United States Department of Agriculture	Natural Resources Conservation Service	5 Radnor Corporate Center, Suite 200 Radnor, PA 19087-4585

Subject: Geophysical Assistance

Date: 7 December 1998

To: Patrick K. Wolf
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Purpose:
To provide electromagnetic induction (EMI) and ground-penetrating radar (GPR) field assistance to the Silurian Reef Study in Erie and Wood Counties, Ohio.

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Activities:
All field activities were completed during the period of 16 to 20 November 1998.

Equipment:
The radar unit used was the Subsurface Interface Radar (SIR) System-2, manufactured by Geophysical Survey Systems, Inc.* The SIR System-2 consists of a digital control unit (DC-2) with keypad, VGA video screen, and connector panel. The 200 and 400 mHz antennas were used in this investigation. A 12-VDC battery powered the system. Morey (1974), Doolittle (1987), and Daniels and others (1988) have discussed the use and operation of GPR. Radar profiles included in this report have been processed through the WINRAD software package.* Processing was limited to signal stacking, horizontal scaling, color transforms and table customizing, and terrain correction. Color transformation and table customization were used to reduce signal amplitudes and background noise.

The electromagnetic induction meters used in this study were the EM38 and EM31, manufactured by Geonics Limited*. These meters are portable and require only one person to operate. McNeill (1986) has described principles of operation. No ground contact is required with these meters. These meters provide limited vertical resolution and depth information. Lateral resolution is approximately equal to the intercoil spacing. The EM38 meter operates at a frequency of 14,600 Hz and

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has theoretical observation depths of about 0.75 and 1.5 meters in the horizontal and vertical dipole orientations, respectively (McNeill, 1986). The EM31 meter operates at a frequency of 9,800 Hz and has theoretical observation depths of about 3 and 6 m in the horizontal and vertical dipole orientations, respectively (McNeill, 1980a). Values of apparent conductivity are expressed in milliSiemens per meter (mS/m).

To help summarize the results of this study, the SURFER for Windows program, developed by Golden Software, Inc.*, was used to construct two-dimensional simulations. Grids were created using kriging methods with an octant search. All grids were smoothed using a cubic spline interpolation.

Field Procedures:

Site selection was based upon soil and bedrock units. At sites selected in Wood and Erie counties, traverses lines were established to evaluate the performance of GPR and EMI. Survey flags were inserted in the ground at an interval of about 15 feet along each traverse line. The survey flags served as observation points. Although, GPR provides a continuous profile of subsurface conditions, interpretations were restricted to the flagged observation points. At each observation point, the radar operator impressed a dashed, vertical line on the radar profile. This line identified an observation point on the radar record. Radar records were reviewed in the field. Measurements were taken at many observation points with an EM38 meter and an EM31 meter in both the horizontal and vertical dipole orientations.

Background:

Silurian carbonate bedrock underlies the eastern portion of the Erie-Huron lake plain (MLRA 99). Principal formations include the Guelph, Greenfield, and Tymochtee dolomites of the Bass Island Group. In some portions of the Erie-Huron lake plain, these formations are exposed or covered by a thin mantle of glacial drift. At the time of Wisconsin glaciation, these areas were covered by glacial lakes and formed "reefs" during periods of high water levels and island during periods of low water levels. Because of extensive preglacial weathering, the upper surface of bedrock is irregular and is covered by a mantle of fragmental materials. The Romeo and Castalia soils were associated with these bedrock highs or reefs (Rapparlie and Urban, 1966; Redmond et al., 1971). The very shallow, poorly drained Romeo soil was mapped as a Lithosol, but is now a member of the loamy, mixed, superactive, mesic Lithic Endoaquolls family. The Castalia soil was mapped as a very deep, Typic Rendolls. During recent modernization of soil surveys these soils have been recorrelated as Marblehead and Castalia. The very shallow, somewhat excessively drained Marblehead soil is a member of the loamy, mixed, superactive, mesic Lithic Hapludolls family. The moderately deep, well drained Castalia soil is a member of the loamy-skeletal, carbonatic, mesic Eutrochreptic Rendolls family. The skeletal nature of these soils makes the determination of bedrock depths exceedingly difficult and time-consuming. The purpose of this study was to evaluate the potentials of ground-penetrating radar and electromagnetic induction for estimating the depths to bedrock and the taxonomic composition of soil map units.

