deviation in the resistivity values. The current electrodes were left in place at 100 meters (328 feet) from the center, and the resistivity was measured at 5-meter (17.3 feet) intervals between them, to profile the surface configuration of a fixed electrical field in what was referred to as an “asymmetrical Schlumberger” profile (Figure 67). This electrode arrangement historically has been called the Gradient array (Whitely, 1973). If the resistivity of the earth is increasing with depth as the plot of sounding P1 suggests, then a uniform rise in measured resistivity with increasing distance from a current electrode would be expected, as is the case between the 5- and 140-meter (17.3- and 459-foot) positions in the profile shown in Figure 67. The steepest slopes on this segment of the curve are nearly symmetrical about the center at 50–60 and 130–140 meters (164–197 and 426–459 feet). A significant anomaly was detected in the interval 140–190 meters (459–623 feet). This appears to be a high-resistivity anomaly whose surface expression is centered at 165 meters (541 feet), though the configuration of the equipotential surfaces concentric to the current electrode at 200 meters (656 feet) makes it likely that the high-resistivity material causing the apparent anomaly lies in the

Figure 61. Solutionally enlarged joint, east end of Ironworks Pike, Fayette County. Joint is 0.8 to 1 meter (2.8 to 3.3 feet) in width and is filled with illuviated clay. View is to south.

Figure 62. Tripotential profile run over solution-enlarged joint with clay filling. Roadcut on Ironworks Pike west of Kentucky Horse Park.

