United States Department of Agriculture	**Natural Resources Conservation Service**	**11 Campus Boulevard Suite 200 Newtown Square, PA 19073**

Subject: -- Geophysical Assistance --

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Purpose:
The purpose of this investigation was to evaluate the use of electromagnetic induction (EMI) and towed array resistivity methods to assess the depths to bedrock in previously mapped soil delineations in Winneshiek County, Iowa. In addition, training and practical exposure to seven different geophysical tools or survey platforms was provided to participants.

Participants:
Eric Brevik, Graduate Student, Agronomy Dept., ISU, Ames, IA
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Bob Vobora, Soil Scientist, USDA-NRCS, Waverly, IA
Richard Taylor, Dualem Inc., Milton, Ontario, Canada
Roger Windhorn, Resource Soil Scientist, USDA-NRCS, Champaign, IL
Dan Withers, Cartographic Technician, USDA-NRCS, Champaign, IL
Calvin Wolter, GIS Analyst, Iowa DNR, Iowa City, IA

Activities:
All field activities were completed during the period of 1 to 3 November 2000.

Results:
1. Soil scientists from four states participated in this unique study. Never before had seven different geophysical instruments or survey platforms been operated in the same field, at the same time, for soil investigations. All participants were instructed in the use and operation of each EMI device. Following instructions, participants conducted EMI surveys in which they appraised the advantages and disadvantages of the various devices for soil/bedrock investigations. The participation and efforts of Illinois's "Veris Cadre" and Rick Taylor of Dualem Inc. added immensely to the success of this study and is deeply appreciated by all.

2. Soil landscapes vary and must be separately evaluated in terms of their suitability for EMI interpretations. Electromagnetic induction techniques provide the most reliable and accurate interpretations in areas where the soils consist of two strongly contrasting layers with each layer composed of fairly homogeneous materials. In soils composed of multiple layers of contrasting materials or single layers having several varying properties (moisture, clay and soluble salt contents) interpretations are more ambiguous or inaccurate.

All EMI tools were strongly and significantly correlated with bedrock depths at Site 1. Soils at this site consisted of uniform, shallow to moderately deep, medium textured materials over limestone bedrock. At Site 2, the topography was more diverse, and the soils contained multiple layers of contrasting coarse to fine textured materials (loess, residuum, till, colluvium) with several varying properties (moisture, clay and carbonate contents, thickness and lateral extent). Interpretations were ambiguous and apparent conductivity could not be correlated with the depth to bedrock. Site 3 consisted of medium textured materials overlying a fine textured residuum over limestone or sandstone bedrock. Interpretations and correlations were improved at Site 3, but still suspected of significant errors.

3. Data collected from different EMI instruments produce similar but not identical results. While line placement and measured values do vary, the general spatial patterns were similar for these instruments at each site. Slight differences in measured values and spatial patterns of apparent conductivity are attributed to differences in the frequency, depth of penetration, volume of soil profiled, and depth-response functions of the instruments, as well as variations in soils and soil properties. Differences in sampling intensity and survey design also affect results.

4. A challenge for field soil scientists using these methods will be to understand where and under what soil conditions these tools can most effectively be applied. This understanding will encourage the collection and dissemination of more accurate and reliable information by consultants using EMI for high intensity and precision farming surveys.

5. Geophysical interpretations are considered preliminary estimates of site conditions. The results of all geophysical investigations are interpretive and do not substitute for direct soil borings. The use of geophysical methods can reduce the number of soil observations, direct their placement, and supplement their interpretations. Interpretations should be verified by ground-truth observations.

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

With kind regards,

James A. Doolittle
Research Soil Scientist

cc:
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Equipment:
Seven different instruments were used in this study. These instruments included the Dualem-2 and Dualem-4 meters; EM31, EM38, and EM38DD meters; GEM300 sensor; and Veris 3100 soil EC mapping system. The depths of penetration for the Dualem-2 and Dualem-4 meters, the EM31, EM38, and EM38DD meters, and the Veris 3100 soil EC mapping system are "geometry limited" and dependent on the instruments intercoil spacing, coil or receiver orientations, and frequency, or the spacing and type of electrode array. The depth of penetration for the GEM300 sensor is considered "skin depth limited" rather than "geometry limited." The skin-depth represents the maximum depth of penetration and is frequency and soil dependent: low frequency signals travel farther through conductive mediums than high frequency signal. The theoretical penetration depth of the GEM300 sensor is dependent upon the bulk conductivity of the profiled earthen material(s) and the operating frequency. For each instrument, lateral resolution is approximately equal to the intercoil or electrode spacing. The Dualem-2 and Dualem-4 meters, the EM31, EM38, and EM38DD meters, and the GEM300 sensor require no ground contact are portable and require only one person to operate. Measurements can be made in either the continuous or station mode

Dualem Inc. manufactures the Dualem-2 and the Dualem-4 meters.[1] Taylor (2000) has described the principles of operation of these meters. These meters operate at a fixed frequency (9,000 Hz) and consist of one transmitter and two receivers. One receiver and the transmitter provide a perpendicular geometry (P). The other receiver provides a horizontal co-planar geometry (HC) with the transmitter. This dual system permits two depths to be measured simultaneously without rotating the coils. Meters are keypad operated and have about 1 megabyte of memory. The Dualem-2 has a 2-m intercoil spacing between the transmitter and the two receivers. It has depths of penetration of 1.3 and 3.0 m in the P and HC geometries, respectively. The Dualem-4 has a 4-m intercoil spacing between the transmitter and the two receivers. It has depths of penetration of 2.5 and 6.0 m in the P and HC geometries, respectively.

Geonics Limited manufacturers the EM38, EM38DD, and the EM31 meters.[1] McNeill (1980) and Geonics Limited (1998) have described principles of operation for the EM31 and the EM38 meters, respectively. The EM38 and EM38DD meters have a 1 m intercoil spacing and operate at a frequency of 14,600 Hz. They have effective penetration depths of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively (Geonics Limited, 1998). One EM38 meter was operated by Dr. Tom Fenton in the continuous mode and towed behind a vehicle. The other EM38 meter was hand carried and operated manually in the station mode. The EM38DD meter malfunctioned and has been returned to Geonics for repairs. Data collected with the EM38DD meter were inaccurate and are not contained in this report. The EM31 meter has a 3.66 m intercoil spacing and operates at a frequency of 9,810 Hz. It has theoretical penetration depths of about 3.0 and 6.0 m in the horizontal and vertical dipole orientations, respectively (McNeill, 1980).

The GEM300 multifrequency sensor is manufactured by Geophysical Survey Systems, Inc.[1] Won and others (1996) have described the use and operation of this sensor. This sensor is configured to simultaneously measure up to 16 frequencies between 330 and 19,950 Hz with a fixed coil separation (1.3 m). Multifrequency sounding with the GEM300 allows multiple depths to be profiled with one pass of the sensor. The GEM300 sensor is keypad operated and has 1.12 megabyte of memory.

The Veris 3100 soil EC mapping system is a towed, multi-electrode resistivity unit manufactured by Veris Technologies.[1] Operating procedures are described by Veris Technologies (1998). The Veris 3100 system converts measurements of apparent resistivity (ohm-m) into measurements of apparent conductivity (mS/m). In isotropic materials, conductivity is the reciprocal of resistivity. The Veris 3100 implement provides two depths of penetration: one for the upper 0 to 30 cm (shallow) and one for the upper 0 to 90 cm (deep) of the soil. The Veris 3100 system has a modified Wenner array with 6 unequally spaced electrodes (coulter-electrodes). Voltage is applied to coulter-electrodes number 2 and 5. The wider-spaced coulter-electrodes (number 1 and 6) measure the current across the 0 to 90 cm depth interval; the more closely spaced coulter-electrodes (number 3 and 4) measure current across the 0 to 30 cm depth interval. The Veris EC system is pulled behind a pickup truck at speeds of about 5 to 10 m/hr. A Trimble 132 GPS receiver was used with the Veris 3100 system.[1] The Latitude-Longitude coordinate system was used.

The positions of observation points for the EM31and EM38 (manually operated) meters, Dualem-2 and the Dualem-4 meters, and GEM300 sensor were obtained with Rockwell Precision Lightweight GPS Receivers (PLGR).[1] The GPS receiver was operated in the continuous and the mixed satellite modes. The Universal Transverse Mercator (UTM) coordinate system was used. Horizontal datum was the North American 1983. Horizontal units were expressed in meters.

To help summarize the results of this study, the SURFER for Windows program, developed by Golden Software, Inc.,[1] was used to construct two-dimensional simulations. Grids were created using kriging methods with an octant search.

Field Procedures:
Parallel survey lines were established at each site. These lines were of varying lengths and spaced about 30 m apart. Along each line,

[1] Trade names are used to provide specific information. Their mention does not constitute endorsement by USDA-NRCS.

survey flags were inserted in the ground at an interval of about 15 meters. Survey flags served as observation points. The coordinates of each observation point were determined with GPS.

The Veris 3100 implement and ISU's EM38 meter were towed behind vehicles along each survey lines. Measurements were continuously recorded and geo-referenced with Trimble GPS receivers. As these mobile units are faster, larger and additional areas were often measured with these instruments. In some areas, because of steep slopes and vegetation, these vehicles had to depart from survey lines and observation points.

As measurements were obtained in both the horizontal and vertical dipole orientations and precise positioning of instruments were required, the EM31and EM38 (manually operated) meters, Dualem-2 and Dualem-4 meters, and GEM300 sensors were operated in a station-to-station rather than a continuous mode. Measurements were taken with the EM31 and EM38 meters placed on the ground surface in both the horizontal and vertical dipole orientations. Measurements were taken at hip-height with the GEM300 sensor in both the horizontal and vertical dipole orientations. Measurements were taken with the Dualem-2 and Dualem-4 meters held at hip-height in both the perpendicular and horizontal coplanar geometries.

Soil borings were taken at several observation points within each study site. Measured depths to bedrock were compared with values of apparent conductivity measured with each EMI instrument with the exceptions of the Veris 3100 soil EC mapping system and the towed EM38 meter.

Interpretation of Data:
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 depth (Greenhouse and Slaine, 1983). Variations in apparent conductivity are caused 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, 1980). The apparent conductivity of soils will increase with increased soluble salts, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976).

Interpretations of 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. Electrical resistivity and EMI integrate the bulk physical and chemical properties of soils 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, intrinsic physical and chemical properties, as well as temporal variations in soil water and temperature, establish a unique or characteristic range of apparent conductivity values.

Electromagnetic induction has been used to assess and map depths to claypans (Doolittle et al., 1994; Stroh et al., 1993; Sudduth and Kitchen, 1993; and Sudduth et al., 1995), and to measure soil water contents (Kachanoski et al., 1988), cation exchange capacity (McBride et al., 1990), field-scale leaching rates of solutes (Slavich and Yang, 1990, Jaynes et al., 1995) and herbicide partition coefficients (Jaynes et al., 1995). Electromagnetic induction has been used as a soil-mapping tool to assist precision farming (Jaynes, 1995; Jaynes et al., 1993; Sudduth et al., 1995). Recently, Sudduth and others (1999) compared the use of electromagnetic induction with resistivity for determining topsoil depth above a claypan.

Electromagnetic induction can provide a relatively inexpensive, fast, and comprehensive means for mapping the depths to bedrock. This technique has been used to determine depths to bedrock (Bork et al., 1998; Doolittle et al., 1998; Palacky and Stephens, 1990; Zalasiewicz et al., 1985) and to locate water-bearing fault or fracture zones in bedrock (Beeson and Jones, 1988; Edet, 1990; Hazell et al., 1988; McNeill, 1991; Olayinka, 1990). In areas of karst, EMI techniques have been used to detect anomalous subsurface patterns indicative of solution features (Canace and Dalton, 1984; Pazuniak, 1989; Robinson-Poteet, 1989; Rumbens, 1990). These studies have documented that EMI is facile, can provide large quantities of data for site characterization and assessments, and can be applied over broad areas and soils.

Discussion:

<u>**Site #1**</u>

The study site was located in a cultivated field, southwest quarter of Section 21, Township 96 N, Range 9 W, near the town of Fort Atkinson. The site is in a mapped area of Rockton loam, 2 to 5 percent slopes; Jacwin loam, 0 to 2 percent slopes; and Jacwin loam, 2 to 5 percent slopes (Kittleson and Dideriksen, 1968). The Rockton series consists of moderately deep, well drained soils that formed in a mantle of loamy sediments and an underlying clayey residuum over limestone bedrock. Rockton is a member of the fine-loamy, mixed, superactive, mesic Typic Argiudolls family. The Jacwin series consists of moderately deep, somewhat poorly drained soils formed in loamy glacial sediments and an underlying residuum weathered from calcareous shale. Jacwin is a member of the fine-loamy over clayey, mixed, mesic Aquic Hapludolls family.

