United States Department of Agriculture
Natural Resource Conservation Service **Chester, PA 19013**

Subject: Electromagnetic study of karst in Warren County, New Jersey; 24 - 25 April 1995

Date: 19 May 1995

To: Gail E. Updegraff
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Purpose:
To explore the potential of using electromagnetic induction (EM) techniques to conduct geophysical assessments in areas of karst.

Participants:
Jim Doolittle, Research Soil Scientist, NRCS, Chester, PA
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Shawn Finn, Assistant State Soil Scientist, Somerset, NJ

Activities:
On April 24 and 25, an EM survey was conducted in an area of karst within the Musconetcong Valley about one mile southeast of Washington in southeast Warren County.

MATERIALS AND METHODS

Equipment

The electromagnetic induction meters were the EM38 and EM31, manufactured by GEONICS Limited. The observation depth of an EM meter is dependent upon intercoil spacing, transmission frequency, and coil orientation relative to the ground surface. The EM38 meter has a fixed intercoil spacing of 1.0 m. It operates at a frequency of 13.2 kHz. The EM38 meter has effective observation depths of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively (McNeill, 1986). The EM31 meter has a fixed intercoil spacing of 3.66 m. It operates at a frequency of 9.8 kHz. The EM31 meter has effective observation depths of about 3 and 6 m in the horizontal and vertical dipole orientations, respectively (McNeill, 1979) Measurements of conductivity are expressed as milliSiemens per meter (mS/m).

Background

Electromagnetic induction (EM) methods provide a relatively inexpensive, fast, and comprehensive means for assessing the depths to bedrock within sites. This technique has been used to determine the depths to bedrock (Palacky and Stephens, 1990; Zalasiewicz et al., 1985) and to locate water-bearing fracture zones in bedrock (McNeill, 1991; Olayinka, 1990). These studies have documented that this noninvasive technique is facile, can provide a large number of observations for site characterization and assessments, and can be applied over broad areas and soils. Maps prepared from correctly interpreted EM data provide a basis for assessing site conditions and planning further investigations.

Electromagnetic induction techniques have been used in areas of karst (Canace and Dalton, 1984; Pazuniak, 1989; Robinson-Poteet, 1989; Rumbens, 1990). In these studies, the use of EM techniques permitted the interpretation of those portions of karstified bedrock not directly observed. These interpretations have enabled the delineation of discontinuities or anomalies in the carbonate bedrock. Anomalies include subsurface voids and channels; discontinuities include zones of higher permeability such as fractures and karstified zones. Often shapes and patterns appearing on computer simulations of the EM data have been used to identify discontinuities or subsurface anomalies.

The study site was established in a cultivated field on an upland area. The study site was located in an area of Washington loam, 3 to 8 percent slopes (Fletcher, 1979). Washington is a member of the fine-loamy, mixed, mesic Ultic Hapludalfs family. This very deep, well drained soil formed in till over limestone bedrock. The description of this map unit stresses that

> "In most places, this soil is underlain by limestone, which is cavernous in places. The location of these caverns is not predictable, but where they occur, the soil has limitations for onsite sewage disposal, building foundations, and roads."

While describing the potential hazard and possibly alarming prospective home or land owners, the map unit description provides little information as to where these features are or are most likely to occur. This study will attempt to predict the depths to limestone bedrock and, by subsurface shapes and patterns, make the location of potential solution features more predictable.

Field Methods

A 400 by 450 foot grid (4.13 acres) was established across the site. The grid interval was 50 feet. This interval provided 90 grid intersections or observation sites.

A transit and stadia rod were used to determine the relative elevation of the surface at each grid intersection. Elevations were not tied to an elevation benchmark; the lowest recorded grid intersection was recorded as the 0.0 foot datum. At each grid intersection, measurements were taken with an EM38 and an EM31 meter. Measurements were taken with each meter placed on the ground surface in both the horizontal and vertical dipole orientations.

At 17 grid intersections, depths to limestone bedrock were determined with hydraulic probes. The recorded depths to bedrock and EM data collected at these grid intersections were compared and used to develop regression equations to predict the depths to bedrock from values of apparent conductivity. To help summarize the results of this survey, the software program SURFER for Windows (Golden Software, Inc.) was used to construct two- and three-dimensional simulations. Data used to construct these simulations were kriged and the resulting matrices smoothed using cubic spline techniques.