Results:

1. Geophysical interpretations are considered preliminary estimates of site conditions. The results of geophysical site investigations do not substitute for direct observations, but rather reduce their number, direct their placement, and supplement their interpretations. Interpretations contained in this report should be verified by ground-truth observations.

2. Ground-penetrating radar can be used successfully to document the depth to bedrock in areas of Silurian reef. The 400 mHz antenna provided the best balance of observation depth and resolution. In areas of moderately deep to very deep soils, GPR provide satisfactory observation depths, high resolution of subsurface features, and interpretable imagery of the bedrock surface. However, in areas mapped as Romeo or Marblehead soils, without processing, GPR was unable to clearly distinguish the bedrock surface and separate very shallow from shallow soils. Processing the radar profiles through WINRAD software improved the definition of the soil/bedrock interface. Computer processing of radar imagery is relatively expensive, time consuming, and not justified for all radar surveys. Except for high profile or risk surveys, or research projects, the use of processing is discouraged.

3. The Silurian reef complex provides an unfavorable environment for EMI. At all sites, apparent conductivity was low and invariable. The range in recorded measurements was commonly less than the recognized range in observation errors (2 to 4 mS/m). Because of the high concentration of rock fragments, contrasts in electrical properties between the soil and the underlying bedrock were insignificant and immeasurable. Neither the EM38 nor the EM31 meter was able to detect differences in electromagnetic properties between the soil and bedrock. In addition, the large amounts of coarse fragments

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made ground-truth observations needed to correlate EMI measurements exceedingly difficult and time-consuming to obtain. As a consequence, the use of EMI was considered inappropriate and unreliable in areas of Marblehead and Castalia soils.

It was my pleasure to work in Ohio and with members of your fine staff.

With kind regards,

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cc:

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RESULTS:

Ground-penetrating radar:

Ground-penetrating radar can be used successfully to document the depth to bedrock in areas of Silurian reef. The 400 mHz antenna provides the best balance of observation depth and resolution. This antenna also provides the most easily interpretable profile of the bedrock surface.

In areas of moderately deep to very deep soils, GPR provide satisfactory observation depths, high resolution of subsurface features, and interpretable imagery of the bedrock surface. Because of the large number of coarse fragments in the soil and the irregular and highly fractured bedrock surface, the dielectric gradient across soil/bedrock interface is slight. As a result, reflections from this interface have low amplitudes and are weakly expressed on radar profiles.

In areas mapped as Romeo or Marblehead soils, without processing, GPR was unable to clearly distinguish the bedrock surface and separate very shallow from shallow soils. In these soils, even with the 400 mHz antenna, the ground and bedrock surfaces were closer than one wavelength. The close proximity of these two interfaces caused the resulting reflections to be partially superimposed. This interference masked the bedrock surface. Processing the radar profiles through WINRAD software improved the definition of the soil/bedrock interface. Computer processing of radar imagery is relatively expensive, time consuming, and not justified for all radar surveys. Except for high profile, risk, or research projects, the use of processing is discouraged. However, in some studies, computer processing of radar imagery has enhanced the resolution of subsurface features and reduced interpretation errors and biases.

Calibration:

Ground-penetrating radar is a time scaled system. This system measures the time that it takes electromagnetic energy to travel from an antenna to an interface (e.g., soil horizon, stratigraphic layer, bedrock surface) and back. To convert the travel time into a depth scale, either the velocity of pulse propagation or the depth to a reflector must be known. The relationships among depth (d), two-way, pulse travel time (t), and velocity of propagation (v) is described in the following equation (Morey, 1974):

$$v = 2d/t$$

The velocity of propagation is principally affected by the dielectric permittivity (e) of the profiled material(s) according to the equation:

$$e = (c/v)^2$$

Where c is the velocity of propagation in a vacuum (0.3 m/nanosecond). A nanosecond (ns) is one billionth of a second. The amount and physical state (temperature dependent) of water have the greatest effect on dielectric permittivity.