Figure 1 shows the spatial distribution of apparent conductivity collected with the EM31 meter at Site 1. The spatial patterns of apparent conductivity collected in the horizontal and vertical dipole orientations are shown in the upper and lower plots, respectively. The depths of penetration are 0 to 3 and 0 to 6 m in the upper and lower plots, respectively. In each plot, the isoline interval is 2 mS/m. The locations of the 127 observation points where measurements were made are shown in the upper plot.

Apparent conductivity was low and comparatively invariable across the site. These observations suggest relatively shallow and uniform depths to the electrically resistive bedrock. A general comparison of the two plots shown in Figure 1 reveals that apparent conductivity decreased and became less variable with increased soil depths. This vertical trend is also attributed to the underlying, more resistive limestone bedrock. In Figure 1, areas with lower conductivity are presumed to have shallower depths to bedrock and lower clay and moisture contents. Based on these assumptions, the plots in Figure 1 indicate that the depths to bedrock are greater in the northwest corner of the study site (upper left-hand corner of the plots).

Basic statistics for the EM31 data are listed in Table 1. Within Site 1, apparent conductivity averaged 12.0 mS/m with a range of 6.4 to 18.5 mS/m in the horizontal dipole orientation (EM31H). Half of the observations had values of apparent conductivity between 10.9 and 12.8 mS/m. For the upper 0 to 6 m of the soil, apparent conductivity averaged 6.7 mS/m with a range of 4.5 to 10.2 mS/m in the vertical dipole orientation (EM31V). Half of the observations had values of apparent conductivity between 6.0 and 7.2 mS/m.

Table 1
Basic Statistics
EM31 Survey
Study Site #1
(All values are in mS/m)

	EM31V	EM31H
Mean	6.7	12.0
Standard Deviation	1.0	1.8
Minimum	4.5	6.4
Maximum	10.2	18.5
First	6.0	10.9
Median	6.6	12.0
Third	7.2	12.8

Figures 2 shows the results of the EMI survey conducted with the GEM300 sensor. Data collected at 14790 Hz and 9810 Hz are shown in the upper and lower sets of plots, respectively. These frequencies were selected as they approximate the frequencies of the EM38 and the EM31 meters. For each frequency, data collected in the horizontal and vertical dipole orientations are shown in the left-hand and right-hand plots, respectively. In each plot, the isoline interval is 4 mS/m. The locations of the 127 observation points where measurements were made are shown in the left-hand plots.

Table 2
Basic Statistics
GEM300 Survey
Study Site #1
(All values are in mS/m)

	Frequency (Hz)			
	9810V	9810H	14790V	14790H
Mean	8.4	8.2	11.0	9.5
Standard Deviation	2.0	1.5	2.1	1.6
Minimum	3.9	4.2	6.5	2.6
Maximum	17.6	13.5	20.9	14.3
First	7.1	7.3	9.6	8.5
Median	8.2	8.3	10.7	9.5
Third	9.4	9.2	12.0	10.5

As measured with this sensor, apparent conductivity was comparatively low and invariable across the site. Measurements obtained in the horizontal dipole orientation are more sensitive to changes in apparent conductivity that occur at shallower soil depths. Measurements obtained in the vertical dipole orientation are more sensitive to changes in apparent conductivity that occurred at greater soil depths. With each frequency, measurements obtained in the vertical dipole orientation were slightly higher and more variable than those obtained in the horizontal dipole orientation. This trend indicates the presence of a more conductive material in the subsurface. The more conductive material may be the clayey residium of the Rockwell soil. However, apparent conductivity decreased with decreasing frequency (greater penetration depths). This trend suggests that with increasing penetration depths the materials become more resistive. The more resistive material is the underlying limestone bedrock.

Table 2 summarizes the GEM300 data collected at Site 1. With a frequency of 9810 Hz, apparent conductivity ranged from 4.2 to 13.5 mS/m in the horizontal dipole orientation (9810H) and from 3.9 to 17.6 mS/m in the vertical dipole orientation (9810V). In the horizontal dipole orientation, half of the observations had values of apparent conductivity between 7.3 and 9.2 mS/m. In the vertical dipole orientation, half of the observations had values of apparent conductivity between 7.1 and 9.4 mS/m. With a frequency of 14790 Hz, apparent conductivity ranged from 2.6 to 14.3 mS/m in the horizontal dipole orientation (14790H) and from 6.5 to 20.9 mS/m in the vertical dipole orientation (14790V). In the horizontal dipole orientation, half of the observations had values of apparent conductivity between 8.5 and 10.5 mS/m. In the vertical dipole orientation, half of the observations having values of apparent conductivity between 9.6 and 12.0 mS/m.

Figure 3 shows the results of the survey conducted with the Dualem meters. Data collected with the Dualem-2 and the Dualem-4 meters are shown in the upper and lower sets of plots, respectively. In Figure 3, data collected in the perpendicular and horizontal coplanar geometries are shown in the left-hand and right-hand plots, respectively. In each plot, the isoline interval is 4 mS/m. The locations of the 127 observation points are shown in the left-hand plots. As with the EM31 meter, values of apparent conductivity decreased and became less variable with increased depth of penetration. For each meter, measurements of apparent conductivity were higher and more variable in the shallower-sensing perpendicular geometry (P). This trend may indicate the higher clay and moisture content of the solum. The lower values of apparent conductivity measured in the horizontal coplanar geometry (HC) probably reflect the increased influence of the underlying, more-resistive, limestone bedrock on the depth-weighted response of the meters.

Table 3 summarizes the apparent conductivity measurements collected with the Dualem-2 and the Dualem-4 at Site 1. The apparent conductivity of the upper 1.3 meters (P-2) averaged 10.6 mS/m with a range of 6.7 to 20.3 mS/m. Half of the observations had values of apparent conductivity between 9.1 and 11.7 mS/m. The apparent conductivity of the upper 2.5 meters (P-4) averaged 7.3 mS/m with a range of 2.9 to 19.2 mS/m. Half of the observations had values of apparent conductivity between 5.8 and 8.3 mS/m. The apparent conductivity of the upper 3.0 meters (HC-2) averaged 4.7 mS/m with a range of 1.5 to 13.0 mS/m. Half of the observations had values of apparent conductivity between 3.9 and 5.2 mS/m. The apparent conductivity of the upper 6.0 meters (HC-4) averaged 5.5 mS/m with a range of 2.5 to 8.8 mS/m. Half of the observations had values of apparent conductivity between 4.9 and 5.9 mS/m.

Table 3
Basic Statistics
DUALEM-2 & DUALEM-4 Meters
Study Site #1
(All values are in mS/m)

	HC-2	P-2	HC-4	P-4
Mean	4.7	10.6	5.5	7.3
Standard Deviation	1.7	2.2	0.9	2.3
Minimum	1.5	6.7	2.5	2.9
Maximum	13.0	20.3	8.8	19.2
First	3.9	9.1	4.9	5.8
Median	4.4	10.1	5.4	6.8
Third	5.2	11.7	5.9	8.3

Figure 4 shows the track and the locations of the 3111 observation points obtained with ISU's towed EM38 meter (upper plot) and the 4257 observations obtained with the Veris 3100 system (middle plot) within Site 1. In Figure 4, spatial patterns of apparent conductivity within the upper 1.5 m, 0.3, and 0.9 m of the soil as measured with these instruments are shown in the upper, middle, and lower plots, respectively. In each plot, the isoline interval is 4 mS/m. These plots cover a much larger area than was surveyed with the other EMI instruments (western portion of plots). Comparatively high and variable conductivities were recorded by the Veris 3100 system for the surface layers (shallow measurements). These values may reflect the added soil moisture from a recent rainfall event. For the 0 to 90 cm depth interval (see lower plot), spatial patterns are assumed to reflect the shallow (0 to 0.5 m) to moderately deep (0.5 to 1.0 m) depths to limestone bedrock. As more of the underlying bedrock is averaged into the EMI response measured with the EM38 meter, values of apparent conductivity decrease and become less variable (see upper plot). At the selected isoline interval, data collected with the Veris 3100 system contains significant amounts of unwanted random noise.

Basic statistics for the towed EM38 meter and the Veris 3100 system surveys of Site 1are listed in Table 4. At Site 1, apparent conductivity data collected with the Veris 3100 system was higher and more variable than data collected with any other EMI instrument. This reflects, in part, the shallower penetration depth of the Veris system. With the Veris 3100 system, for the upper 0 to 30 cm (shallow) of the soil, apparent conductivity averaged 20.9 mS/m with a range of 8.3 to 33.1 mS/m. Half of the observations had values of apparent conductivity between 18.1 and 23.9 mS/m. For the upper 0 to 90 cm (deep) of the soil, apparent conductivity averaged 16.4 mS/m with a range of -25.0 to 134.9 mS/m. Half of the observations had values of apparent conductivity between 14.5 and 18.1 mS/m. Negative values are attributed to poor ground contact of the coulter-electrodes (caused by large clods or rock fragments). When contact is lost, a measurement of about –25 mS/m is typically recorded with the Veris 3100 system. The maximum value (134.9 mS/m) probably reflects contact with a discarded, metallic farm artifact.

The towed EM38 meter was operated in the vertical dipole orientation. With this meter, apparent conductivity averaged 13.7 mS/m with a range of 6.9 to 28.0 mS/m. Half of the observations had values of apparent conductivity between 12.5 and 14.5 mS/m. In the area surveyed with the other EMI instruments, the towed EM38 meter measured slightly higher values of apparent conductivity, but recorded similar spatial patterns.

Table 4
Basic Statistics
ISU's Towed EM38 Meter and Veris 3100 Survey
Site #1
(All values are in mS/m)

	EM38 (vertical)	VERIS (shallow)	VERIS (deep)
Mean	13.7	20.9	16.4
Standard Deviation	1.9	4.1	4.2
Minimum	6.9	8.3	-25.0
Maximum	28.0	33.1	134.9
First	12.5	18.1	14.5
Median	13.6	21.2	16.2
Third	14.5	23.9	18.1

At Site 1, similar spatial patterns were obtained with each device (see figures 1, 2, 3, and 4). Dissimilarities in apparent conductivity measurements among these devices are attributed to differences in system calibration by manufacturers, intercoil spacing, depth and volume of soil profiled, and frequencies. With minor exceptions and regardless of device, volume of soil profiled, purported penetration depths, or sampling frequency, the plotted spatial patterns appear similar with all devices.

Table 5 is a correlation matrix for the four instruments used at Site 1 in the station-to-station mode. This matrix is based on measurements made at 127 observation points. Although extreme caution should be used in interpreting these correlation coefficients, the strong positive correlations among these instruments suggest that they are measuring similar volumes of earthen materials and providing similar results. In general and with the exception of the EM31 and the Dualem-4 meters, high correlations can be found in the data collected with the same instruments but at different frequencies, and dipole or receiver orientations. The strongest correlations were obtained between data collected with the GEM300 sensor operating at 14790 Hz in the vertical dipole orientation (14790V) and data obtained with the Dualem-2 and Dualem-4 in the perpendicular geometry (P-2, P-4). Strong correlations were also achieved between data collected with the GEM300 sensor operating at 9810 Hz in the vertical dipole orientation (9810V) and data obtained with the Dualem-2 and Dualem-4 in the perpendicular geometry. Strong correlations were also achieved between data collected with the EM31 meter in the horizontal dipole orientation (EM31H) and the GEM300 sensor at both frequencies, and the Dualem-2 and Dualem-4 in the perpendicular geometry. Relationships were lower between data collected with the EM31 meter in the vertical dipole orientation (EM31V) and the GEM300 sensor at both frequencies, and the Dualem-2 and Dualem-4 in the horizontal coplanar geometry (HC-2, HC-4).

Table 5
Correlation Matrix for Instruments used at Site 1
(N = 127)

	EM31V	EM31H	9810V	9810H	14790V	14790H	HC-2	P-2	HC-4	P-4
EM31V	1.000									
EM31H	0.535	1.000								
9810V	0.724	0.868	1.000							
9810H	0.535	0.826	0.867	1.000						
14790V	0.739	0.871	0.983	0.859	1.000					
14790H	0.570	0.797	0.809	0.773	0.817	1.000				
HC-2	0.737	0.647	0.755	0.622	0.779	0.551	1.000			
P-2	0.610	0.850	0.929	0.842	0.933	0.779	0.742	1.000		
HC-4	0.737	0.410	0.566	0.394	0.591	0.400	0.694	0.397	1.000	
P-4	0.741	0.843	0.945	0.818	0.985	0.772	0.816	0.926	0.617	1.000

At the eight observation points, responses from four instruments were compared with measured depths to bedrock (see Table 6). Areas with greater depths to bedrock generally had higher EMI responses. Moderate to high correlations were obtained with the EM31 meter, Dualem-2 and Dualem-4 meters, and GEM300 sensor, and the measured depths to bedrock. A strong and significant correlation (r = 0.91; 0.001 level) was obtained between depth to bedrock and EMI response obtained with the GEM300 senor, operating at 14790 Hz and in the horizontal dipole orientation. In addition, strong correlations were also obtained with the EM31 meter in the horizontal dipole orientation (.003 level), the GEM300 sensor operating at 9810 Hz in the vertical (.003 level) and horizontal (.004 level) dipole orientations, and the Dualem-2 in the perpendicular geometry (.005 level).