EM Survey
Figures 1 is a two-dimensional contour plot of the study site. In Figure 1, all measurements are in feet. The contour interval is 1 foot. Within the site, relief was about 25 feet. The highest-lying area and steepest slopes were located in the southwest corner of the site. Several small areas of exposed limestone bedrock formed benches on intermediate slope positions. The lowest-lying area and most gentle slopes were located in north and northeast portions of the site. It was assumed that the depth to bedrock would be relatively shallow on the convex, upper sideslopes and benches, and deep on the concave, lower sideslopes.

Interpretations of the EM data are based on the identification of spatial patterns within the data set. Figures 2 and 3 are two-dimensional plots of the EM data collected with the EM38 meter in the horizontal and vertical dipole orientations, respectively. Figures 4 and 5 are two-dimensional plots of the EM data collected with the EM31 meter in the horizontal and vertical dipole orientations, respectively. In each plot, the interval is 2 mS/m.

Comparing Figures 2, 3, 4, and 5, values of apparent conductivity, as a rule, decrease with increasing observation depth (responses of the EM38 meter were greater than those of the EM31 meter, and, for each meter, responses in the horizontal dipole orientation were typically greater than those in vertical dipole orientation). The site was characterized as consisting of a relatively thin (0 to 25 foot) mantle of medium-textured till overlying more resistive limestone bedrock. The higher EM responses at shallow observation depths were attributed to the greater clay and moisture contents of the till. The lower EM responses with increased observation depths were attributed to the more resistive nature of the underlying limestone bedrock.

Figures 2, 3, 4, and 5 provide numerical values which represent subsurface features and properties within the mass of earthen material profiled with each meter and coil orientation. With knowledge of the influencing soil, hydrologic, and geologic site conditions, these values can be correctly interpreted and used to assess the depth to bedrock.

Table 1
Karst Study Site in Warren County, New Jersey
(all values are in mS/m)

				Quartiles			
Meter	Orientation	Minimum	Maximum	1st	Median	3rd	Average
EM38	Horizontal	2.5	9.0	4.0	4.5	5.5	4.7
EM38	Vertical	0.5	7.0	2.5	3.0	4.0	3.4
EM31	Horizontal	2.0	11.5	5.0	6.0	8.0	6.4
EM31	Vertical	1.0	11.5	3.5	4.5	6.5	5.2

Basic statistics for the EM data collected at the Washington site are displayed in Table 1. Variations in each meters response can be related to differences in soil depth. Areas of low conductivity were assumed to have shallower depths to bedrock than areas having high conductivity. EM responses became more variable with increasing observation depth. This relationship was believed to represent variations in the thickness, moisture, and clay contents of the till and the variable depths to bedrock.

Depth to Bedrock

Variations in the depth response of the EM meters conformed with the basic conceptual model of the site. For the purpose of this investigation, the site was assumed to consist of two principal layers: till and bedrock. The medium-textured till has a higher clay content and was presumed to have higher apparent conductivity values than the underlying limestone bedrock.

Thickness of till varied across the site because of erosion, deposition, and landscape position. Because of differences in clay and moisture contents between the till and the underlying bedrock, vertical contrasts in electrical conductivity were assumed to exist. It was assumed that variations in the magnitude of the EM response could provide estimates of the thickness of the till or the depth to bedrock.

At the seventeen, probed observation points, the depth to bedrock averaged 86.8 inches and ranged from 29 to 140 inches. A comparison of soil probe and EM data collected at the seventeen observation points revealed positive relationships between the observed depths to bedrock and the EM data (see Table 2).

Table 2

Relationship Among EM Measurements and Depth to Limestone Bedrock
(17 observations)

Meter and Orientation	r^2
EM38 Meter (Horizontal Dipole Orientation)	0.547005
EM38 Meter (Vertical Dipole Orientation)	0.737720
EM31 Meter (Horizontal Dipole Orientation)	0.645797
EM31 Meter (Vertical Dipole Orientation)	0.650131

Generally, the use of EM techniques has been most successful in areas where subsurface properties are reasonably homogeneous, the effects of one property (e.g. clay, water, or salt content) dominates over the other properties, and variations in EM response can be related to changes in the dominant property (Cook et al., 1992). Within the study site, measurements taken with the EM meters were comparatively low and varied from 0.5 to 11.5 mS/m (see Table 1). While the site was fairly homogeneous in terms of subsurface properties, the relatively low apparent conductivity of the till and its similarity with the underlying bedrock, reduced the influence of the depth to till (clay content and thickness) on EM responses. Consequently, variations in EM response were less strongly related to changes in till thickness or depth to bedrock.