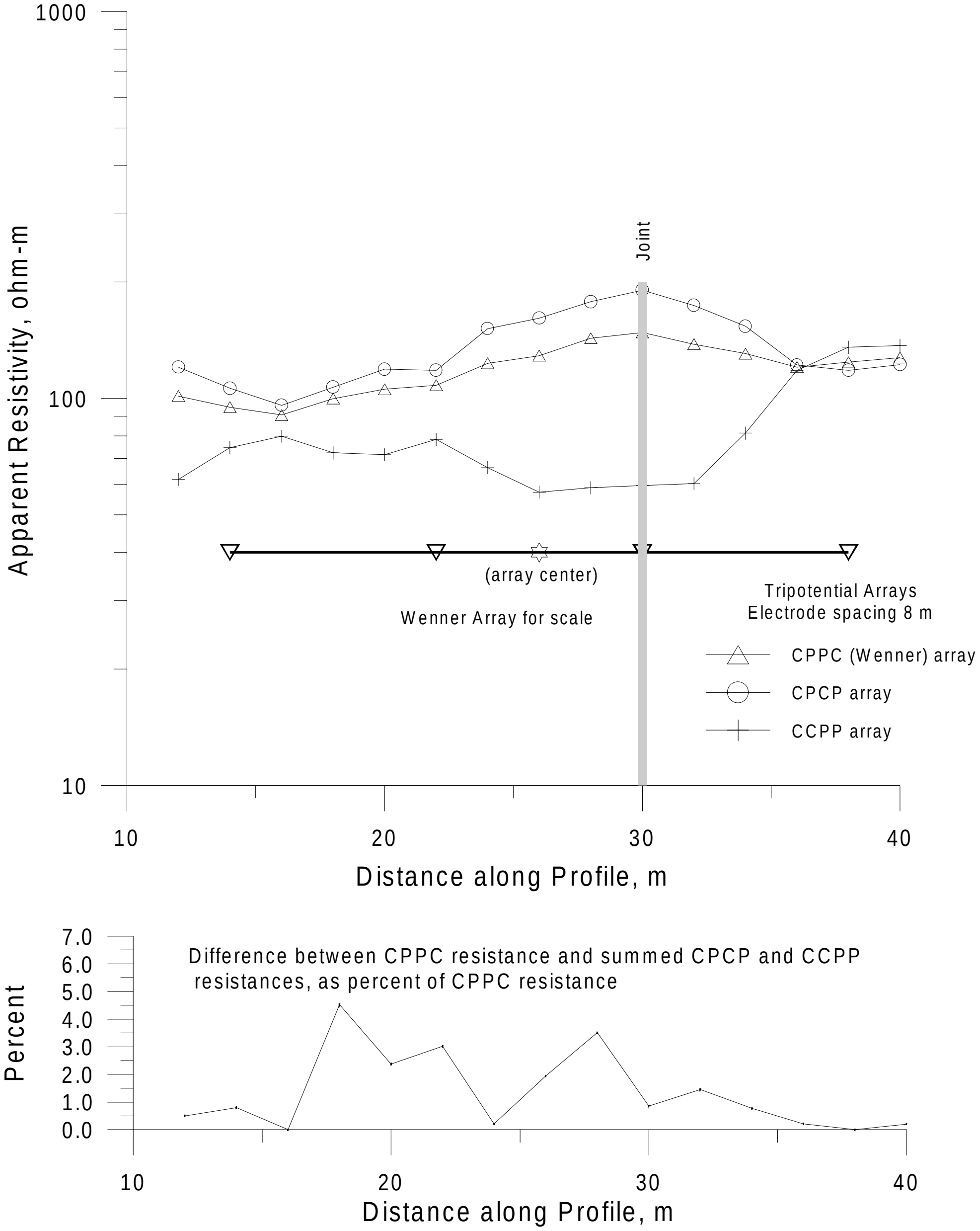
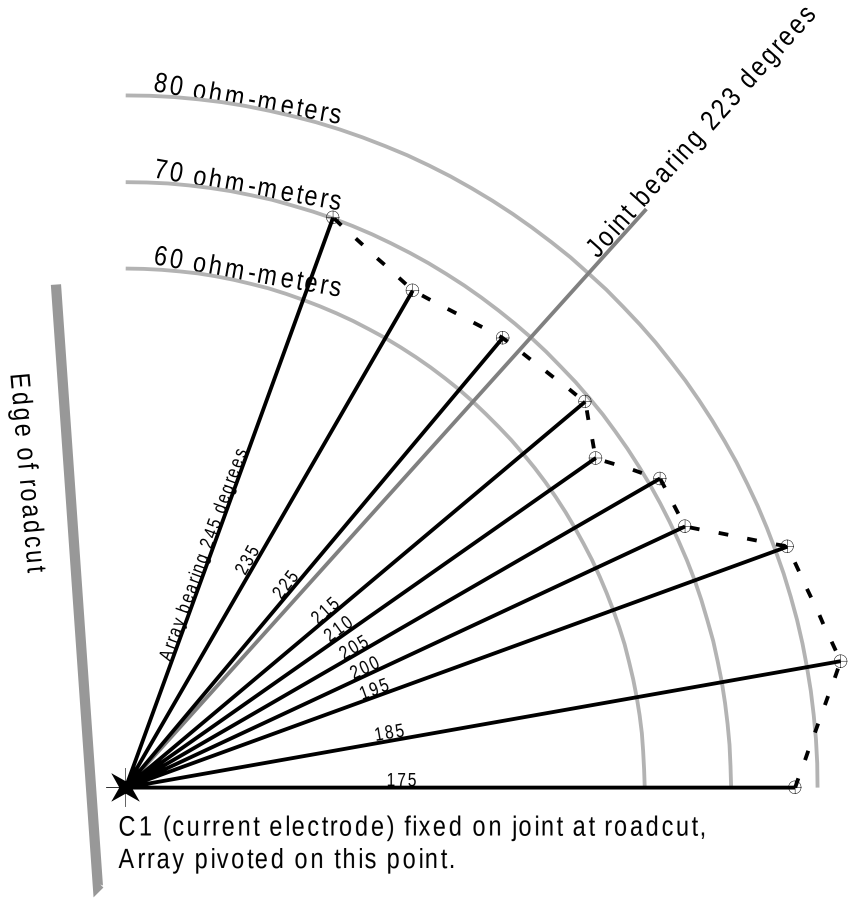


Figure 63. Fan profile results. Length of solid lines represents apparent resistivity at that bearing. Wenner array = 8 meters. Highway right-of-way on Ironworks Pike.