Table 6
Correlations between the measured depth to bedrock (inches) and EMI response (mS/m) for different instruments, dipole orientations, and frequencies.
Site #1

DEPTH	EM31V	EM31H	9810V	9810H	14790V	14790H	HC-2	P-2	HC-4	P-4
17	5.5	11.2	7.0	6.6	9.5	8.9	2.5	8.9	4.8	5.7
17	5.7	12.2	7.4	8.4	10.3	9.5	2.9	10.6	4.9	6
12	6.2	10.1	5.2	6.5	7.8	7.4	1.6	6.7	5.3	3.7
18	5.8	11.3	7.9	9.8	10.2	9.3	2.4	11.1	3.5	5.9
28	7.4	14.2	11.0	10.4	13.4	11.3	6	12.9	5.9	9.2
21	5.2	13.6	8.7	9.9	10.7	10.6	4.3	11.6	4.5	6.1
20	5.8	13.9	8.7	8.7	11.7	10.5	3.9	11.5	4.8	8
28	10.2	18.5	17.6	13.5	20.9	14.3	13	20.3	8.8	19.2
Correlation	0.702	0.872	0.871	0.859	0.842	0.913	0.829	0.854	0.631	0.796
Probability	0.047	0.003	0.003	0.004	0.006	0.001	0.008	0.005	0.087	0.025

Data collected with the GEM300 sensor at the eight sampling points were used to develop the following predictive regression equation:

$$D = -5.24 + (2.481 * 14790Hz) \quad [1]$$

where "D" is depth to bedrock (in) and "14790 Hz" is the apparent conductivity (mS/m) measured with the GEM300 sensor at an operating frequency of 14790 Hz and in the horizontal dipole orientation.

Based on 127 EMI measurements and predictive Equation [1], the average depth to bedrock at the 127 observation points was 18.4 inches with a range of about 16 to 30 inches. One-half of the observations had depths to bedrock between 15.8 and 20.8 inches. The bedrock was shallow at 68 percent, and moderately deep at 32 percent of the observation points. The preponderance of shallow and moderately deep soils is in accord with the sampling that was conducted at this site, but appears to conflict with the delineated soil map units.

Figure 5 is a two-dimensional simulation showing the predicted distribution of depths to bedrock across the study site. Depths are based on EMI measurements and predictive Equation [1]. The spatial patterns indicate that the depths to bedrock are shallow and moderately deep across the site.

Site #2

The study site was located in southwest quarter of Section 27, Township 99 N, Range 9 W. The site was in pasture. The site included mapped areas of Fayette silt loam, 9 to 14 percent slopes, moderately eroded; and Nordness silt loam, 5 to 14 percent slopes (Kittleson and Dideriksen, 1968). The Fayette series consists of deep, well drained, moderately permeable soils formed in loess on uplands. Fayette is a member of the fine-silty, mixed, superactive, mesic Typic Hapludalfs family. The Nordness series consists of shallow, well drained soils formed in loamy or silty material and a thin layer of clayey residuum over limestone bedrock on uplands. Nordness is a member of the loamy, mixed, superactive, mesic Lithic Hapludalfs family.

Spatial patterns collected with both the EM38 and the EM31 meters were similar and conformed with observed topographic and known soil patterns. Figure 6 shows the results of the survey conducted with the EM31 meter. The locations of the 102 observation points where measurements were obtained with the EM31 meter are shown in the upper plot. In each plot, the isoline interval is 5 mS/m. Values of apparent conductivity were lowest on the higher-lying, western portion of the study site (left-hand portion of the plots) where the Nordness unit was mapped. The depth to bedrock is shallowest in this portion of the site. Values increase towards the east (right-hand portion of the plots) where the Fayette unit was mapped and depths to bedrock are deeper. Comparing the two plots, apparent conductivity increased and was more variable with increased soil depths (measurements obtained in the deeper-sensing, vertical dipole orientation are greater than measurements obtained in the shallower-sensing, horizontal dipole orientation).

Figure 7 shows the results of the survey conducted with the EM38 meter. The locations of the 102 observation points where measurements were obtained with the EM38 meter are shown in the upper plot. In each plot, the isoline interval is 5 mS/m. As with the measurements obtained with the EM31 meter (see Figure 6), lower values of apparent conductivity were recorded on the higher-lying, western portion of the study site where the Nordness unit was mapped. In addition, apparent conductivity increased and was more variable with increased depth of penetration (vertical dipole measurements greater than horizontal dipole measurements). However, compared with data collected with the EM31 meter, data collected with the EM38 meter were slightly lower and less variable.

Table 7
Basic Statistics
Geonic Limited Meters
Study Site #2
(All values are in mS/m)

	EM38H	EM38V	EM31H	EM31V
Average	11.1	16.7	17.8	19.6
Standard Deviation	3.7	5.2	6.3	8.4
Minimum	1.4	3.3	3.2	1.8
Maximum	20.9	25.8	28.2	33.4
First	8.7	13.8	14.3	14.6
Median	10.8	17.6	20.3	22.8
Third	13.8	20.3	21.8	25.9

Table 7 summarizes the apparent conductivity measurements collected with the EM38 and EM31 meters at Site 2. The apparent conductivity of the upper 0.75-meter (EM38H) averaged 11.1 mS/m with a range of 1.4 to 20.9 mS/m. Half of the observations had values of apparent conductivity between 8.7 and 13.8 mS/m. The apparent conductivity of the upper 1.5 meters (EM38V) averaged 16.7 mS/m with a range of 3.3 to 25.2 mS/m. Half of the observations had values of apparent conductivity between 13.8 and 20.3 mS/m. The apparent conductivity of the upper 3.0-meter (EM31H) averaged 17.8 mS/m with a range of 3.2 to 28.2 mS/m. Half of the observations had values of apparent conductivity between 14.3 and 21.8 mS/m. The apparent conductivity of the upper 6.0 meters (EM31V) averaged 19.6 mS/m with a range of 1.8 to 33.4 mS/m. Half of the observations had values of apparent conductivity between 14.6 and 25.9 mS/m.

Figure 8 shows the results of the survey conducted with the GEM300 sensor. The locations of the 102 observation points are shown in the upper plot. In each plot, the isoline interval is 5 mS/m. For this study site, three frequencies were selected: 9810, 14790, and 19950 Hz. The latter frequency is the highest available on the GEM300 sensor. For each frequency, measurements of apparent conductivity obtained with the GEM300 sensor were higher and more variable in the vertical than in the horizontal dipole orientation. In Figure 8, plots of apparent conductivity prepared from data collected at different frequencies, but with similar dipole orientations, look remarkably similar. Although spatial patterns change slightly, values and patterns of apparent conductivity appear to remain constant with changes in frequency. The use of multiple frequencies does not appear to change the spatial patterns nor provide additional information.

A shallowly buried, metallic artifact was detected with the GEM300 sensor. This anomaly is more apparent in data collected in the horizontal dipole orientation and at higher frequencies. This anomaly has been identified in each of the horizontal dipole plots (see "A" in Figure 8). It area of interference (negative conductivity values) has been colored blue in Figure 8.

Table 8 summarizes the apparent conductivity data collected with the GEM300 sensor at Site 2. With a frequency of 9810 Hz, apparent conductivity ranged from –9.9 to 17.6 mS/m in the horizontal dipole orientation and from –1.3 to 25.5 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observations had values of apparent conductivity between 7.8 and 12.5 mS/m. In the vertical dipole orientation, half of the observations had values of apparent conductivity between 8.5 and 18.2 mS/m. With a frequency of 14790 Hz, apparent conductivity ranged from –37.9 to 19.6 mS/m in the horizontal dipole orientation and from 1.9 to 29.2 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observations had values of apparent conductivity between 10.1 and 14.9 mS/m. In the vertical dipole orientation, half of the observations had values of apparent conductivity between 11.5 and 22.0 mS/m. With a frequency of 19950 Hz, apparent conductivity ranged from –49.8 to 18.5 mS/m in the horizontal dipole orientation and from 1.6 to 29.8 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observations had values of apparent conductivity between 9.0 and 14.0 mS/m. In the vertical dipole orientation, half of the observations had values of apparent conductivity between 11.2 and 22.2 mS/m.

Table 8
Basic Statistics
GEM300 Survey
Study Site #2
(All values are in mS/m)

	9810V	9810H	14790V	14790H	19950V	19950H
Average	13.4	9.9	17.0	11.8	16.9	10.8
Standard Deviation	7.0	4.3	7.2	6.3	7.5	7.3
Minimum	-1.3	-9.9	1.9	-37.2	1.6	-49.8
Maximum	25.5	17.6	29.2	19.6	29.8	18.5
First	8.5	7.8	11.5	10.1	11.2	9.0
Median	15.7	10.8	19.7	13.2	20.1	12.3
Third	18.2	12.5	22.0	14.9	22.2	14.0

Figure 9 shows the results of the survey conducted with the Dualem meters. Data collected with the Dualem-2 are shown in the upper two plots. Data collected with the Dualem-4 are shown in the lower two plots. In Figure 9, plots of apparent conductivity data collected with each meter in the perpendicular and horizontal coplanar geometries have been labeled with the letters "P" and "HC," respectively. In each plot, the isoline interval is 5 mS/m. The locations of the 102 observation points where measurements were made with these meters are shown in the upper plots. Once again, while line placement and measured values do vary, the general spatial patterns are similar to those obtained with the EM31 meter and the GEM300 sensor. Measurements and spatial patterns of apparent conductivity obtain in the shallower-sensing, perpendicular geometry are most similar to those obtain in the shallower-sensing horizontal dipole orientation with the EM38 and EM31 meters and the GEM300 sensor. Measurements and spatial patterns of apparent conductivity obtain in the deeper-sensing horizontal coplanar geometry are most similar to those obtain in the deeper-sensing vertical dipole orientation with the EM38 and EM31 meters, and the GEM300 sensor.

Table 9
Basic Statistics
Dualem-2 & Dualem-4 Meters
Study Site #2
(All values are in mS/m)

	HC-2	P-2	HC-4	P-4
Average	15.1	11.5	17.5	16.3
Standard Deviation	7.4	3.4	7.5	7.2
Minimum	-2.2	3.5	0.1	0.8
Maximum	26.8	20.7	29.6	30.9
First	10.7	10.0	12.6	12.0
Median	18.0	12.0	20.2	18.1
Third	19.8	13.9	23.3	21.1

Table 9 summarizes the apparent conductivity measurements collected with the Dualem-2 and the Dualem-4 at Site 2. For each meter, measurements of apparent conductivity were lower and less variable in the shallower-sensing perpendicular coplanar geometry (P). The higher values of apparent conductivity measured in the horizontal coplanar geometry (HC) are believed to reflect higher moisture and clay contents at lower soil depths. The apparent conductivity of the upper 1.3 meters (P-2; measured with the Dualem-2 meter in the perpendicular geometry) averaged 11.5 mS/m with a range of 3.5 to 20.7 mS/m. Half of the observations had values of apparent conductivity between 10.0 and 13.9 mS/m. The apparent conductivity of the upper 2.5 meters (P-4; measured with the Dualem-4 meter in the perpendicular geometry) averaged 16.3 mS/m with a range of 0.8 to 30.9 mS/m. Half of the observations had values of apparent conductivity between 12.0 and 21.1 mS/m. The apparent conductivity of the upper 3.0 meters (HC-2; measured with the Dualem-2 meter in the horizontal coplanar geometry) averaged 15.1 mS/m with a range of –2.2 to 26.8 mS/m. Half of the observations had values of apparent conductivity between 10.7 and 19.8 mS/m. The apparent conductivity of the upper 6.0 meters (HC-4; measured with the Dualem-4 meter in the horizontal coplanar geometry) averaged 17.5 mS/m with a range of 0.1 to 29.6 mS/m. Half of the observations had values of apparent conductivity between 12.6 and 23.3 mS/m.

At Site 2, the towed EM38 meter and the Veris 3100 soil EC mapping system covered larger areas in a very short period of time. Each instruments surveyed a slightly different area. Figure 10 shows the track and the locations of the 330 observation points obtained with ISU's towed EM38 meter (upper plot) and the 571 observations obtained with the Veris 3100 system (middle plot) at Site 2. In Figure 10, spatial patterns of apparent conductivity within the upper 1.5 m, 0.3, and 0.9 m of the soil as measured with these instruments are shown in the upper, middle, and lower plots, respectively. In each plot, the isoline interval is 5 mS/m. As captured in these plots, apparent conductivity increases with increased depth of penetration.

Table 10
Basic Statistics
ISU's Towed EM38 Meter and Veris 3100 Survey
Site #2
(All values are in mS/m)

	EM38V	SHALLOW	DEEP
Average	18.7	6.3	14.8
Standard Deviation	3.9	2.4	4.6
Minimum	6.7	2.8	4.8
Maximum	28.1	24.7	39.7
First	16.4	4.6	11.5
Median	19.2	5.7	14.5
Third	21.3	7.3	18.0

Basic statistics for the towed EM38 meter and the Veris 3100 system for Site 2 are listed in Table 10. At Site 2, apparent conductivity for the 0 to 30 cm depth layer (shallow data that was collected with the Veris 3100 system) was lower and less variable than data collected for any other layer with any other EMI instrument. With the Veris 3100 system, data for the 0 to 90 cm depth layer (deep) was intermediary between data collected with the EM38 meter in the horizontal (0 to 75 cm) and vertical (0 to 150 cm) dipole orientations (see Table 7).