Data collected with the EM38 meter in the vertical dipole orientations had the highest correlation with the depth to bedrock ($r^2 = 0.737720$) and were used to develop a predictive regression equation:

$$D = -19.68877 + (34.50842 * EM38V) \qquad [1]$$

where "D" is depth to bedrock (inches) and "EM38V" is the apparent conductivity (mS/m) measured with the EM38 meter in the vertical dipole orientation. Within the study site, measured depths to bedrock exceeded the observation depth of the EM38 meter. When only those observation points having measured depths to bedrock within the observational range of the EM38 meter in the vertical dipole orientation (0 to 1.5 m) were compared, the coefficient of determination (r^2) improved slightly to 0.764079. The lack of a more robust relationship was attributed to variations in other soil properties (i.e. texture, thickness, and depth to argillic horizon, coarse fragments, and moisture content), and the irregular surface and karstified nature of the underlying carbonate rock. In addition, measurement error was introduced into the data set as measurements were averaged and rounded-off, and differences in the area profiled with the meter versus the point or column of soil observed with the hydraulic probe. Acknowledging these deficiencies, Equation [1] was used to estimate the depth to bedrock at each grid intersection.

Based on 90, EM38 measurements and the predictive equation [1], the average depth to bedrock was estimated to be 116 inches with a range of 18 to 262 inches. One-half of the observations had depths to bedrock between 99 and 116 inches. Bedrock was shallow (<20 in) at 1 percent, moderately deep (20 to 40 in) at 1 percent, deep (40 to 60 in) at 10 percent, and very deep (>60 in) at 88 percent of the observation points.

Figure 6 is a two-dimensional plot showing the distribution of depths to bedrock. In this figure, all measurements are in feet. In Figure 6, spatial patterns indicate that the depths to bedrock are variable over relatively short distances. Areas shallow to bedrock form pinnacles or occur as sinuous bands, and are more common on higher-lying, more sloping areas. Areas deep to bedrock appear as circular depressions or linear troughs, and are more common on lower-lying, less sloping areas.

Figure 7 is a three-dimensional surface net diagram of the study site showing the distribution of depths to the bedrock in relation to the soil surface. Areas having greater thicknesses of till occur principally on lower-lying plane and concave slope positions, but also occur in small interconnected areas between bedrock benches. The shallowest depths to bedrock occur on higher-lying convex sideslopes.

RESULTS

1. Results from field work in Warren County indicate that EM techniques can be used to estimate the depths to limestone bedrock. Values of apparent conductivity can be used to develop regression equations to predict the depth to bedrock. Systematic observations with EM techniques can be used to help delineate areas underlain by solution features and more prone to differential subsidence. As the depth to the

bedrock influences water movement through this landscape, the techniques used in this study can also be used to create a conceptual model of how and where water moves through the landscape.

2. Interpretations made from EM data should be verified by a limited number of auger observations.

It has been my pleasure to assist in this project.