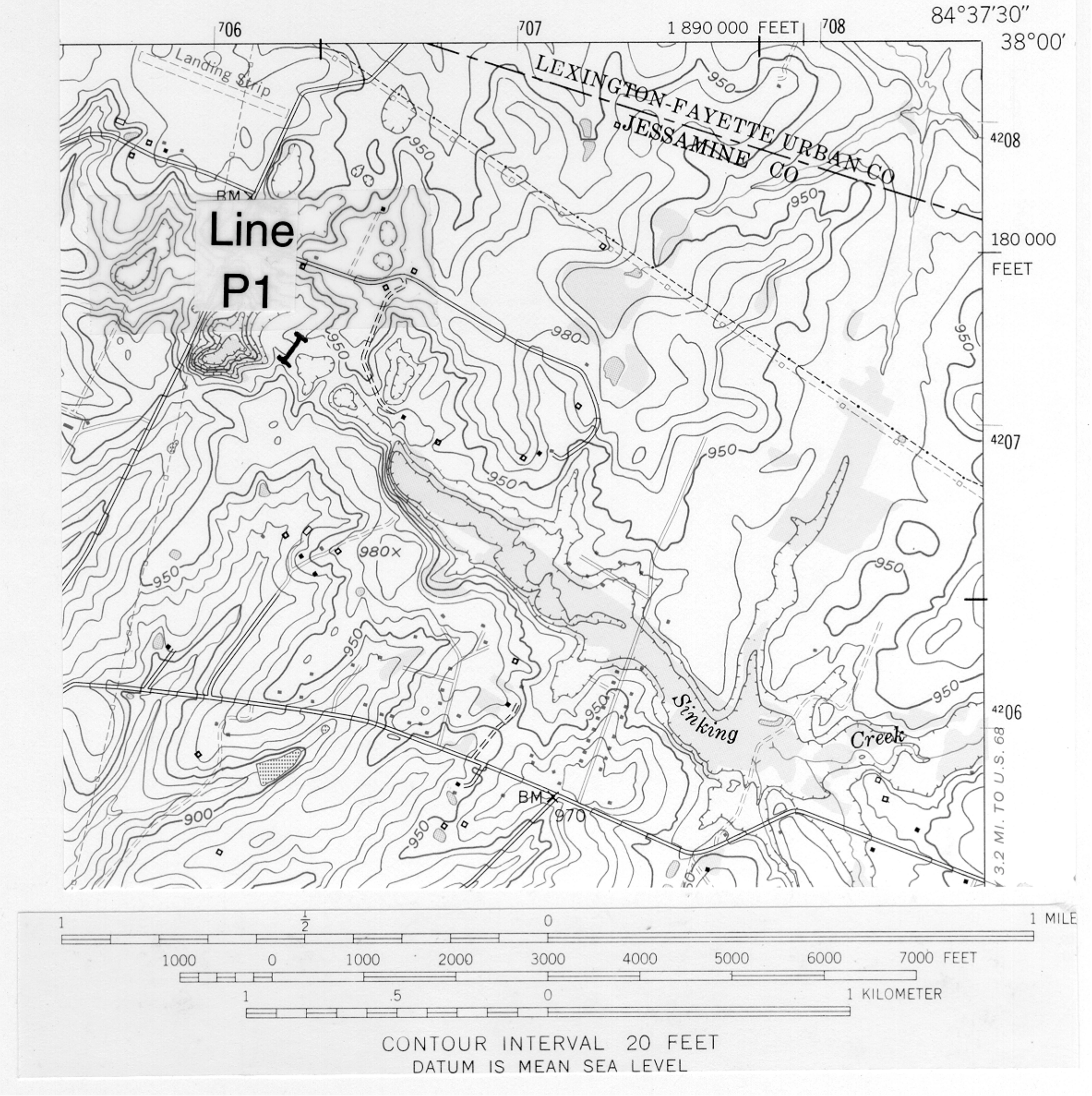


Figure 64. Sinking Creek study area. Northeast part of the Keene 7.5’ quadrangle (USGS, 1:24,000), Kentucky.

Figure 65. Location map, Sinking Creek Karst Basin study, Denver Dillingham farm, Jessamine County, Kentucky.