Velocities of propagation and depth scales were calculated at each site. A metallic reflector was buried at depths of about 20 inches. The depth to this reflector was used to determine the dielectric permittivity and velocity of propagation. Based on the round-trip travel time to the buried reflector, the averaged velocity of propagation through the upper part of the soil profile was determined and used to depth scale the radar record. Table 1 lists the calculated velocities of propagation and the dielectric permittivity at different sites. With the exception of the Castalia site, the velocity of propagation and the dielectric permittivity of these map units are remarkably similar. The similarity is related to comparable soil texture and water contents.

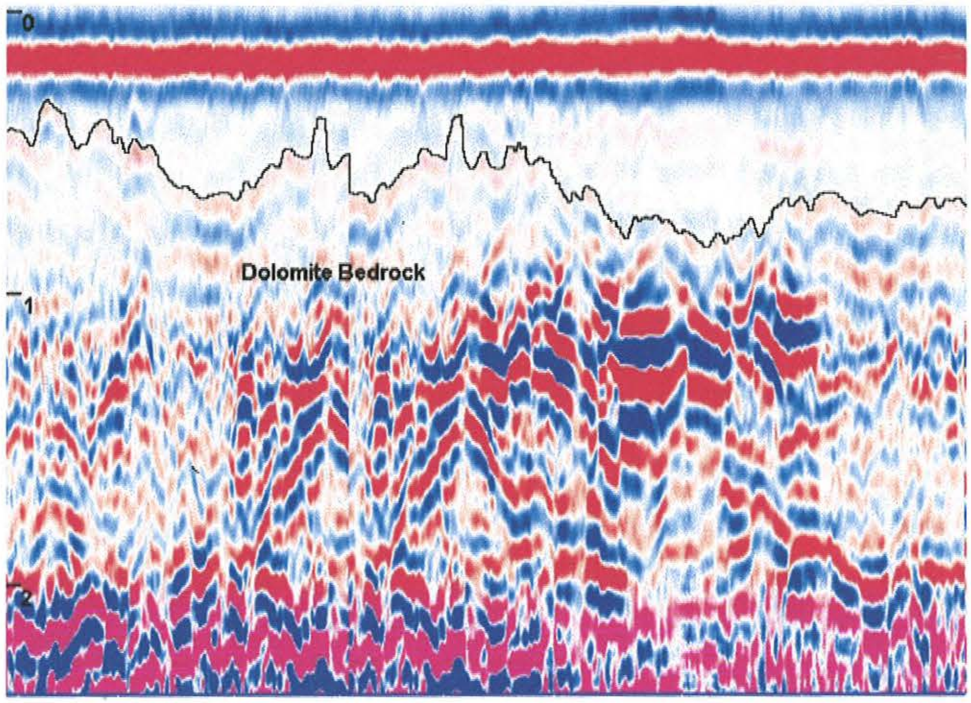
Table 1

Results of Calibration Trials

Map Unit	Velocity	Dielectric Permittivity	County
Dunbridge stony loam, 0-2 percent slopes	0.1296 m/ns	5.36	Wood
Dunbridge stony loam, 0-2 percent slopes	0.1288 m/ns	5.42	Wood
Marblehead	0.1222 m/ns	6.03	Erie
Castalia	0.1524 m/ns	3.87	Erie

For the purpose of this investigation, large differences in the velocity of propagation were not assumed to exist along traverse lines. While the actual measurements are considered close approximations, the grouping of observation points into relative soil depth classes (shallow, moderately deep, deep, and very deep) is more accurate and is preferred.