With kind regards

Jim Doolittle

James A. Doolittle
Research Soil Scientist

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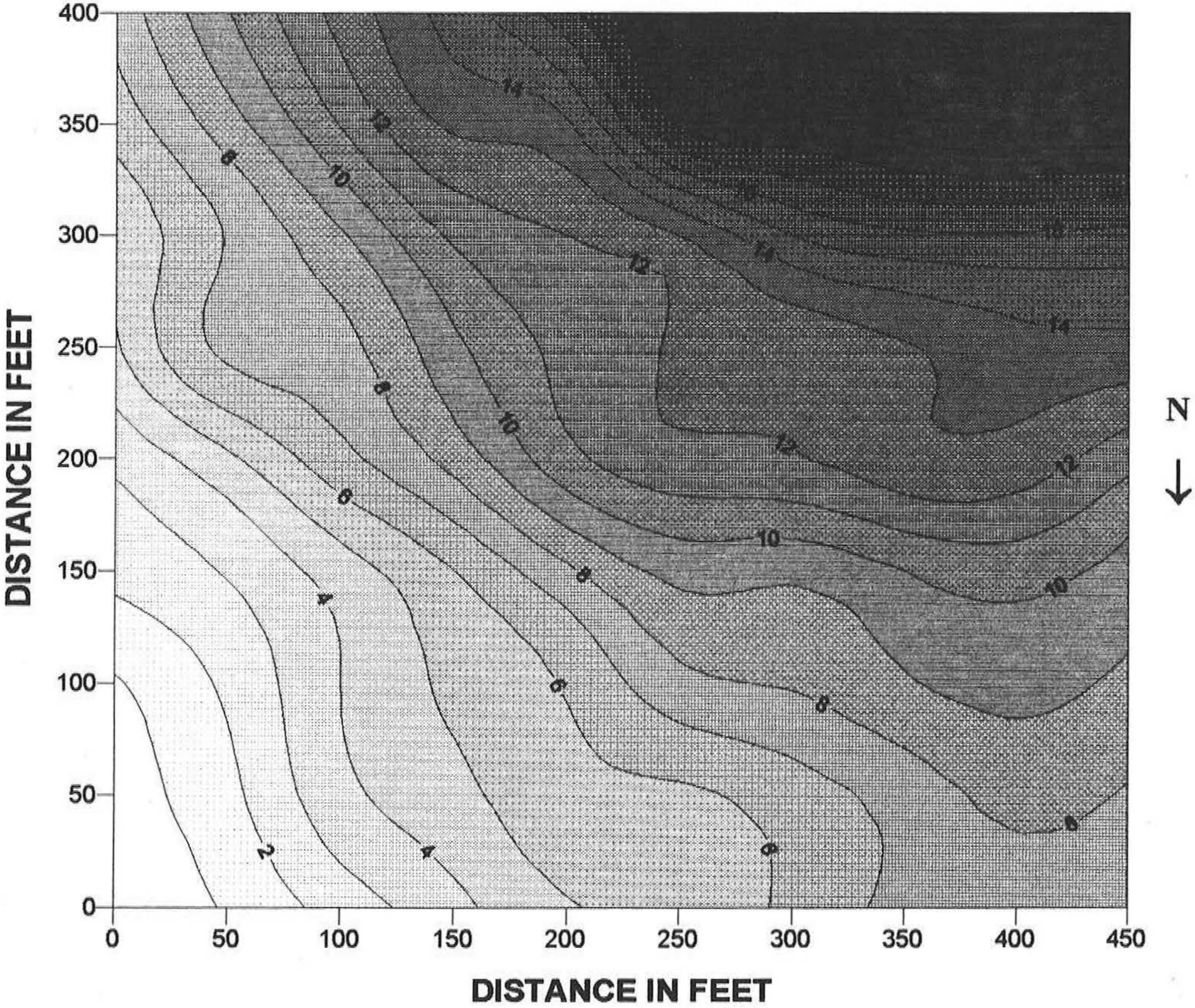
KARST STUDY SITE