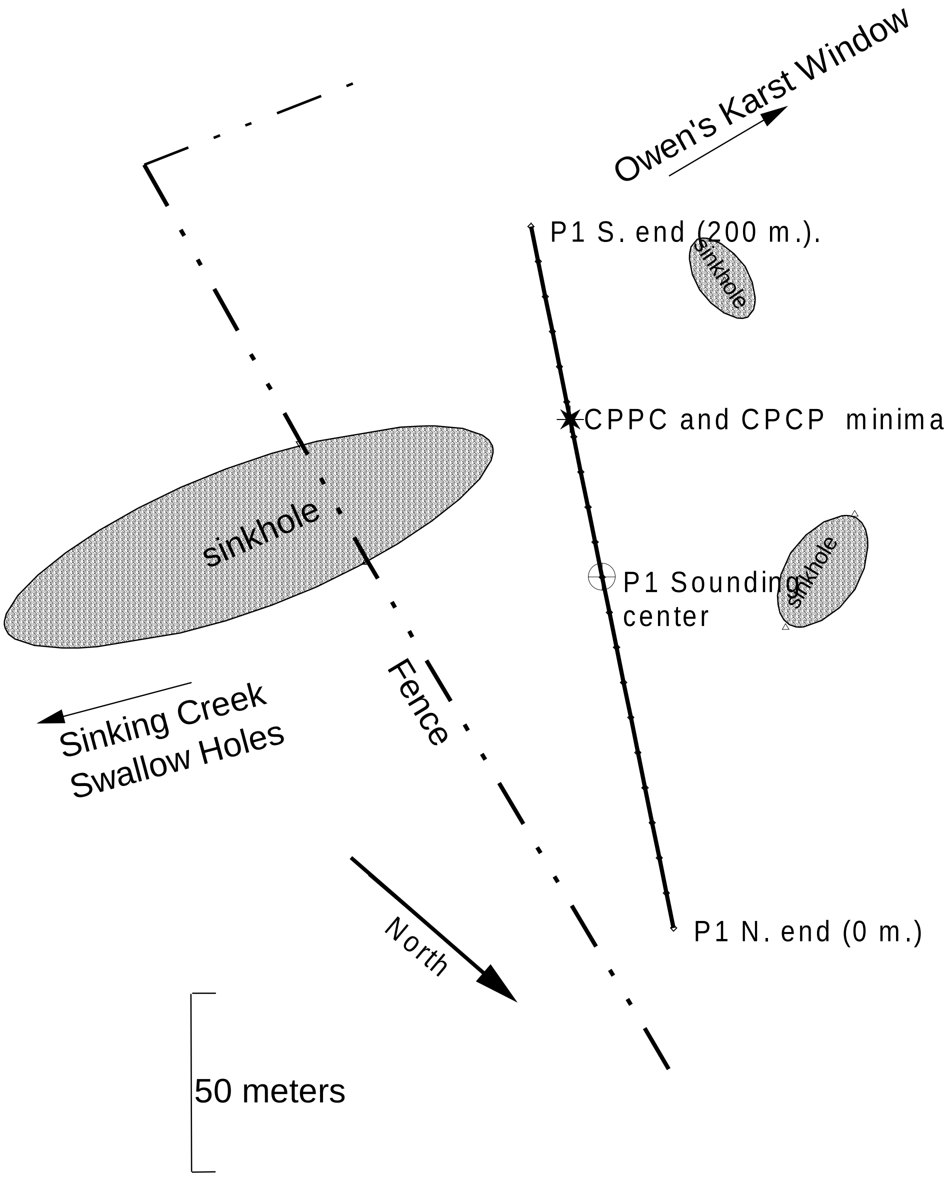


Figure 66. Sounding using Schlumberger array. Sinking Creek Karst Basin study.