This trend follows the close similarity and orderly trends of EMI data collected with the Veris 3100 and the EM38 and EM31 meters at other sites.

With the Veris 3100 system, for the 0 to 30 cm depth layer, apparent conductivity averaged 6.3 mS/m with a range of 2.8 to 24.7 mS/m. Half of the observations had values of apparent conductivity between 4.6 and 7.3 mS/m. These lower values presumably reflect the lower soil moisture and clay contents of the surface layers within this pasture. For the 0 to 90 cm depth layer, apparent conductivity averaged 14.8 mS/m with a range of 4.8 to 39.7 mS/m. Half of the observations had values of apparent conductivity between 11.5 and 18.0 mS/m. The towed EM38 meter was operated in the vertical dipole orientation. With this meter, apparent conductivity averaged 18.7 mS/m and ranged from 6.7 to 28.1 mS/m. Half of the observations had values of apparent conductivity between 16.4 and 21.3 mS/m.

Soils were observed at nine observation points within Site 2. Brief profile descriptions of these soils were obtained. Soils were exceeding diverse. Bedrock was observed in only three holes at depths ranging from 41 to 142 inches. Differences in soil type, texture, parent material (loess, till, and coarse-textured colluvium), depth, carbonates, and moisture and clay contents were described. The correlations shown in tables 11 and 12 are based on only the three sampling points where bedrock was observed. Only data collected with the EM31 meter in the vertical dipole orientation were strongly correlated with the depth to bedrock (significant at 0.025 level). For the other instruments and orientations shown in tables 11 and 12, correlations and probability levels were low.

Table 11
Correlations between the measured depth to bedrock (inches) and EMI response (mS/m) for the EM31 and EM38 meters, and the GEM300 sensor.
Site #2

DEPTH	EM31H	EM31V	EM38H	EM38V	9810H	9810V	14790H	14790V	19950H	19950V
71	20.1	15.2	14.5	22.1	10.8	9.9	12.8	13.4	11.9	13.8
41	16.7	14.5	10.3	16.9	12.3	15.7	14.3	19.8	14.7	20.5
142	17.8	19.4	7.9	15.6	9.9	13.7	14.2	17.5	13.9	17.5
CORRELATION	0.092	0.987	-0.563	-0.408	-0.931	-0.116	0.170	-0.132	-0.051	-0.231
PROBABILITY	0.935	0.025	0.566	0.699	0.125	0.918	0.879	0.906	0.964	0.834

The low correlations obtained with these EMI instruments at Site 2 are, in part, related to the topographic diversity of the site, variations in parent materials, and spatial and vertical differences in clay, moisture and calcium carbonate contents. In addition, cattle heavily grazed this site and their droppings may have influenced EMI responses. Poor survey control was also exercised at this site and large spatial discrepancies often existed between the points of soil observation and the points of observation made with the different instruments.

Table 12
Correlations between the measured depth to bedrock (inches) and EMI response (mS/m) for the Dualem-2 and Dualem-4 meters.
Site #2

DEPTH	P-2	HC2	P-4	HC-4
71	12.5	14.2	14.9	11.6
41	14.1	18.9	18.6	17.1
142	10.8	16.2	17.1	17.6
CORRELATION	-0.977	-0.370	-0.184	0.301
PROBABILITY	0.044	0.729	0.869	0.782

Table 13 is a correlation matrix for four of the instruments used at Site 2. Strong positive correlations among these instruments suggest that they may be measuring similar depths and volumes of earthen materials, and may provide similar results. With the exception of the

EM38 meter, high correlations can be found in the data sets collected with the same instruments but at different frequencies or receiver orientations. Data collected with the EM38 meter in the horizontal dipole orientation was conspicuously weakly correlated with data collected with the other instruments. Data from the EM31 meter was strongly correlated with data collected with the GEM300 sensor in the vertical dipole orientation, the Dualem-2 meter in the horizontal coplanar geometry, and the Dualem-4 meter in both geometries. Data collected with the GEM300 sensor in the vertical dipole orientation was strongly correlated with data collected with the Dualem meters.

Table 13
Correlation Matrix for Instruments used at Site 2
(N = 102)

	EM31-H	EM31-V	EM38-H	EM38-V	9810H	9810V	14790H	14790V	19950H	19950V	HC-2	P-2	HC-4	P-4
EM31H	1.000													
EM31V	0.878	1.000												
EM38H	0.373	0.207	1.000											
EM38V	0.595	0.499	0.460	1.000										
9810H	0.792	0.685	0.459	0.547	1.000									
9810V	0.930	0.915	0.342	0.559	0.841	1.000								
14790H	0.532	0.455	0.304	0.369	0.901	0.624	1.000							
14790V	0.907	0.895	0.334	0.547	0.864	0.993	0.677	1.000						
19950H	0.468	0.403	0.271	0.334	0.863	0.570	0.993	0.629	1.000					
19950V	0.885	0.870	0.343	0.541	0.872	0.981	0.704	0.995	0.659	1.000				
HC-2	0.933	0.941	0.266	0.556	0.735	0.953	0.488	0.930	0.437	0.905	1.000			
P-2	0.818	0.599	0.491	0.571	0.749	0.779	0.503	0.758	0.447	0.736	0.752	1.000		
HC-4	0.841	0.970	0.179	0.466	0.642	0.903	0.435	0.889	0.389	0.867	0.930	0.537	1.000	
P-4	0.936	0.874	0.392	0.591	0.771	0.939	0.493	0.991	0.431	0.885	0.951	0.865	0.840	1.000

<u>Site #3</u>

The study site was located in southeast quarter of Section 27, Township 99 N, Range 7 W. The field was in CRP. The site included mapped areas of Dubuque silt loam, 14 to 18 percent slopes, moderately eroded; and Palsgrove silt loam, 14 to 18 percent slopes, moderately eroded (Kittleson and Dideriksen, 1968). The Dubuque series consists of well drained, moderately deep soils formed in loess and a thin layer of residuum overlying limestone bedrock. Dubuque is a member of the fine-silty, mixed, superactive, mesic Typic Hapludalfs family. The Palsgrove series consists of deep, well drained soils on hill slopes. These soils formed in loess and residuum weathered from limestone. Palsgrove is a member of the fine-silty, mixed, superactive, mesic Typic Hapludalfs family.

Figure 11 shows the results of the survey conducted with the EM31 meter. The locations of the 53 observation points where measurements were obtained with the EM31 meter are shown in the left-hand plot. The isoline interval is 2 mS/m. This interval is within the range of observation errors. However, the interval was chosen because of the low variability of apparent conductivity within the site. Values of apparent conductivity were highest along a ridgeline that extends across the central portion of the study site in a north-south direction. Along this ridgeline, soils are more eroded and shallower to finer-textured Bt horizon materials. Values of apparent conductivity were lower on lower-lying sideslope positions that flank the ridgeline. These areas are presumed to have a deeper mantle of colluvium. In general, apparent conductivity decreased and was less variable with increased soil depths (measurements obtained in the shallower-sensing, horizontal dipole orientation are greater than measurements obtained in the deeper-sensing, vertical dipole orientation).

Figure 12 shows the results of the survey conducted with the EM38 meter. The locations of the 53 observation points where measurements were obtained with the EM38 meter are shown in the left-hand plot. Once again, the isoline interval is 2 mS/m. In both dipole orientations, higher values of apparent conductivity were recorded with the EM38 meter on the highest-lying portion of the ridgeline located in the southern (lower) part of the study site. However, the remainder of the ridgeline is poorly defined in the plots of data collected with the EM38 meter. In addition, high values of apparent conductivity are recorded with the EM38 meter in the vertical dipole orientation at the base of steep sideslopes in the northwest (upper left-hand) portion of the study site.

Table 14 summarizes the apparent conductivity measurements collected with the EM38 and EM31 meters at Site 3. The apparent conductivity of the upper 0.75-meter EM38H) averaged 10.2 mS/m with a range of 4.4 to 19.0 mS/m. Half of the observations had values of apparent conductivity between 8.7 and 11.8 mS/m. The apparent conductivity of the upper 1.5 meters (EM38V) averaged 12.1 mS/m with a range of 1.9 to 23.1 mS/m. Half of the observations had values of apparent conductivity between 9.2 and 15.9 mS/m. The apparent conductivity of the upper 3.0-meter (EM31H) averaged 14.2 mS/m with a range of 6.5 to 21.0 mS/m. Half of the observations had values of apparent conductivity between 12.2 and 16.4 mS/m. The apparent conductivity of the upper 6.0 meters (EM31V) averaged 11.4 mS/m with a range of 3.4 to 19.1 mS/m. Half of the observations had values of apparent conductivity between 9.2 and 13.9 mS/m.

Table 14
Basic Statistics
Geonic Limited Meters
Study Site #3
(All values are in mS/m)

	EM31-H	EM31-V	EM38-H	EM38-V
Average	14.2	11.4	10.2	12.1
Standard Deviation	2.8	3.3	3.0	4.6
Minimum	6.5	3.4	4.4	1.9
Maximum	21.0	19.1	19.0	23.1
First	12.2	9.2	8.7	9.2
Median	14.1	11.2	10.1	11.5
Third	16.4	13.9	11.8	15.9

Figure 13 shows the results of the survey conducted with the GEM300 sensor at frequencies of 9810 and 14790 Hz. The locations of the 53 observation points are shown in the extreme left-hand plot. In each plot, the isoline interval is 2 mS/m. For this study site, three frequencies were selected: 9810, 14790, and 19950 Hz. For each frequency, measurements of apparent conductivity were higher and more variable in the vertical than in the horizontal dipole orientation. In Figure 13, plots prepared from data collected with different dipole orientations are the most dissimilar. Once again, more information can be derived concerning site conditions from plots prepared from GEM300 data collected at different dipole orientations than data collected at different frequencies. Although spatial patterns vary slightly, values and patterns of apparent conductivity appear to remain steady at different frequencies. The use of multiple frequencies does not appear to modify the spatial patterns nor provide additional information.

Table 15
Basic Statistics
GEM300 Survey
Study Site #3
(All values are in mS/m)

	9810H	9810V	14790H	14790V	19950H	19950V
Average	4.6	7.3	6.0	10.0	3.6	7.9
Standard Deviation	2.3	3.5	2.1	4.1	2.2	3.8
Minimum	-0.5	-2.0	0.6	0.0	-1.6	-2.2
Maximum	11.3	13.7	10.9	23.2	8.1	14.8
First	3.3	5.0	4.7	7.8	2.1	5.9
Median	3.9	6.8	5.7	9.7	3.1	7.9
Third	5.9	10.2	7.4	12.8	5.0	11.2

Table 15 summarizes the GEM300 data collected at Site 3. With each frequency, apparent conductivity was higher and more variable in the deeper sensing vertical than in the shallower-sensing horizontal dipole orientations. With a frequency of 9810 Hz, apparent conductivity averaged 4.6 mS/m and ranged from –0.5 to 11.3 mS/m in the horizontal dipole orientation. In the horizontal dipole orientation, half of the observations had values of apparent conductivity between 3.3 and 5.9 mS/m. With a frequency of 9810 Hz, apparent conductivity averaged 7.3 mS/m and ranged from –2.0 to 13.7 mS/m in the vertical dipole orientation. In the vertical dipole orientation, half of the observations had values of apparent conductivity between 5.0 and 10.2 mS/m. With a frequency of 14790 Hz, apparent conductivity averaged 6.0 mS/m and ranged from 0.6 to 10.9 mS/m in the horizontal dipole orientation. In the horizontal dipole orientation, half of the observations had values of apparent conductivity between 4.7 and 7.4 mS/m. With a frequency of 14790 Hz, apparent conductivity averaged 10.0 mS/m and ranged from 0.0 to 23.2 mS/m in the vertical dipole orientation. In the vertical dipole orientation, half of the observations had values of apparent conductivity between 7.8 and 12.8 mS/m. With a frequency of 19950 Hz, apparent conductivity averaged 3.6 mS/m and ranged from -1.6 to 8.1 mS/m in the horizontal dipole orientation. In the horizontal dipole orientation, half of the observations had values of apparent conductivity between 2.1 and 5.0mS/m. With a frequency of 19950 Hz, apparent conductivity averaged 7.9 mS/m and ranged from –2.2 to 14.8 mS/m in the vertical dipole orientation. In the vertical dipole orientation, half of the observations had values of apparent conductivity between 5.9 and 11.2 mS/m.