WARREN COUNTY, NEW JERSEY

RELATIVE TOPOGRAPHY



KARST STUDY SITE
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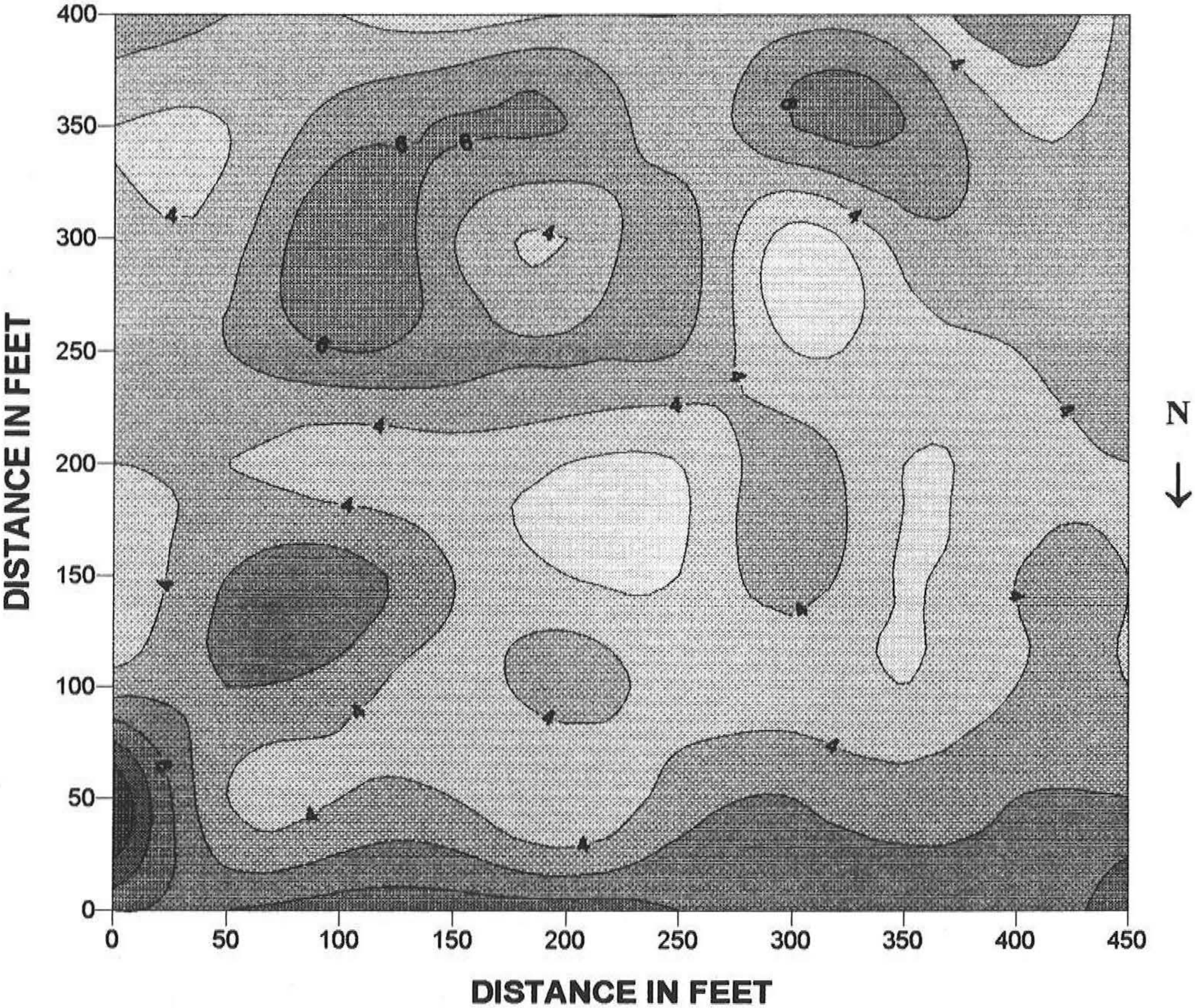
EM38 METER
HORIZONTAL DIPOLE ORIENTATION