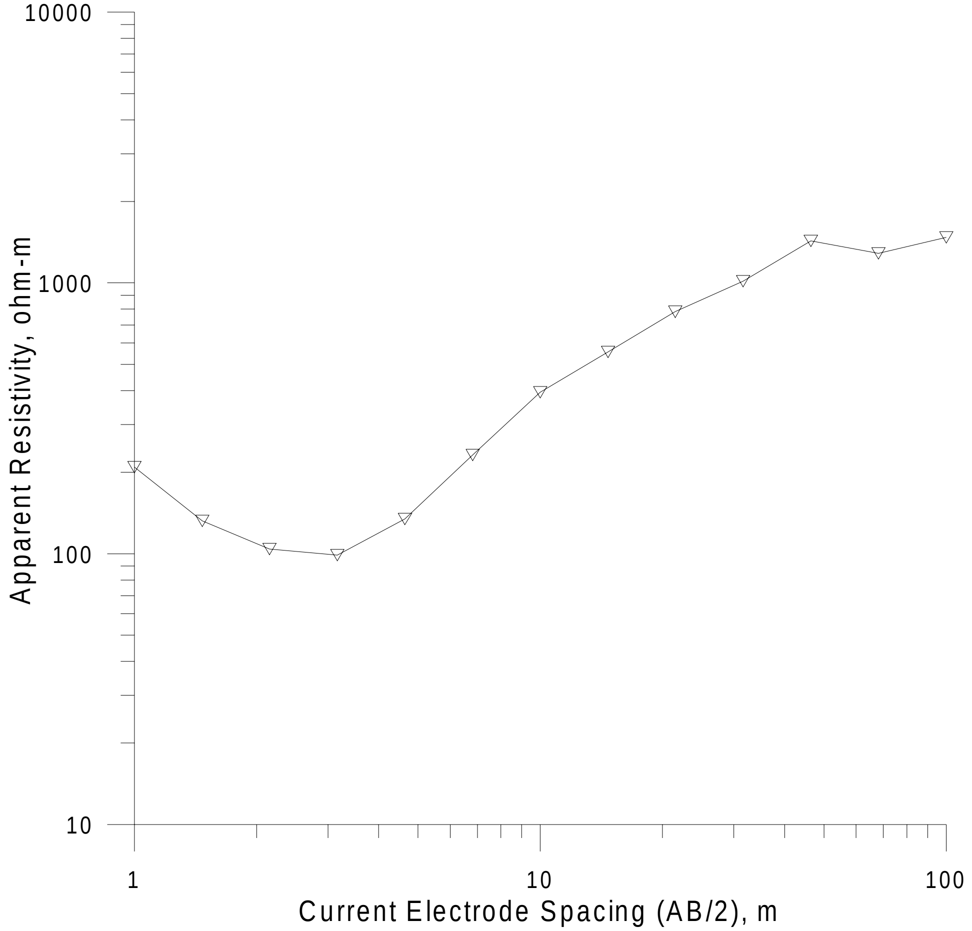
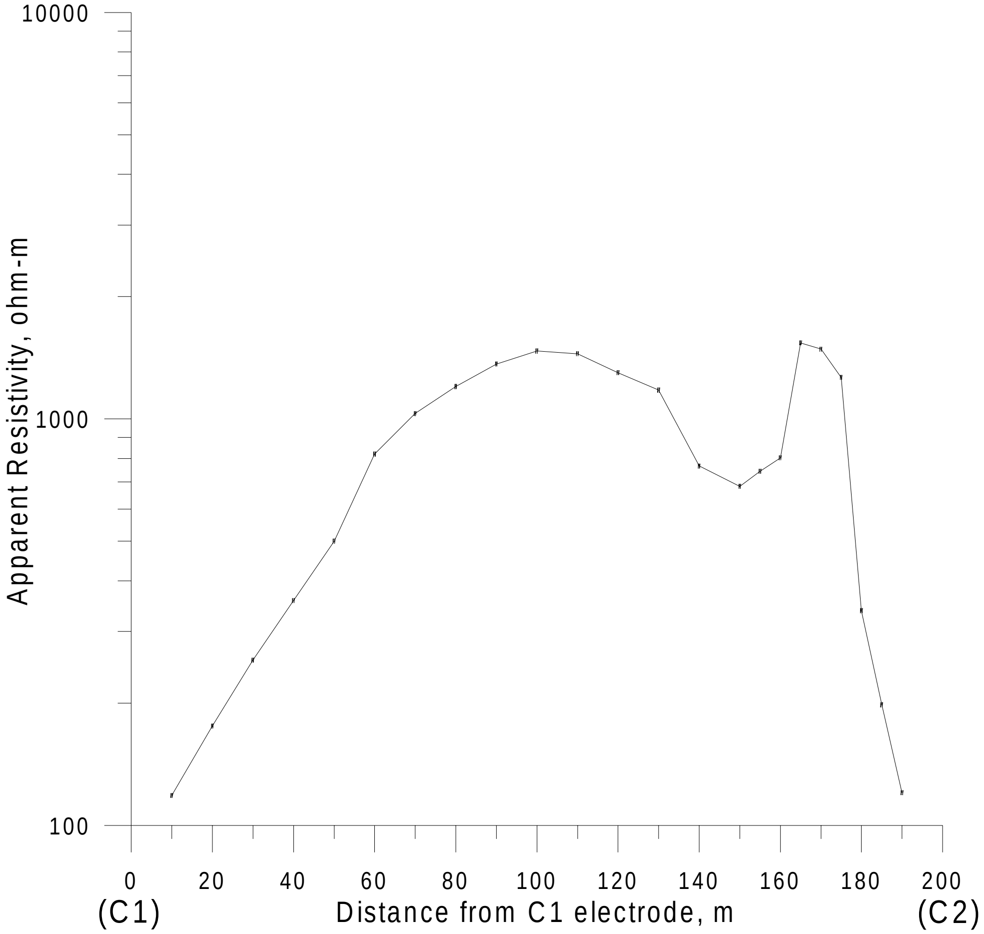


Figure 67. Profile between stationary-current electrodes (asymmetrical Schlumberger array), Line P1. Potential electrode spacing 10 meters. Sinking Creek Karst Basin study.



shallow subsurface between 165 and 200 meters (541 and 656 feet). It is interpreted here to be caused by air-filled solution cavities, now abandoned by flowing water. It is also possible that the anomaly is the signature of the Brannon Member, asserting itself in the apparent-resistivity curve at the southwest end of the line.