Details:
Site #1 was located near Lucy in an area Castalia-Marblehead complex. Figure 1 is a representative radar profile from Site #1. This profile was obtained with the 400 mHz antenna. In Figure 1, the depth (vertical) scale is in meters. Compared with the horizontal scale (distance), the vertical scale is exaggerated. The series of blue and red parallel lines at the top of the radar profile represents the soil surface. Because of the large number of coarse fragments in Castalia and Marblehead soils, the dielectric permittivity across the soil/bedrock interface are closely similar. The similarity in relative dielectric permittivity between the two materials results in low reflection coefficients and low amplitude reflected signals. As a consequence, the bedrock surface appears faint, but is traceable across the profile. In Figure 1, the bedrock surface has been highlighted with a dark line. Stronger reflections are apparent within the bedrock. These reflections are parallel with the surface and are presumed to represent contrasting layers within the bedrock.



At Site #1, traverse line 1 was conducted in an area that had been mapped as Dunbridge stony loam, 0 to 2 percent slopes. Traverse lines 2 ,3 and 4 were conducted in an area that had been mapped as Romeo soils. In the area that had been mapped as Dunbridge stony loam, 0 to 2 percent slopes, bedrock was moderately deep (20 to 40 inches) at 92 percent, and deep (40 to 60 inches) at 8 percent of the observation points. In the area that had been mapped as Romeo soils, bedrock was shallow (0 to 20 inches) at 47 percent and moderately deep at 53 percent of the observation points. The following tables list the interpreted depths to bedrock (in inches) along these traverse lines. Observation numbers represent distance in feet along the traverse line.

Traverse #1

Observation	Depth
0	33
15	32
45	29
60	38
75	34
90	32
105	37
120	32
135	41
150	38
165	38
180	35

Traverse #2

Observation	Depth
0	12
15	14
45	16
60	16
75	10
90	21
105	28
120	31
135	39
150	33
165	31
180	32

Traverse #3

Observation	Depth
0	15
15	17
45	13
60	23
75	15
90	19
105	18
120	26

Traverse #4

Observation	Depth
0	12
15	14
45	21
60	20
75	17
90	21
105	27
120	16
135	28
150	30
165	27
180	27

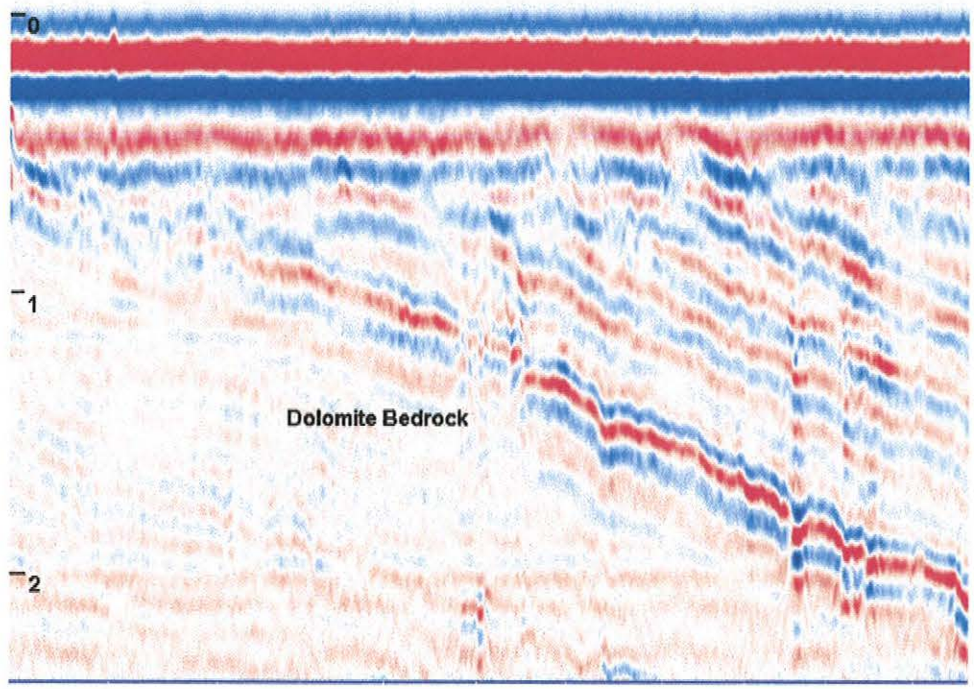
Pemberville Traverse Line

Observation	Depth
0	52
15	48
45	53
60	36
75	29
90	29
105	54
120	74
135	79
150	55
165	52
180	46