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EM38 METER
VERTICAL DIPOLE ORIENTATION

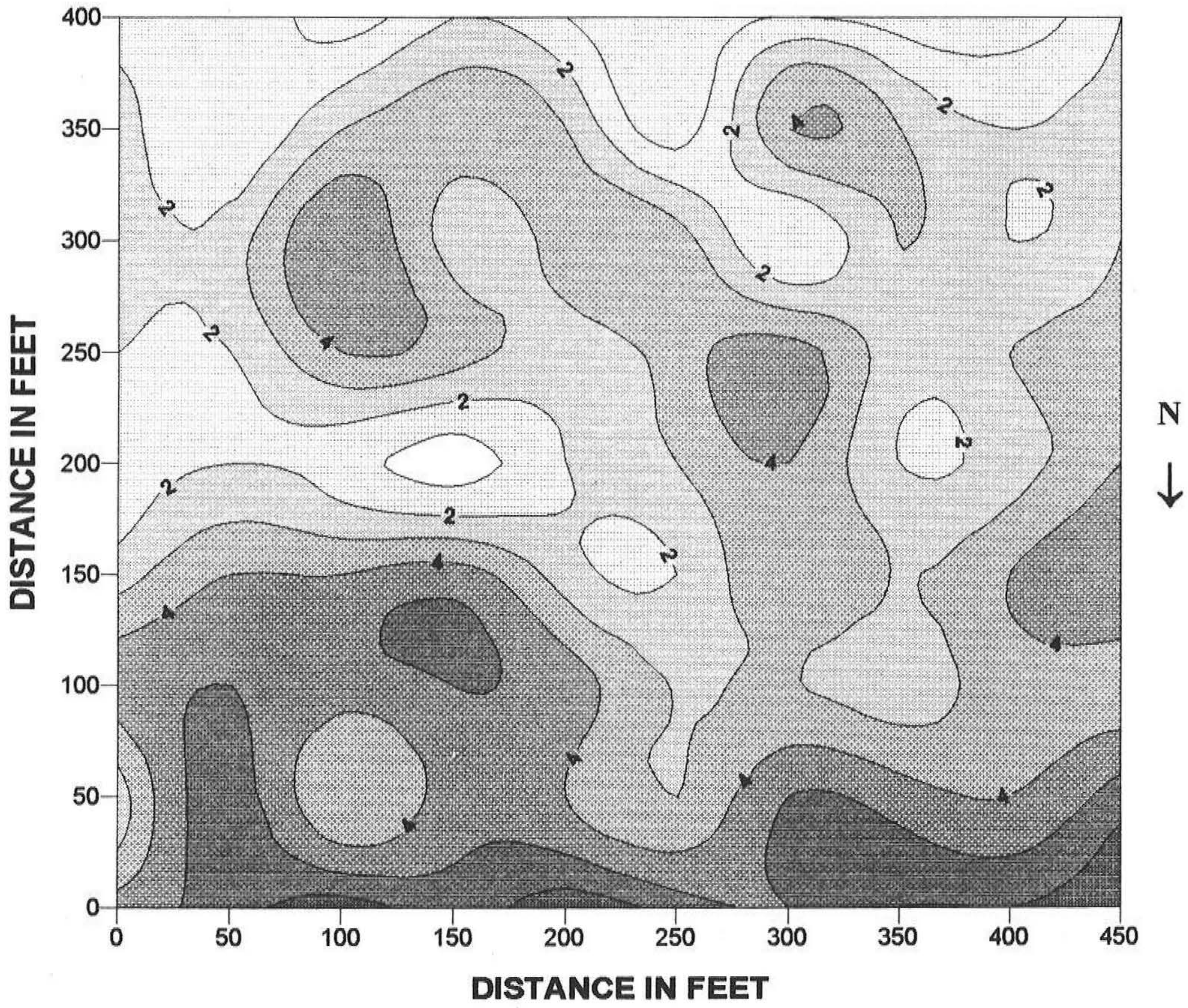

Figure 4

KARST STUDY SITE
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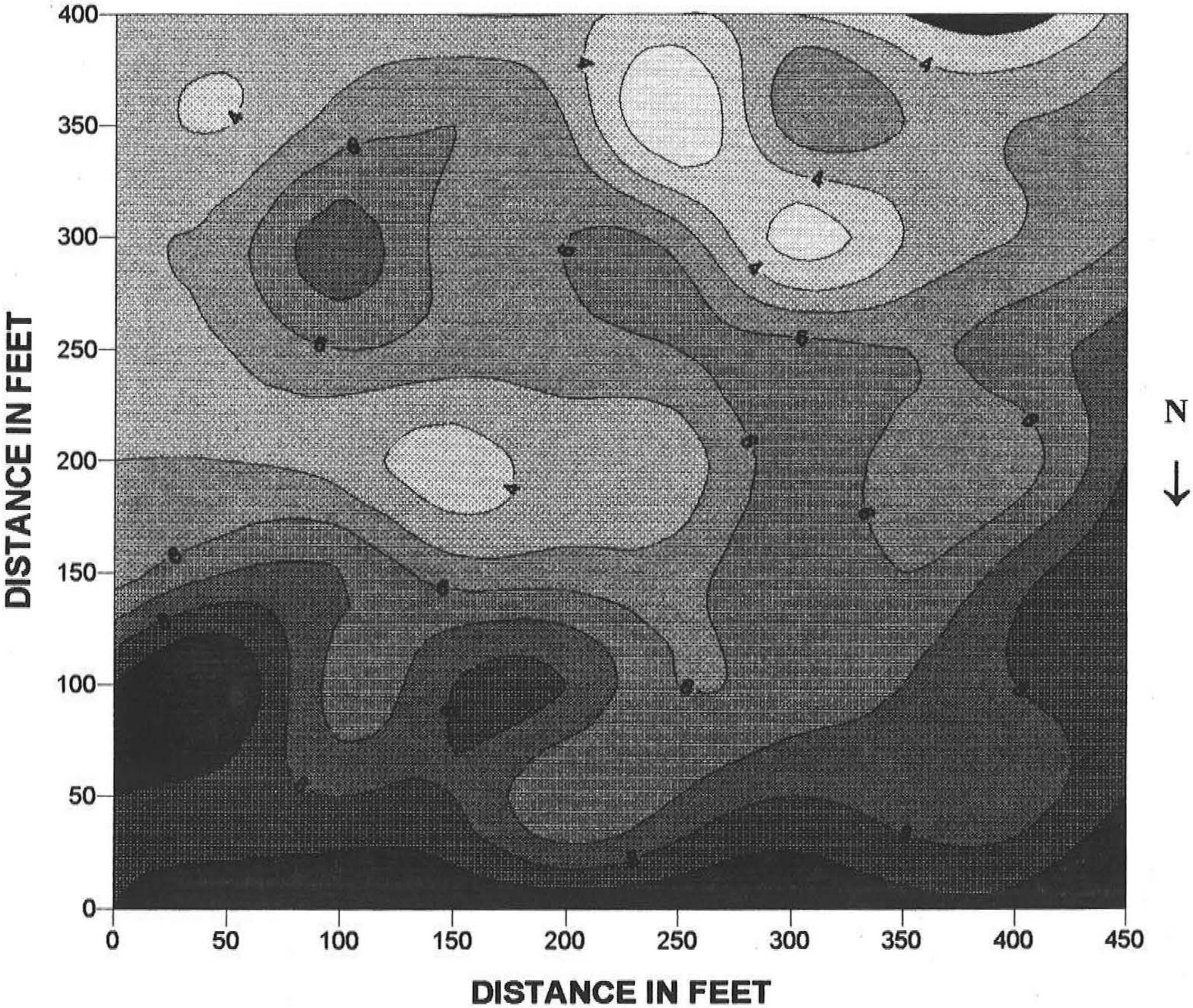
EM31 METER
HORIZONTAL DIPOLE ORIENTATION