A profile using the Tripotential method was conducted over the line covered by sounding P1. Figure 68 shows the apparent resistivities measured along line P1, and the topographic profile. The resistivity profile rises smoothly between centers -7.5 and 82.5 meters (-25 and 271 feet). At 92.5 meters (303 feet) the CPCP- and CCPP-array resistivities diverge wildly, probably a result of thin soil noted in that vicinity. The CPPC (Wenner) resistivity rises continuously (unaffected by the apparent anomaly at 92.5 meters [303 feet]) to the 112.5-meter (369-foot) position. Between 122.5 and 157.5 meters (402 and 517 feet) a clear anomaly of low apparent resistivity exists in both the CPPC and CPCP curves, mirrored by a rise in CCPP resistivity. South of the 157.5-meter (517-foot) position, the CPPC and CPCP resistivities rise to levels higher than those north of the low anomaly.

Figure 69 details the interpretation of data obtained at line P1. The anomaly between 112.5 and 157.5 meters (402 and 517 feet) is interpreted as being caused by a zone of water-bearing conduits known to connect the swallow holes of Sinking Creek and the springs of Owens Karst Window. Ogden and Eddy (1984) encountered resistivity anomalies using the Tripotential technique in a carbonate terrain in Arkansas which later were drilled and found to correspond to water-bearing fractures; the signatures encountered in the present study were remarkably similar. The high-resistivity anomaly between 165 and 200 meters (541 and 656 feet) discovered during the “asymmetric Schlumberger” profile could not be examined in Tripotential profiling because of physical obstacles to the electrode array that did not interfere with the modified Schlumberger array, but is believed to have been caused by lowered resistivity of the rocks owing to air-filled cavities somewhere in the interval.

GENERAL CONCLUSIONS

1. Conduits of both large and small size can register as low-resistivity anomalies on profiles (Lines B and A; Figures 42 and 51) and on soundings (L-1 and G-4; Figures 43 and 52).
2. Lateral discontinuities, including known conduits, can register as anomalies on profiles, but the signal is noisy and an anomaly produced by low-resistivity material can be flanked by spiked resistivity highs, probably as a result of “image effects.” The resulting anomaly is wider than the feature itself, and the boundaries of the geologic contrast that produce the anomaly may not be represented by the limits of the anomalous resistivity readings (Figure 42, Line B, east end of line).
3. Lateral discontinuities in the surface or subsurface can create irregularities and abrupt changes in slope in apparent-resistivity curves for soundings using the Schlumberger array that confound efforts to match them with published examples of layered models, or to meaningfully model them as a layered earth using commercial software (Sounding H-7, Figures 23 and 24). This circumstance probably is due to expanding the current electrodes across the discontinuities, creating radical and non-symmetrical changes in the electrical field. This results in abrupt changes in the resistivity read at the potential electrodes in the center of the array (Zhody and others, 1974). The requirement of lateral continuity of model layers (necessary for manual curve-matching or modeling software) is violated in this situation. Taking soundings over the same center point but with perpendicular orientation of the array can alert the researcher to the existence of lateral discontinuities (soundings HP-1A and HP-1B, Figure 49).
4. Any sounding curve can be duplicated accurately by a family or families of models. For this reason, selection and inversion of models is best accomplished by constraining the model with as much known geological and geophysical data as are available. These can include (but are not limited to) thicknesses of soil layers, depth to water, and the probable resistivity of a layer. Modeling of Line A’ was undertaken using some of this information, with two out of the four modeled soundings converging to the field data within 5 percent, and the others to 15 and 11 percent.
5. Effects of relative elevation and drainage features can be noticeable on profiles and should be remarked in the field notes of resistivity surveying. If possible, elevation data, even roughly measured, should be taken and plotted with the resistivity data. Trends and anomalies resulting from elevation changes and drainage features can mask anomalies due to subsurface features, or surface-induced anomalies can be falsely interpreted as reflecting conditions in the subsurface. For example, the large central anomaly on Profile C (Figure 39) is probably due to an abundance of water near the soil-bedrock interface in the vicinity of Cane Run rather than to a low-resistivity zone in the deeper subsurface.
6. Diagnostic signatures of known geophysical and geological features are of great value to research-

Figure 68. Tripotential profile of Line P1, electrode spacing (a) 25 meters. Sinking Creek Karst Basin study.