Site #2 was located near the town of Pemberville in an area Castalia-Marblehead complex. This area was formerly mapped as Dunbridge stony loam, 0 to 2 percent slopes. Several pits had been excavated at this site. These pits confirmed that the bedrock surface was highly irregular and variable in depth. Ground-penetrating radar provided a continuous record of the bedrock surface. Both the 200 and 400 mHz antennas provided satisfactory observation depths and resolution of the soil/bedrock interface. Once again, because of the large number of coarse fragments in the soil, the dielectric permittivity across the soil/bedrock interface was closely similar. This similarity in relative dielectric permittivity between the two materials resulted in low reflection coefficients and low amplitude reflected signals. As a consequence, the bedrock surface was faint, but traceable across the radar profiles. Along the traverse line, GPR revealed that bedrock was moderately deep at 25 percent, deep at 58 percent, and very deep (> 60 inches) at 17 percent of the observation points. The following table lists the interpreted depths to bedrock (in inches) along this traverse line. Observation numbers represent distance in feet along the traverse line.

Site #3 was located in Erie County in an area of Marblehead loam 0 to 6 percent slopes. The site was located near the town of Castalia and is the type location for Marblehead soils. A survey grid with 63 observation points was established at this site. The grid interval was 25 feet. The radar profiles from this site were processed using the WINRAD software. Based on 63 observations, GPR revealed that bedrock was very shallow (0 to 10 inches) at 14 percent, shallow at 82 percent, and moderately deep at 2 percent of the observation points. The average depth to bedrock was 14.3 inches with a standard deviation of 3.4 inches. Bedrock was exposed at 2 percent of the observation points.

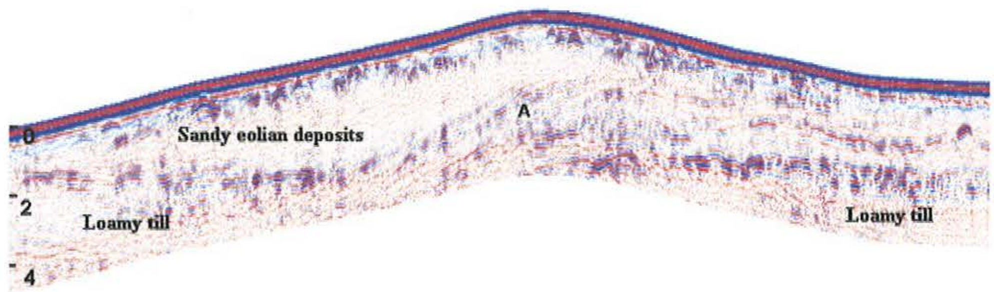
Site #4 was located in areas of Castalia very channery silt loam , 0 to 2 percent slopes, and Castalia very channery silt loam, 2 to 6 percent slopes. The site was located near the town of Castalia in Erie County. Figure 2 is a representative radar profile from Site #4. This profile was obtained with the 400 mHz antenna. In Figure 2, the depth scale is in meters. Compared with the horizontal scale (distance), the vertical scale (depth) is exaggerated. The series of blue and red parallel lines at the top of the radar profile represents the soil surface. The first major subsurface reflection (next sequence of red and blue lines) represents the bedrock surface. The depth to this interface is remarkably uniform across this profile. The inclined, parallel subsurface reflections represent contrasting layers within the bedrock. These reflections intercept but do not cross the soil/bedrock interface.



Site #5 was located near the town of Wingston in Wood County. The site was located in areas of Spinks loamy fine sand, 12 to 18 percent slopes, and Rimer and Tedrow loamy fine sands over clay, 0 to 2 percent slopes. Spinks soil is a member of the sandy, mixed, mesic Lamellic Hapludalfs family. Rimer soil is a member of the loamy, mixed, active, mesic Aquic Arenic Hapludalfs family. Tedrow soil is a member of the mixed, mesic Aquic Udipsamments family. The traverse crossed a low dune.