Figure 14 shows the results of the survey conducted with the Dualem meters at Site 3. In Figure 14, plots of the data collected with each meter in the perpendicular and horizontal coplanar geometries have been labeled with the letters "P" and "HC," respectively. In each plot, the isoline interval is 2 mS/m. The locations of the 53 observation points are shown in the extreme left-hand plots. Plots prepared from data collected with the Dualem meters are similar to those prepared from data collected with the EM38 and EM31 meters, and the GEM300 sensor.

Table 16
Basic Statistics
Dualem-2 & Dualem-4 Meters
Study Site #3
(All values are in mS/m)

	HC-2	P-2	HC-4	P-4
Average	10.1	11.9	9.5	12.1
Standard Deviation	3.2	2.6	2.5	3.7
Minimum	2.7	6.0	4.1	3.8
Maximum	16.5	17.4	15.8	19.4
First	7.7	10.5	8.1	9.8
Median	9.9	11.6	9.5	11.1
Third	12.3	13.8	10.8	15.4

Table 16 summarizes the apparent conductivity measurements collected with the Dualem-2 and the Dualem-4 at Site 3. With the Dualem-2, apparent conductivity averaged 11.9 mS/m with a range of 6.0 to 17.4 mS/m in the perpendicular geometry (P-2). Half of the observations had values of apparent conductivity between 10.5 and 13.8 mS/m. In the horizontal coplanar geometry (HC-2), apparent conductivity averaged 10.1 mS/m with a range of 2.7 to 16.5 mS/m. Half of the observations had values of apparent conductivity between 7.7 and 12.3 mS/m. With the Dualem-4, apparent conductivity averaged 12.1 mS/m with a range of 3.8 to 19.4 mS/m in the perpendicular geometry (P-4). Half of the observations had values of apparent conductivity between 9.8 and 15.4 mS/m. In the horizontal coplanar geometry (HC-4), apparent conductivity averaged 9.5 mS/m with a range of 4.1 to 15.8 mS/m. Half of the observations had values of apparent conductivity between 8.1 and 10.8 mS/m.

Table 17
Basic Statistics
Veris 3100 Survey
Site #3
(All values are in mS/m)

	SHALLOW	DEEP
Average	19.4	28.9
Standard Deviation	11.4	9.0
Minimum	-26.0	8.5
Maximum	132.5	68.8
First	14.6	22.7
Median	18.0	28.6
Third	23.5	35.3

At Site 3, the towed EM38 meter was not used. Figure 15 shows spatial patterns of apparent conductivity obtained with the Veris 3100 system at Site 3. The left-hand plot shows the track and the locations of the 780 observation points obtained with the Veris 3100 system. In each plot, the isoline interval is 5 mS/m. Areas with negative conductivity values have been colored blue in these plots. Negative values could indicate poor ground contact of the coulter-electrodes (caused by thick vegetation or rock fragments). When contact is lost, a measurement of about –25 mS/m is typically recorded with the Veris 3100 system. As captured in the plots appearing in Figure 15, apparent conductivity generally increases with increased depth of penetration. Data collected with the Veris 3100 system in the deep mode appears similar to data collected with the other instruments (see figures 12, 13, and 14).

Basic statistics for the Veris 3100 system for Site 3 are listed in Table 17. With the Veris 3100 system, for the 0 to 30 cm depth layer (shallow), apparent conductivity averaged 19.4 mS/m with a range of –26.0 to 132.5 mS/m. Half of the observations had values of apparent conductivity between 14.6 and 23.5 mS/m. For the 0 to 90 cm depth layer (deep), apparent conductivity averaged 28.9 mS/m with a range of 8.5 to 68.8 mS/m. Half of the observations had values of apparent conductivity between 22.7 and 35.3 mS/m.

Soils were observed at eight observation points within Site 3. Brief profile descriptions of these soils were obtained. Soils observed included Fayette, Palsgrove, and Village. The Village is a very deep, well-drained soil that forms in a mantle of loess overlying clayey pedisediment or residuum weathered from dolomite. Village is a member of the fine-silty over clayey, mixed, mesic Typic Hapludalfs family. Bedrock was observed in six holes at depths ranging from 43 to 80 inches. Differences in soil type, texture, parent material (loess, residium, and pedisediments), depth, and moisture and clay contents were described. The correlations shown in tables 18 and 19 are based on the measured depths to bedrock and the responses of the different EMI instruments. Data collected with the EM38 meter in the horizontal dipole orientation were the most strongly correlated (0.951) with the depth to bedrock (significant at 0.002 level). However, this relationship was considered coincidental, as the measured depths to bedrock at the six sampling sites were all outside the effective penetration depth of the EM38 meter in the horizontal dipole orientation (about 30 inches). Data collected with the EM38 meter in the vertical dipole orientation were also strongly correlated (0.883) with the depth to bedrock (significant at 0.030 level). In addition, data collected with the Dualem-2 meter in the perpendicular geometry were strongly correlated (0.835) with the depth to bedrock (significant at 0.029 level). For the other instruments and orientations shown in tables 18 and 19, correlations were lower and probability levels not as significant.

Table 18
Correlations between the measured depth to bedrock (inches) and EMI response (mS/m) for the EM31 and EM38 meters, and the GEM300 sensor.
Site #3

DEPTH	EM31-H	EM31-V	EM38H	EM38V	9810H	9810V	14790H	14790V	19950H	19950V
72	17.4	11.7	16.6	18.7	6.7	9.9	8.5	12.2	4.9	10.2
80	17.9	15.0	16.3	17.2	6.8	11.4	7.0	23.2	6.0	11.7
60	13.5	11.6	9.5	7.9	3.9	5.4	4.9	8.4	2.5	6.7
60	21.0	19.1	12.6	17.0	9.0	13.5	10.3	17.1	8.1	14.8
43	12.2	12.3	5.0	5.4	1.7	4.5	3.7	6.5	0.9	5.2
52	9.2	3.4	6.7	6.8	2.4	1.7	4.0	4.4	1.8	2.6
Correlation	0.622	0.345	0.951	0.883	0.696	0.667	0.578	0.804	0.655	0.623
Probability	0.173	0.495	0.002	0.030	0.111	0.133	0.216	0.042	0.144	0.172

Table 19
Correlations between the measured depth to bedrock (inches) and EMI response (mS/m) for the Dualem-2 and Dualem-4 meters.
Site #3

DEPTH	HC-2	P-2	HC-4	P-4
72	11.6	16.1	8.5	15.8
80	14.3	15.9	11	16.4
60	9.3	10.7	9.2	11.7
60	16.3	16.1	14	18.1
43	6.5	8.2	10.5	8.5
52	3.9	8.5	4.9	6.3
Correlation	0.675	0.835	0.181	0.739
Probability	0.126	0.029	0.727	0.080

The comparatively high correlations obtained with these EMI instruments at Site 3 were surprising considering the topographic diversity, variations in parent materials, and spatial and vertical differences in observed clay and moisture contents across the site. Data collected with the EM38 meter in the vertical dipole orientation at the six sampling points were used to develop the following predictive regression equation:

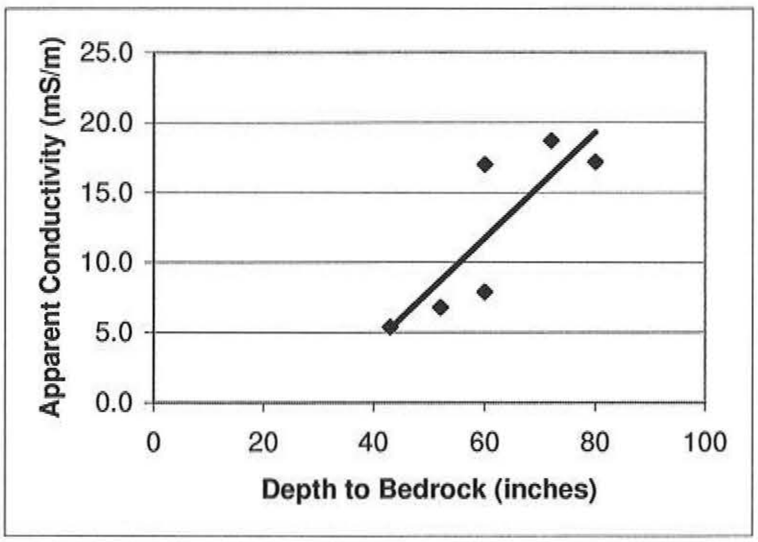
$$D = -25.06 + (2.87 * EM38\text{-}V) \quad [2]$$

where "D" is depth to bedrock (in) and "EM38-V" is the apparent conductivity (mS/m) measured with the EM38 meter in the vertical dipole orientation.

Based on 53 EMI measurements and predictive Equation [2], the average depth to bedrock was 61 inches with a range of about 42 to 82 inches. One-half of the observations had depths to bedrock between 56 and 68 inches. The bedrock was deep at 51 percent, and very deep at 49 percent of the observation points.

Figure 16 is a two-dimensional simulation showing the predicted distribution of depths to bedrock across the study site. Depths are based on EMI measurements and predictive Equation [1]. The spatial patterns indicate that the depths to bedrock are deep and very deep across the site.

Comparisons were also made between the measured depths to the finer-textured 2B horizon and apparent conductivity as measured with these instruments at each of the eight sampling sites. Correlations and probability levels were low. The relationship between depth to bedrock and the response of the EM38 meter in the vertical dipole orientation was troubling. The coefficients used in Equation [2] are relatively large. These large coefficients will magnify small measurement errors. In addition, the effective penetration depth of the EM38 meter in the vertical dipole orientation is only about 60 inches. Within the site, soils were highly complex and soil properties were considered too variable to provide a simple relationship between depth to bedrock and apparent conductivity. Graph 1 show the relationship between depth to bedrock and the response of the EM38 meter in the vertical dipole orientation at six sampling points. As shown in this chart, values of apparent conductivity in excess of about 17 mS/m are associated with soil depths greater than about 60 inches. Although one trend line is shown in Graph 1, the data suggest the possibility of two separate populations or a curvilinear rather than linear relationship between the variables. With the EM38 meter, values of apparent conductivity did not exceed 23 mS/m within this study site. Observed depths to bedrock within the site exceed the effective observation depth of the EM38 meter and values in excess of 17 mS/m should indicate areas of very deep (> 60 inches) soils. Considering the know depths to bedrock within the study site, it would have been more reassuring had a different EMI instrument with a more appropriate depth of penetration provided a stronger and more significant relationship with the depth to bedrock. Base on knowledge of the site, the present data is suspected of error.



Graph 1. Relationship between the measured depths to bedrock (inches) and apparent conductivity as measured with the EM38 meter in the vertical dipole orientation.

Table 14 is the correlation matrix for four of the instruments used at Site 3. Strong positive correlations suggest that different instruments may be measuring similar depths and volumes of earthen materials and can provide similar results. In general and with the exception of the EM38 meter, high correlations can be found in the data sets collected with the same instruments but at different frequencies, dipole orientations, or receiver orientations. Compared with Site 2, data collected with the EM38 meter in the horizontal dipole orientation was more strongly correlated with data collected with the other instruments especially the Dualem-2 meter in the perpendicular geometry. Once again, data from the EM31 meter were moderately to strongly correlated with data collected at different frequencies and dipole orientations with the GEM300 sensor and with the Dualem-2 meter in the horizontal coplanar geometry. Data collected with the EM31 meter in the horizontal dipole orientation were also moderately strongly correlated with data collected with the Dualem meters in the perpendicular geometry. Data collected with the GEM300 sensor in both dipole orientations were strongly correlated with data collected with both Dualem meters in the perpendicular geometry and with the Dualem-2 in the horizontal coplanar geometry.