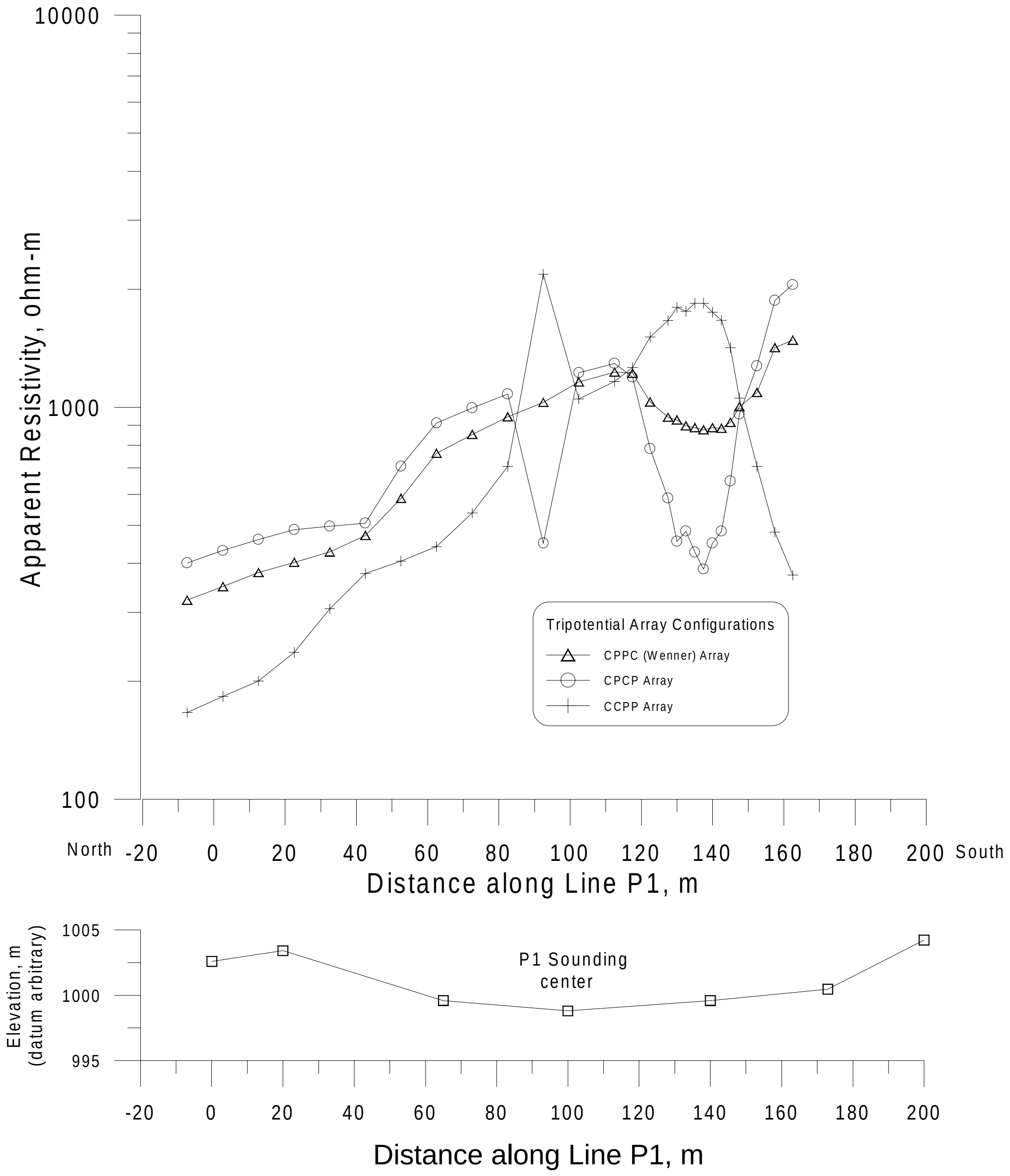
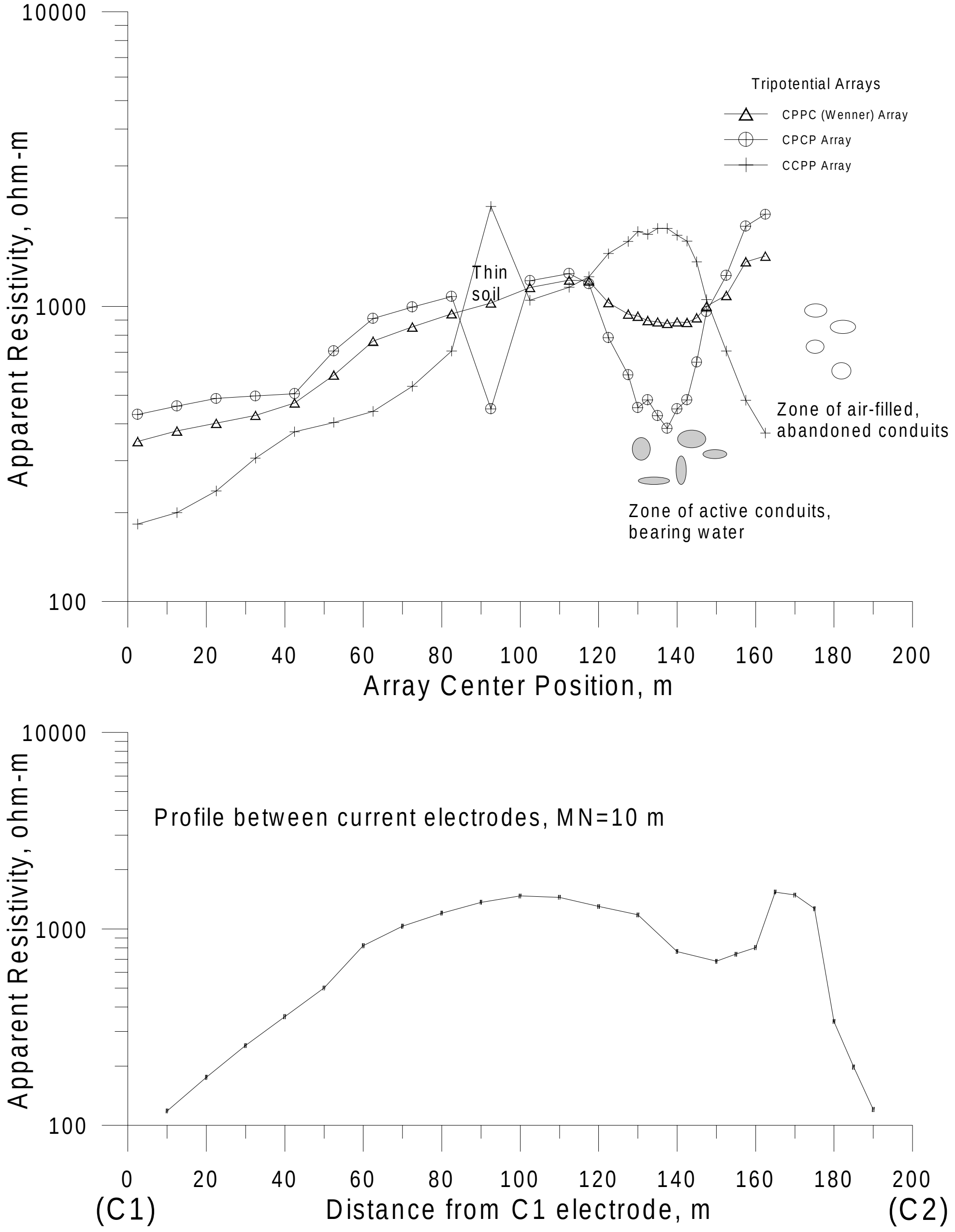