Figure 3 is a processed portion of the radar profile from this traverse. The radar profile was obtained with the 400 mHz antenna. This profile has been *terrain corrected.* Terrain correction is a process whereby the surface of the radar profile is adjusted to conform to the ground topography. In this example, no ground elevations were obtained. To produce this topography, it was assumed that the depth to the loamy till was constant.

In Figure 3, the depth scale is in meters. Compared with the horizontal scale (distance), the vertical scale (depth) is exaggerated. In Figure 3, the soil surface is represented by the series of dark, closely spaced, blue and red parallel lines that extend across the upper part of the profile. Numerous point reflectors are apparent below the surface reflections. Point reflectors are presumed to represent roots and buried cultural features. More deeply buried subsurface reflectors apparent in this figure include stratification or lamellae within the eolian deposits (A), and a lower-lying, highly contrasting layer of loamy till.



Electromagnetic Induction

Electromagnetic induction (EMI) is a noninvasive geophysical tool that can be used for detailed site investigations. Advantages of EMI are its portability, speed of operation, flexible observation depths (with commercially available systems from about 0.75 to 60 m), moderate resolution of subsurface features, and comprehensive coverage. Results of EMI surveys are interpretable in the field. This geophysical method can provide in a relatively short time the large number of observations that are needed to comprehensively cover sites. Maps prepared from correctly interpreted EMI data provide the basis for assessing site conditions, planning further investigations, and siting monitoring wells.

Electromagnetic induction uses electromagnetic energy to measure the apparent conductivity of earthen materials. Apparent conductivity is a weighted, average conductivity measurement for a column of earthen materials to a specific observation depth (Greenhouse and Slaine, 1983). Variations in apparent conductivity are produced by changes in the electrical conductivity of earthen materials. The electrical conductivity of soils is influenced by the type and concentration of ions in solution, the amount and type of clays in the soil matrix, the volumetric water content, and the temperature and phase of the soil water (McNeill, 1980b). The apparent conductivity of soils increases with increases in soluble salts, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976).

Electromagnetic induction measures variations in apparent electrical conductivity. Interpretations of the EMI data are based on the identification of spatial patterns within data sets. Though seldom diagnostic in themselves, lateral and vertical variations in apparent conductivity have been used to infer changes in soils and soil properties. Electromagnetic induction integrates the bulk physical and chemical properties within a defined observation depth into a single value. As a consequence, measurements can be associated with changes in soils and soil map units (Hoekstra et al., 1992; Jaynes et al., 1993, Doolittle et al.. 1996). For each soil, inherent physical and chemical properties, as well as temporal variations in soil water and temperature, establish a unique and characteristic range of apparent conductivity values.

Electromagnetic induction is not suitable for use in all soil investigations. Generally, the use of EMI has been most successful in areas where subsurface properties are reasonably homogeneous. This technique has been most effective in areas where the effects of one property (e.g., clay, water, or salt content) dominate over the other properties. In these areas, variations in apparent conductivity can be directly related to changes in the dominant property (Cook et al., 1989).

The Silurian reef complex provided an unfavorable environment for the use of EMI. Depth to bedrock is the principal difference between the Marblehead and Castalia soils. An EMI meter must be sensitive to the differences existing between soil horizons or layers. In other words, to be effective, a meter must be able to detect differences in electromagnetic properties between the layers. Because of the high concentration of rock fragments in the solum, the contrast in electrical properties between the soil and the underlying bedrock was insignificant and immeasurable.

The soil, having greater clay and moisture contents than the underlying dolomite, should be more conductive. Before the EM survey, it was theorized that shallow soils would have lower values of apparent conductivity than moderately deep or deep soils. Deep soils were expected to have higher values of apparent conductivity than moderately deep soils. However, these relationships were obscured by the large amounts of rock fragments (50 to 90 percent) in the soils..