Table 20
Correlation Matrix for Instruments used at Site 3
(N = 54)

	EM31-H	EM31-V	EM38-H	EM38-V	9810H	9810V	14790H	14790V	19950H	19950V	HC-2	PC-2	HC-4	PC-4
EM31H	1.000													
EM31V	0.751	1.000												
EM38H	0.520	0.209	1.000											
EM38V	0.612	0.286	0.683	1.000										
9810H	0.842	0.650	0.613	0.662	1.000									
9810V	0.899	0.802	0.559	0.652	0.927	1.000								
14790H	0.892	0.689	0.590	0.678	0.964	0.951	1.000							
14790V	0.861	0.773	0.572	0.644	0.869	0.946	0.875	1.000						
19950H	0.885	0.703	0.523	0.638	0.946	0.944	0.964	0.901	1.000					
19950V	0.869	0.810	0.514	0.637	0.899	0.987	0.935	0.938	0.931	1.000				
HC-2	0.901	0.828	0.492	0.624	0.853	0.918	0.892	0.893	0.884	0.907	1.000			
P-2	0.800	0.514	0.792	0.811	0.873	0.872	0.898	0.854	0.858	0.852	0.809	1.000		
HC-4	0.714	0.893	0.129	0.257	0.570	0.713	0.613	0.681	0.651	0.725	0.759	0.396	1.000	
P-4	0.904	0.756	0.543	0.631	0.834	0.899	0.888	0.866	0.865	0.880	0.928	0.827	0.732	1.000

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EMI SURVEY
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EM31 METER