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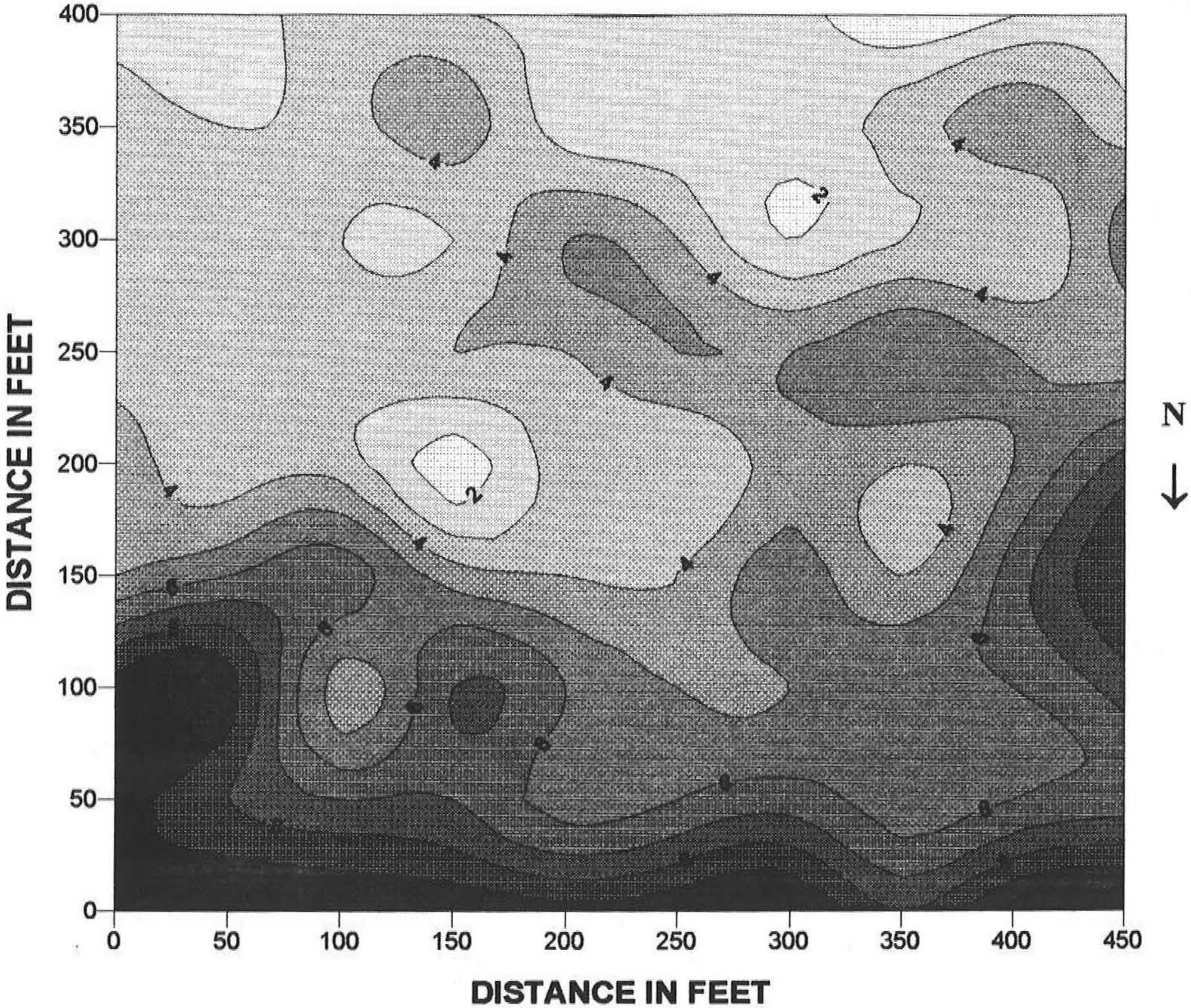
EM31 METER
VERTICAL DIPOLE ORIENTATION