Electromagnetic induction methods were used at Site #1and at Site #3. Site #1 was located in an area of Castalia-Marblehead complex. Site #3 was located in an area of Marblehead loam , 0 to 6 percent slopes. At both sites, apparent conductivity was low and invariable. The range in recorded measurements was commonly less than the recognized range in observation errors (2 to 4 mS/m). The large amounts of coarse fragments contained in these soils obscured differences existing between soil and bedrock. Neither the EM38 nor the EM31 meter was able to detect differences in electromagnetic properties between the soil and bedrock. In addition, the large amounts of coarse fragments made ground-truth observations needed to correlate EMI measurements exceedingly difficult and time-consuming to obtain. As a consequence, the use of EMI was considered inappropriate and unreliable in areas of Marblehead and Castalia.

At Site #1, the highest averaged values of apparent conductivity were obtain with the EM38 meter in the shallower-sensing horizontal dipole orientation. This relationship reflects the increased weighting of the soil materials at shallow depths. At Site #1 measurements (11 observations) taken with the EM38 meter in the horizontal dipole orientation (0 to 0.75 m) averaged 2.58 mS/m with a standard deviation of 0.5219. One half of the observations had values of apparent conductivity between 1.9 and 2.8 mS/m. Measurements taken with the EM38 meter in the vertical dipole orientation (0 to 1.5 m) averaged 1.61 mS/m with a standard deviation of 0.4621. One half of the observations had values of apparent conductivity between 0.9 and 2.2 mS/m.

Measurements of apparent conductivity obtained with the deeper-sensing EM31 meter were generally slightly lower than those obtained with EM38 meter. This relationship reflects the increased influence of the dolomite bedrock in measurements obtained with the deeper-sensing EM31 meter. Measurements taken with the EM31 meter in the horizontal dipole orientation (0 to 3 m) averaged 1.92 mS/m with a standard deviation of 0.5606. One half of the observations had values of apparent conductivity between 0.2 and 2.4 mS/m. Measurements taken with the EM31 meter in the vertical dipole orientation (0 to 6.0 m) averaged 1.93 mS/m with a standard deviation of 0.4957. One half of the observations had values of apparent conductivity between 1.4 and 3.4 mS/m.

At Site #3, measurements were obtained with the EM38 meter in the horizontal dipole orientation only. Measurements (54 observations) averaged 2.1mS/m with a range of 1.0 to 6.1 mS/m and a standard deviation of 0.8024. One half of the observations had values of apparent conductivity between 1.66 and 2.22 mS/m.

At Site #3, measurements were obtained with the EM31 meter held at hip-height (1 meter above the ground surface). Measurements taken with the EM31 meter in the horizontal dipole orientation (0 to 2 m) averaged 2.3 mS/m with a standard deviation of 0.2238. One half of the observations had values of apparent conductivity between 2.2 and 2.4 mS/m. Measurements taken with the EM31 meter in the vertical dipole orientation (0 to 5.0 m) averaged 2.6 mS/m with a standard deviation of 0.1560. One half of the observations had values of apparent conductivity between 2.6 and 2.8 mS/m.

A 200 by 150 foot grid was established across Site #3. Within this site, values of apparent conductivity measured with the EM38 and EM31 meters are too low and invariable to reliably plot. However, to demonstrate the use of computer-graphic techniques, the EMI data have been plotted in Figures 4 and 5.

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EMI SURVEY
AREA OF MARBLEHEAD LOAM, 0 TO 9 PERCENT SLOPES
ERIE COUNTY, OHIO
EM38 METER