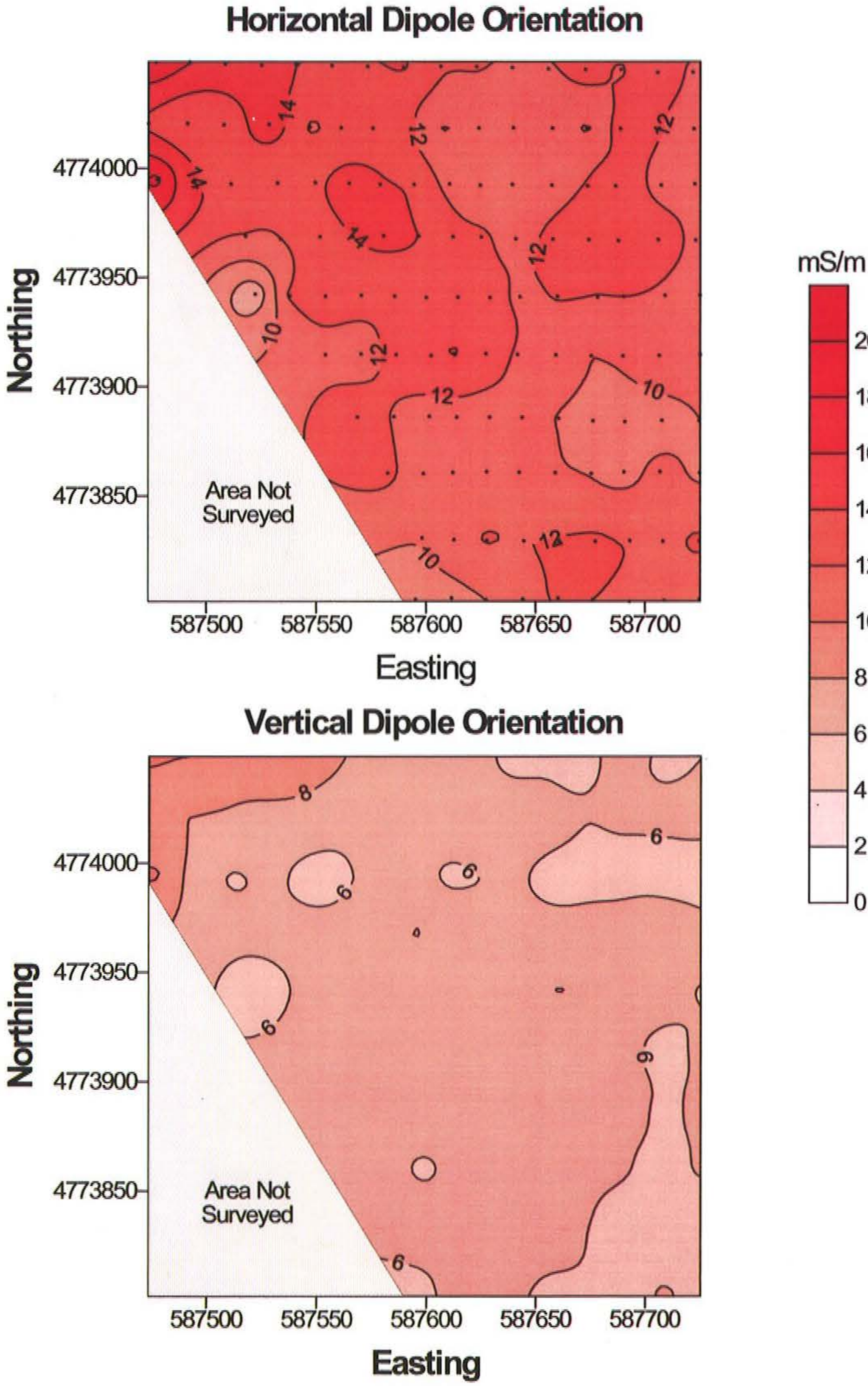

Figure 1

EMI SURVEY
IOWA SITE #1
GEM300 SENSOR

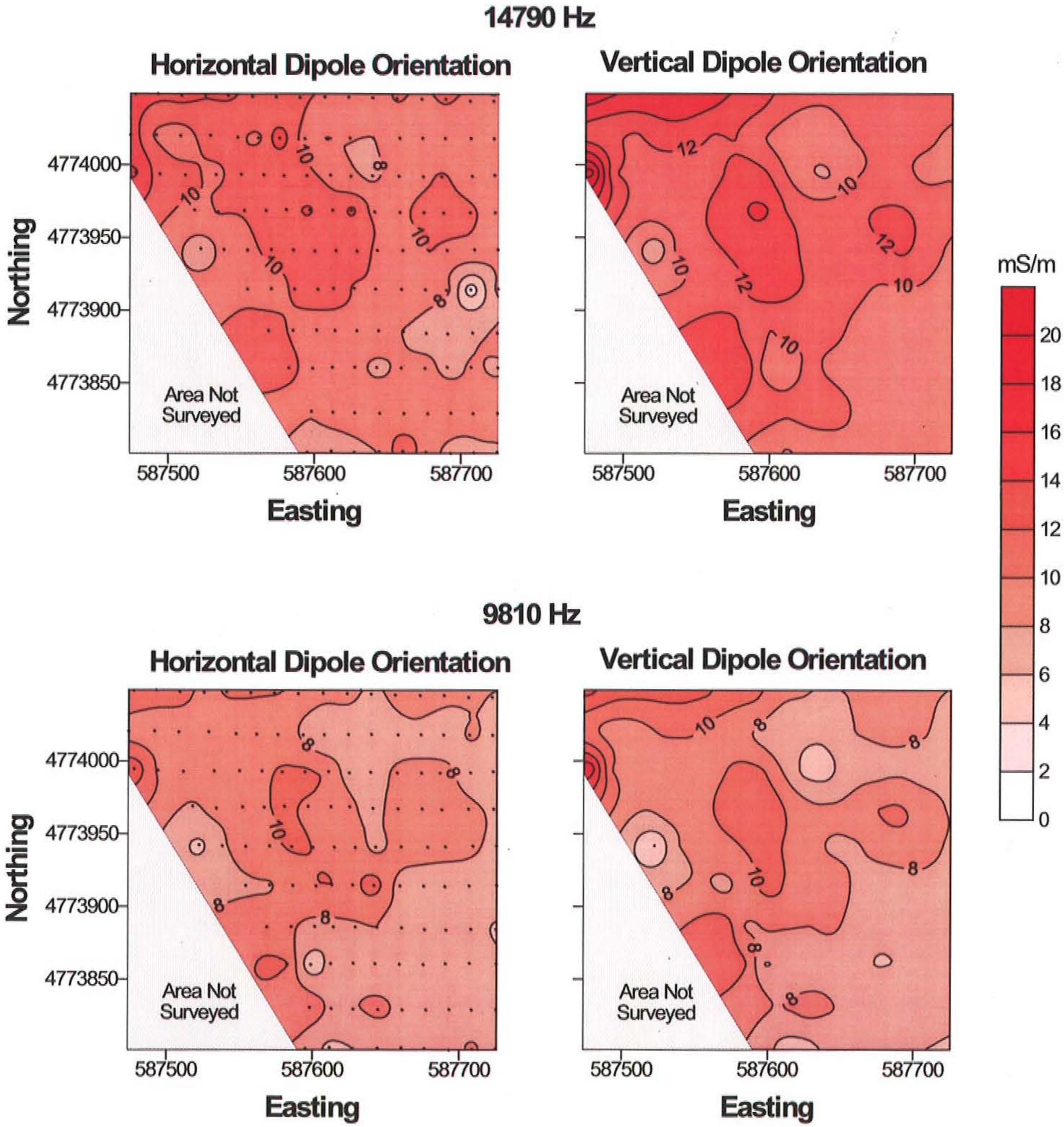

Figure 2

EMI SURVEY
IOWA SITE #1
DUALEM

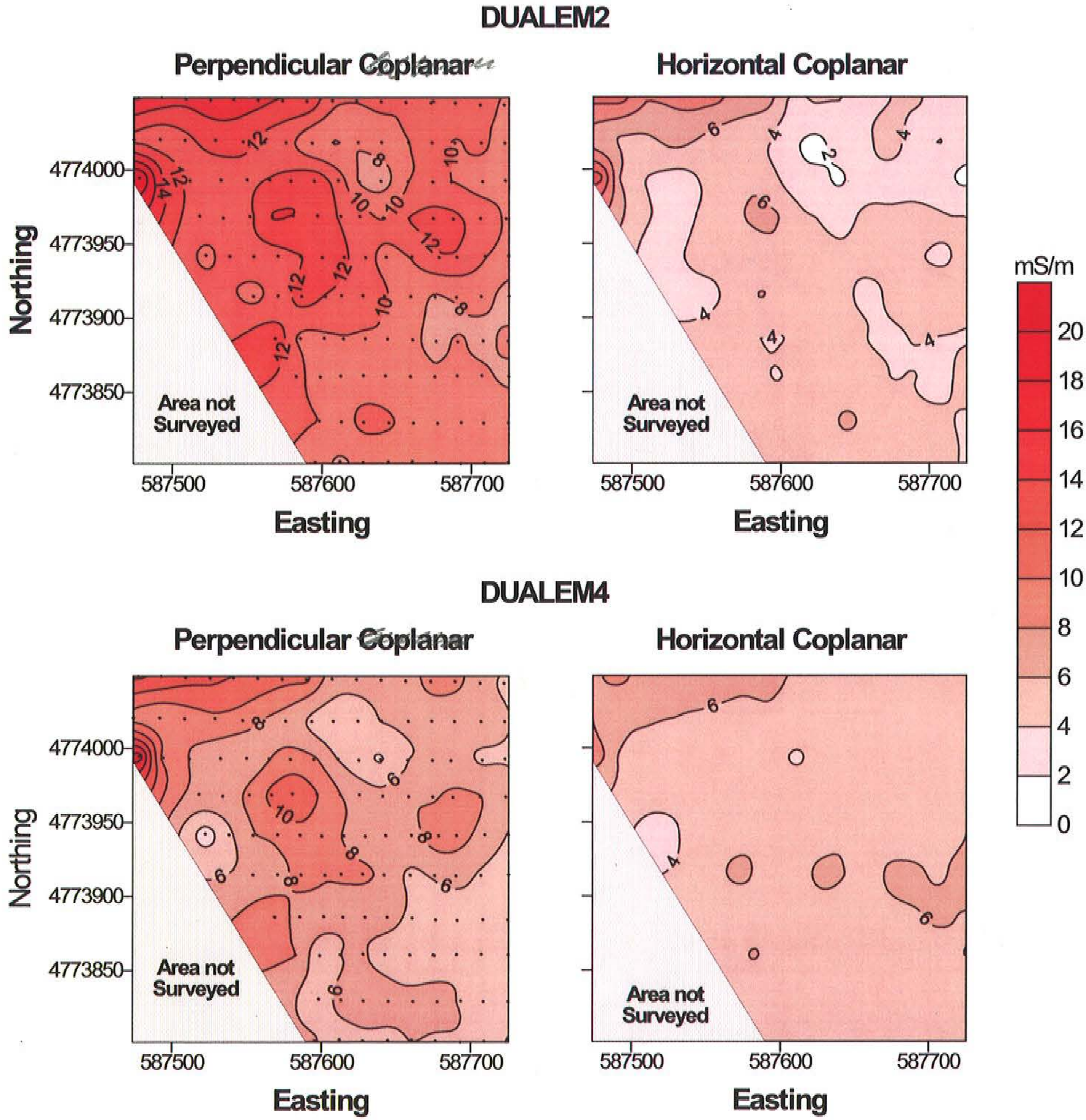

Figure 3

EMI SURVEY
IOWA SITE #1
TOWED EM38 METER & VERIS 3100 SYSTEM

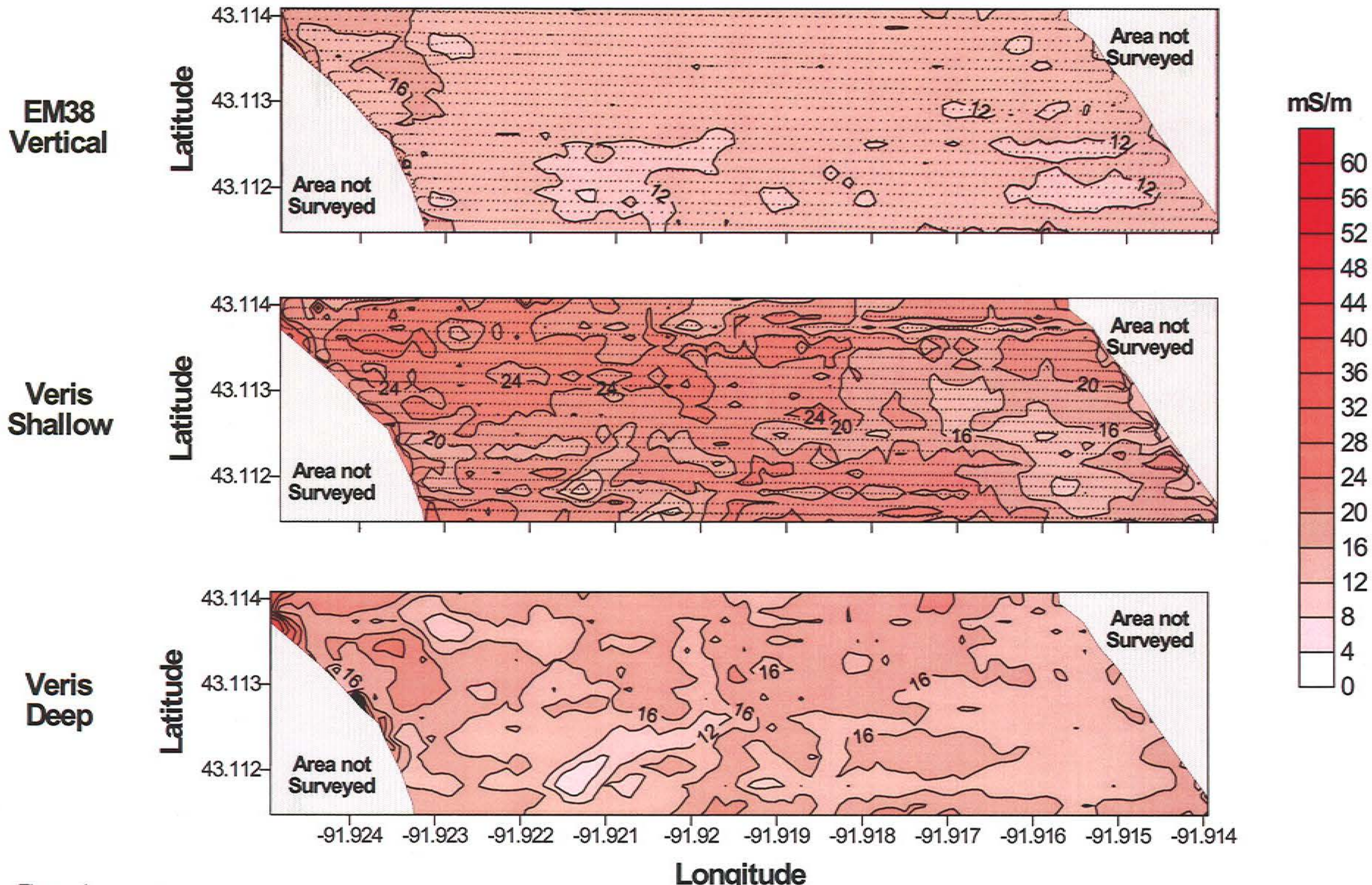

Figure 4

SEM SURVEY
IOWA SITE #1
INTERPRETED DEPTH TO LIMESTONE BEDROCK

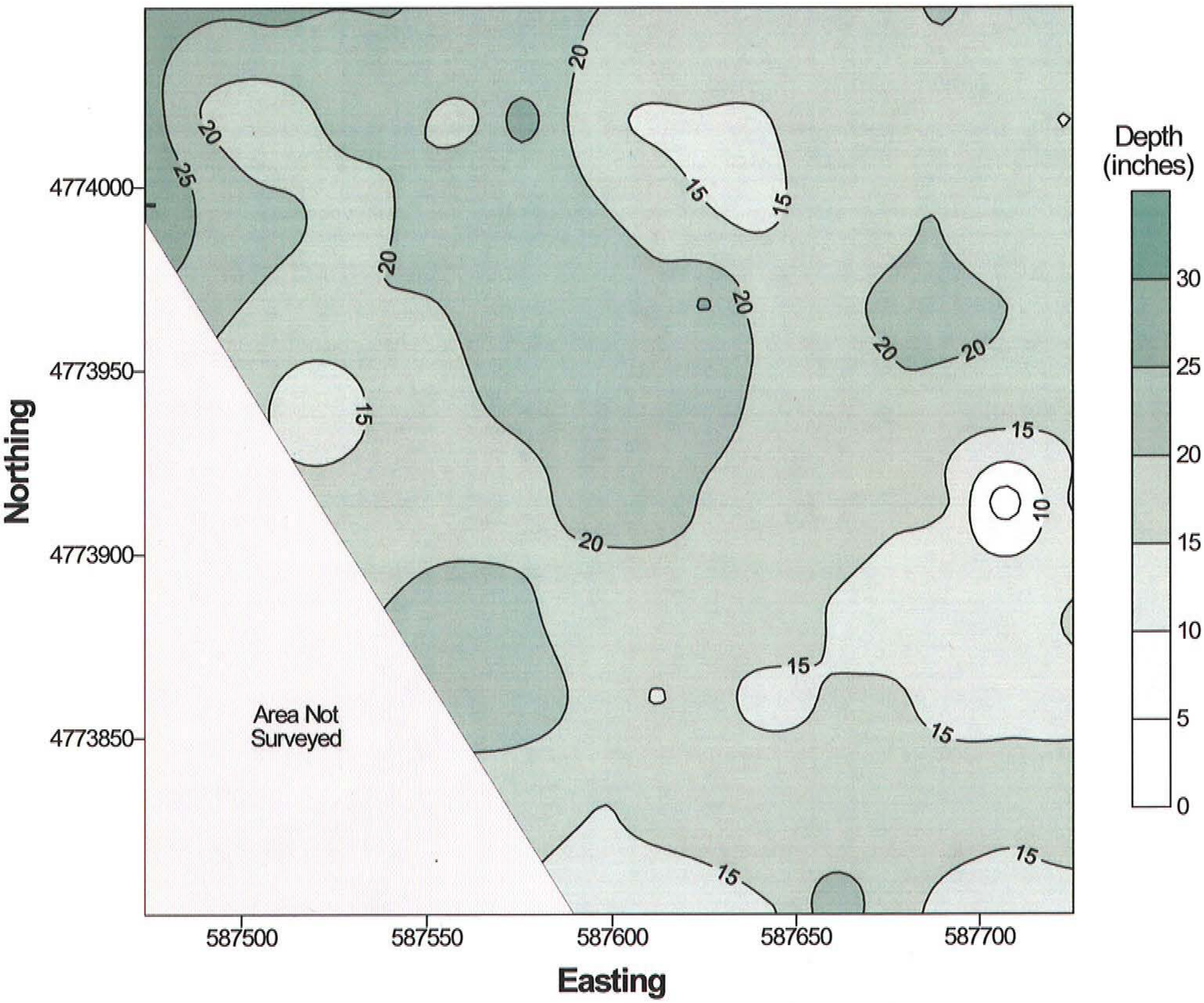

Figure 5

EMI SURVEY