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DEPTH TO BEDROCK

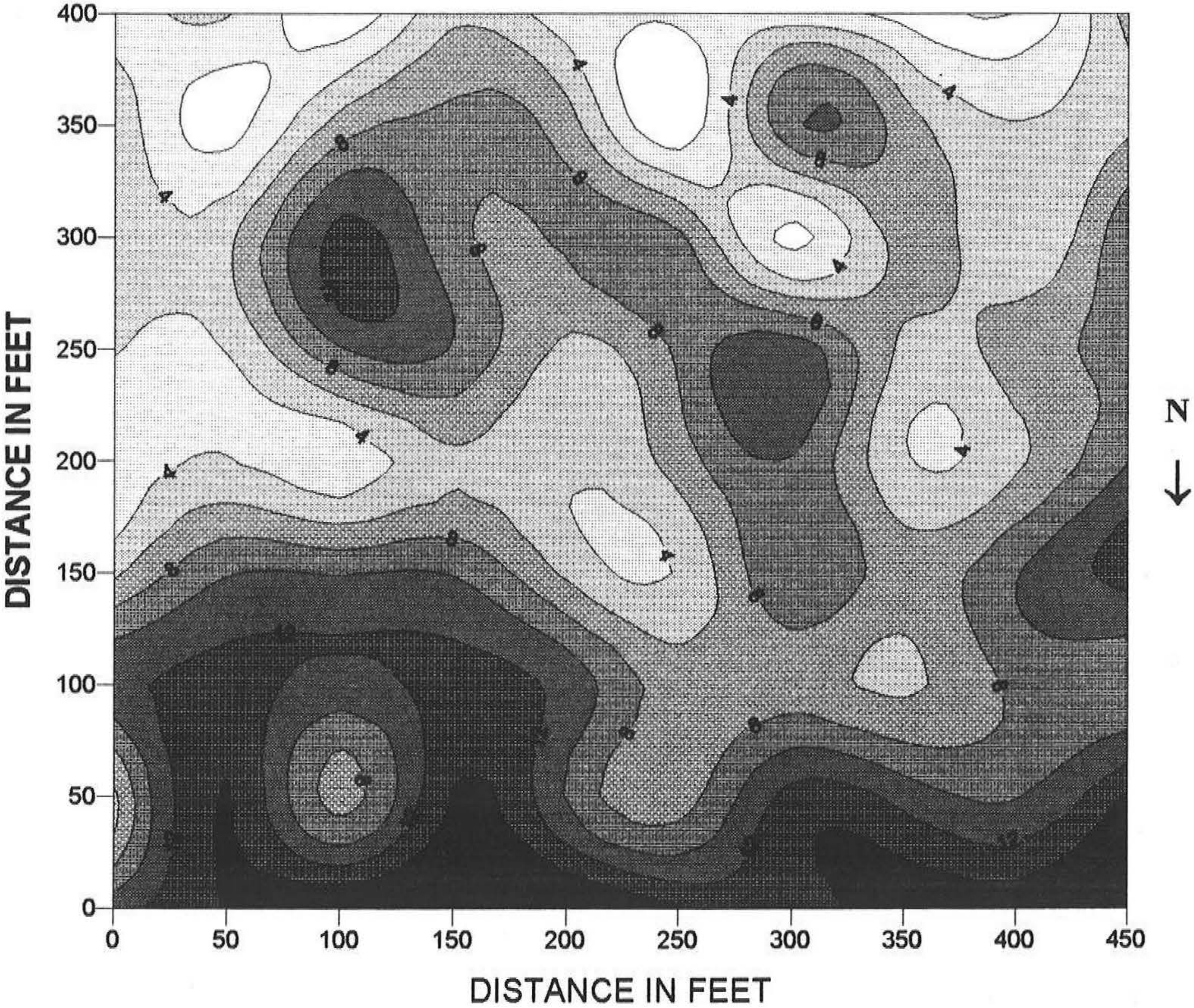

Figure 7

KARST STUDY SITE
WARREN COUNTY, NEW JERSEY

DEPTH TO BEDROCK