Figure 69. Interpretation of Line P1, Sinking Creek Karst Basin study.



ers in the field of exploration geophysics. Caution must be exercised, however, when interpreting anomalies (or the lack thereof) based on similarity to a diagnostic signature; many different conditions of soil, rock, water, and the geoelectric response of them in their particular geometry affect the resistivity measured at an interval. The response may vary with time, as hydrologic conditions can change and soil moisture levels fluctuate. Nonetheless, this researcher recommends that work in any given locale be prefaced with a series of measurements using different arrays over a designated "course" where the geology is, to some degree at least, well understood by the interpreter of the data. Repeating the resistivity measurement of various points at different soil-moisture or hydrogeologic conditions can be useful if data from a site are taken at separated times or after rainfall. Ideally, a researcher would develop a library of diagnostic studies pertaining to different areas, arrays, and subsurface geometries.

7. The response of the electrical field to near-surface conditions is very important. Wet ground, soil moisture and the ability of different soils to retain moisture, and the presence or absence of water at the soil-rock interface can have a profound impact upon the apparent resistivities, even when the electrode array is arranged to measure the resistivity at greater depths. When taking resistivity soundings it is important to keep in mind that eliminating short-spacing readings can hamper detailed interpretation of sounding data, in spite of field time saved.
8. Arrays other than the symmetrical Schlumberger array and the Wenner array were shown to clearly identify anomalies in the Sinking Creek Karst Basin study. Adoption of other methods such as the combination profile of Dutta and others (1970), where a fixed-current electrode was substituted for one of the moving-current electrodes and a measurement made at every position in addition to the standard profile, could lead to the clearer delineation of anomalies. Use of uncommon arrays must be accompanied by a thorough understanding of the geometries of their electrical fields, so that the true subsurface position of anomalous bodies can be properly established. The methods employed in the survey of Line P-1 in the Sinking Creek Karst Basin study successfully obtained such data, and other arrays await testing in the Inner Bluegrass.

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