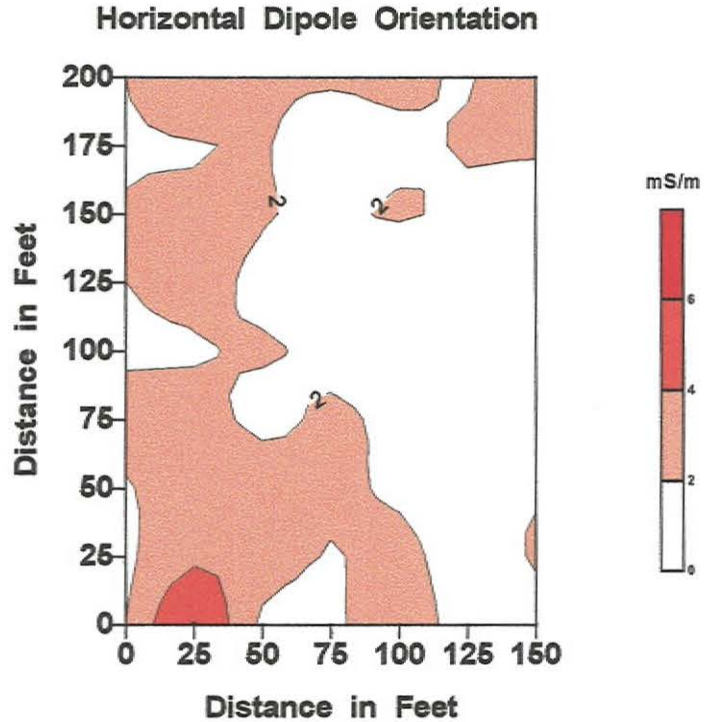

FIGURE 4

EMI SURVEY
AREA OF MARBLEHEAD LOAM, 0 TO 9 PERCENT SLOPES
ERIE COUNTY, OHIO
EM31 METER

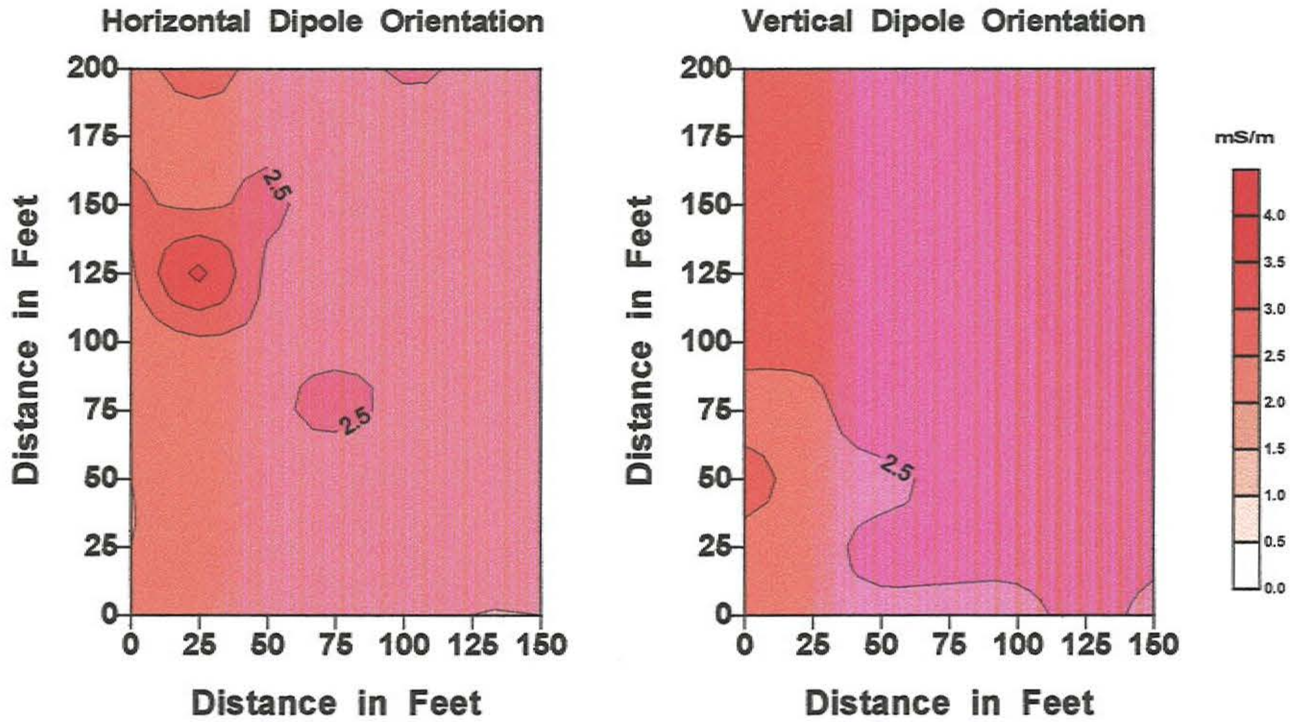

FIGURE 5