SITE #2
EM31 METER

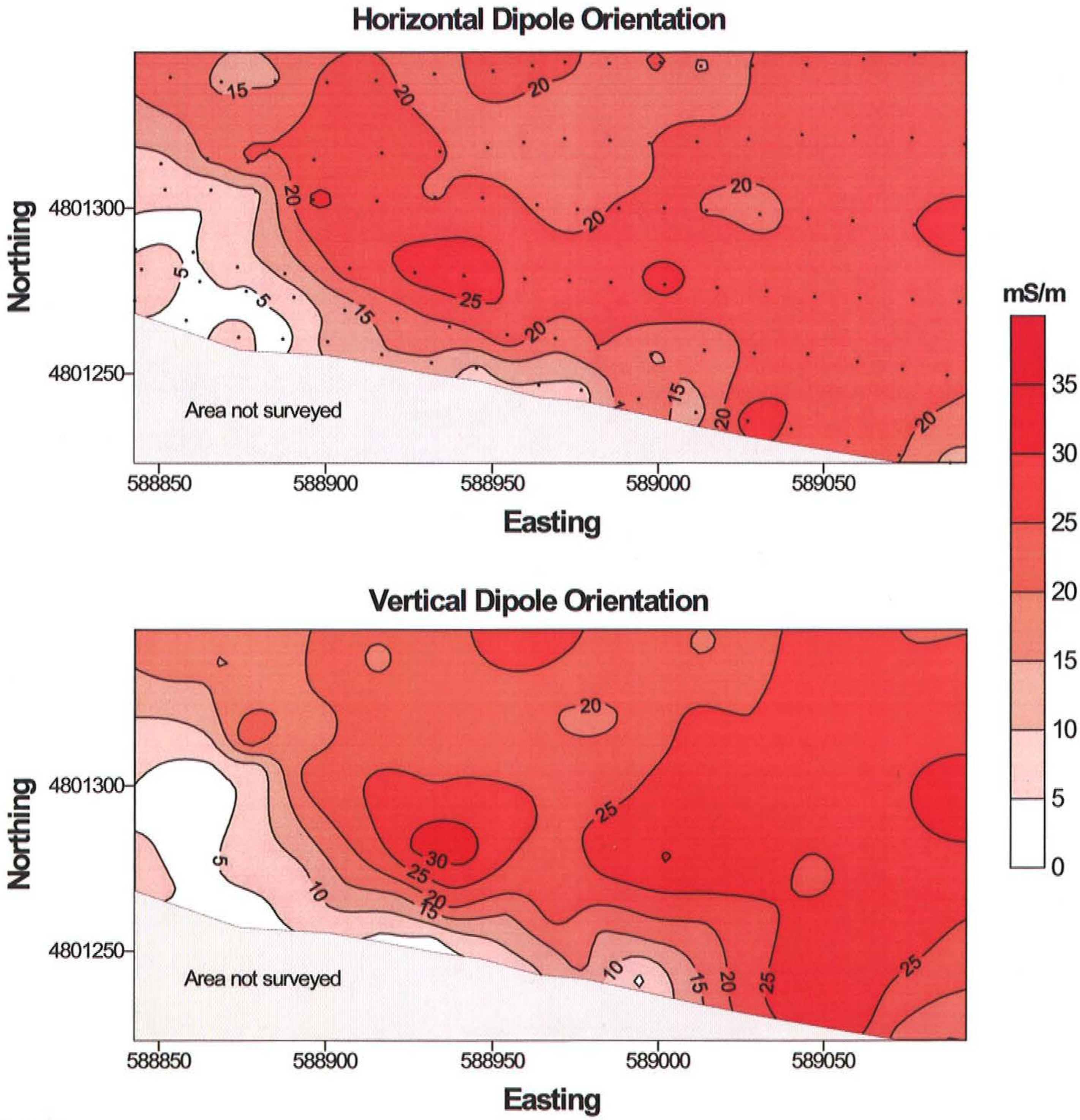

Figure 6

EMI SURVEY
SITE #2
EM38 METER

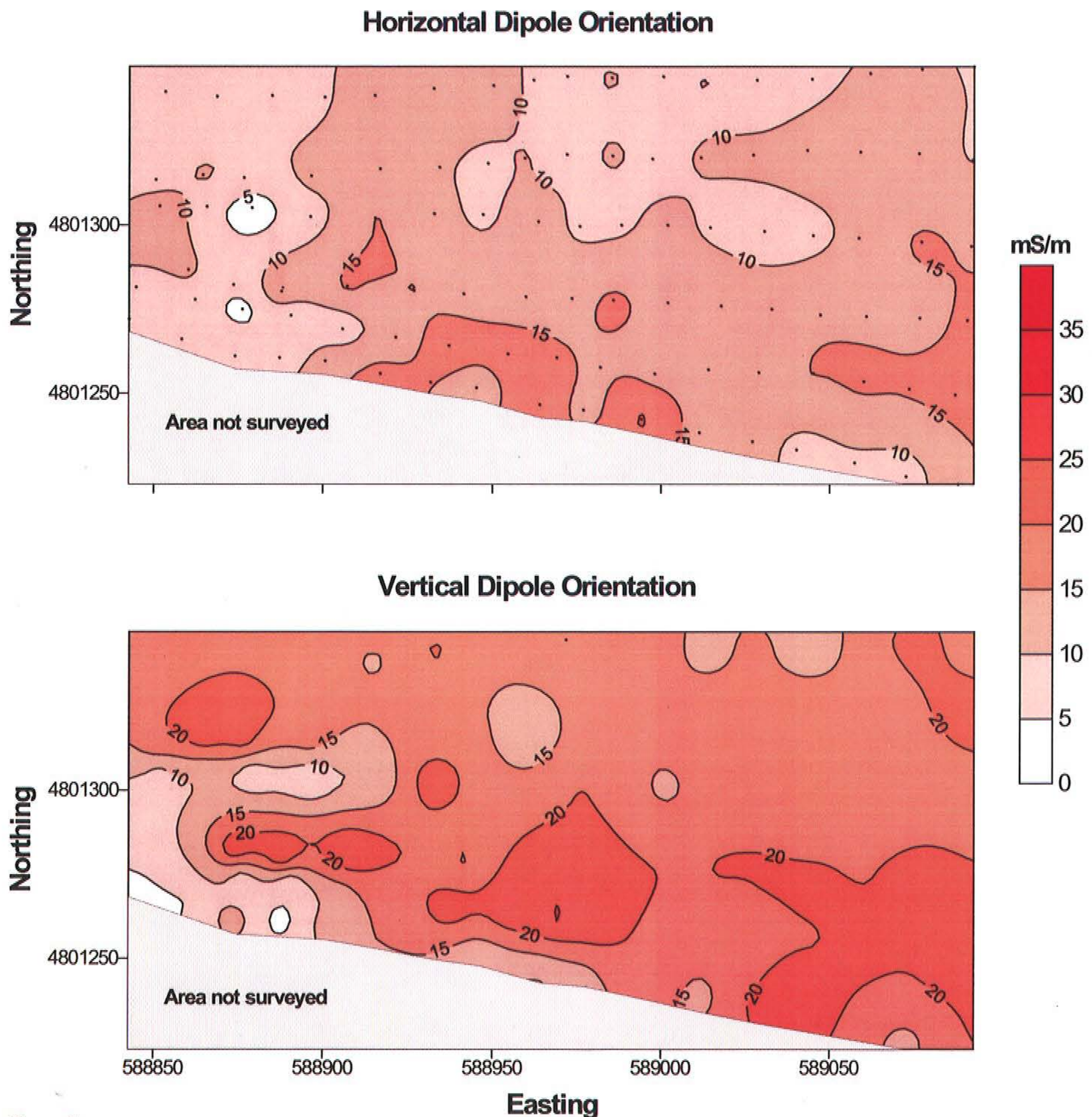

Figure 7

EMI SURVEY
SITE #2
GEM300 SENSOR

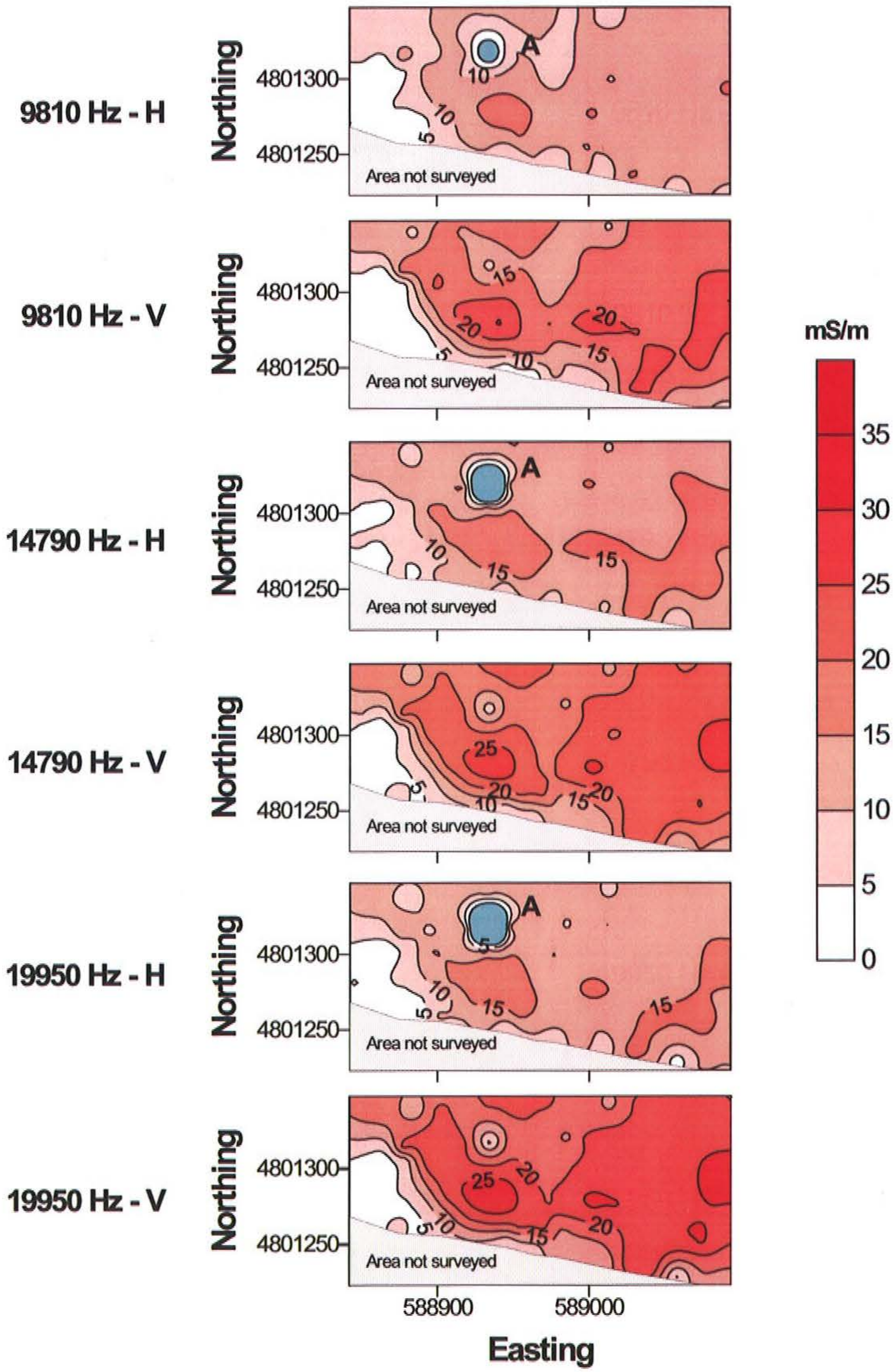

Figure 8

EMI SURVEY
SITE 2
DUALEM

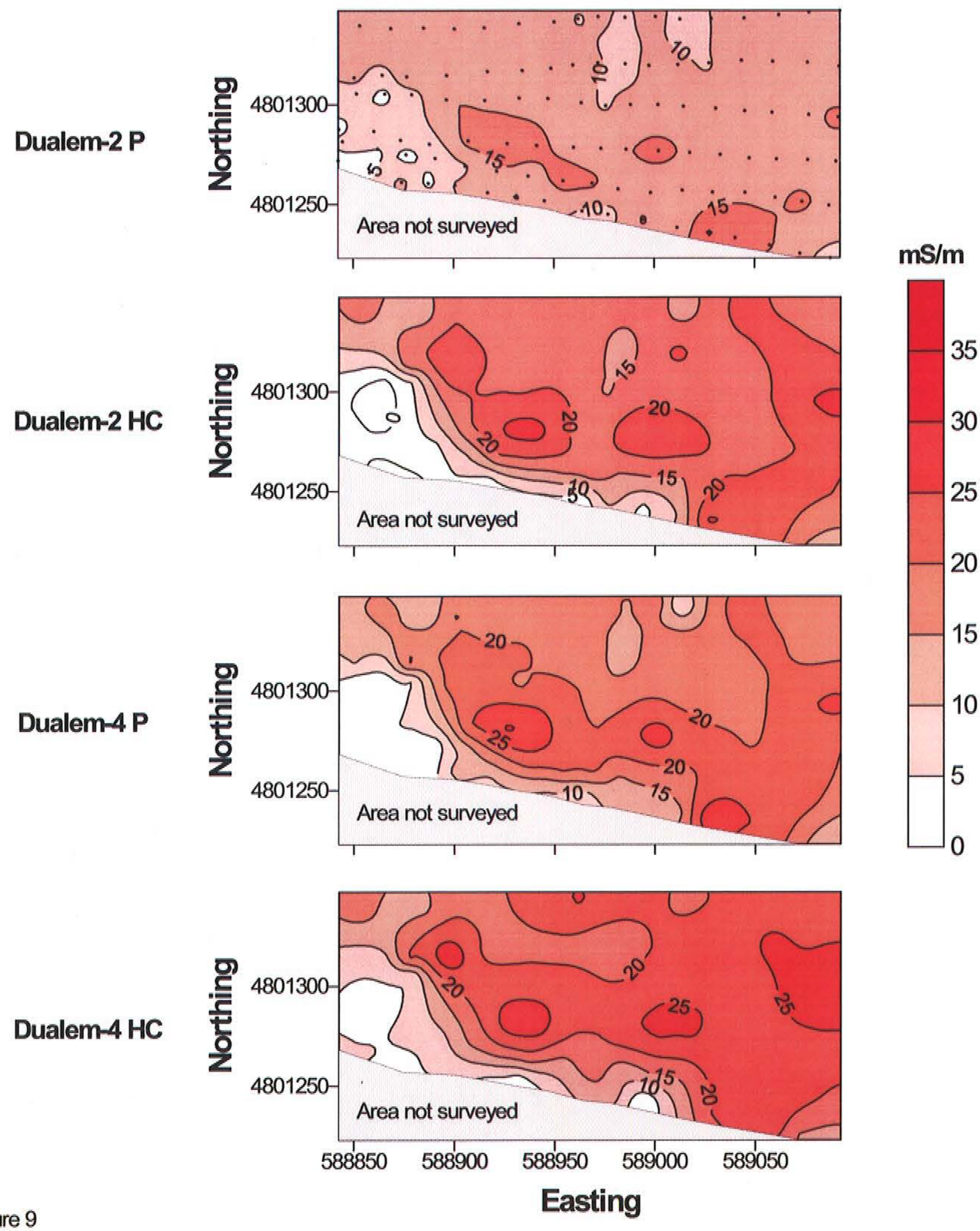

Figure 9

EMI SURVEY
SITE #2
TOWED EM38 METER & VERIS 3100 SYSTEM

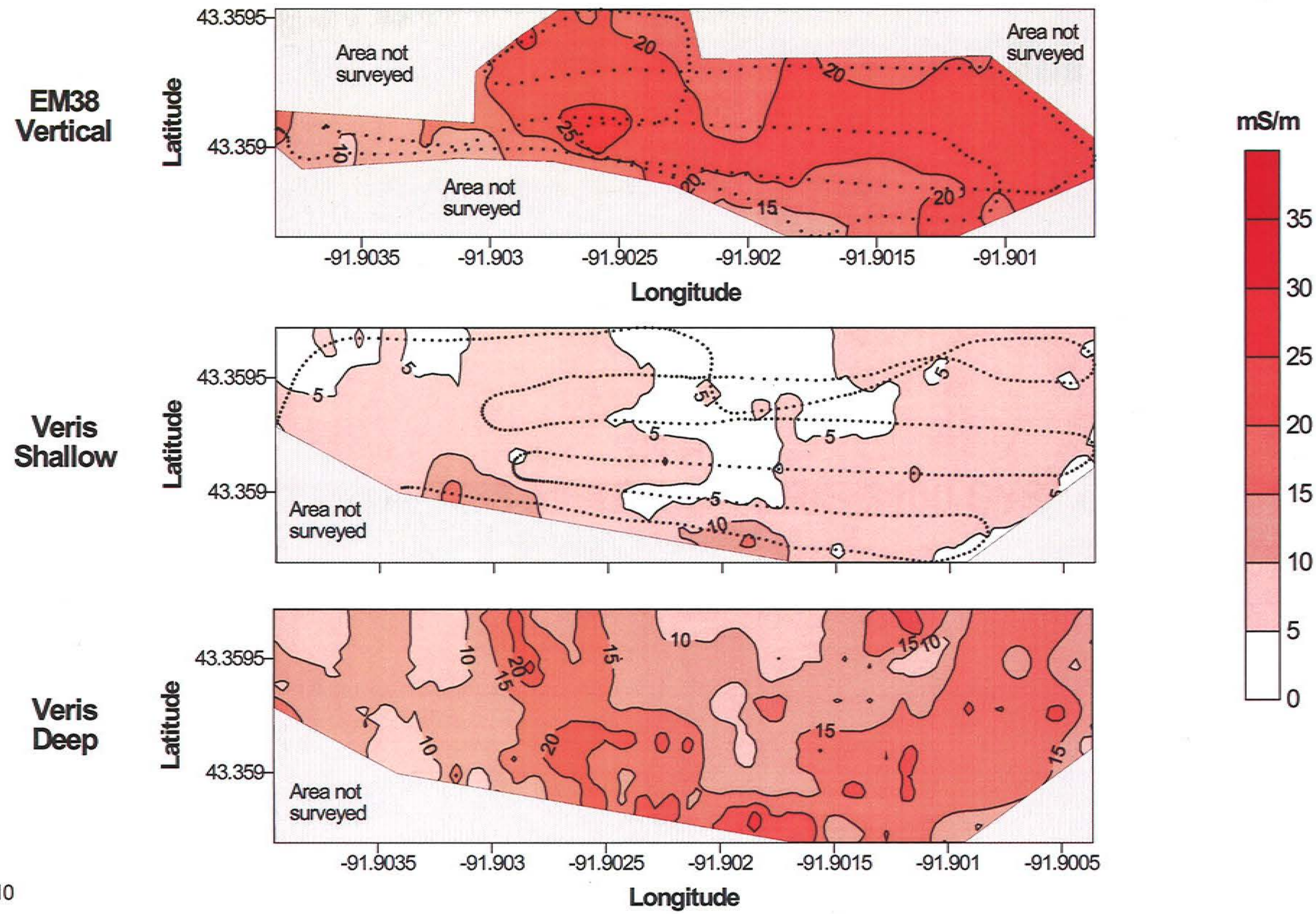

Figure 10

EMI SURVEY
SITE #3
EM31 METER

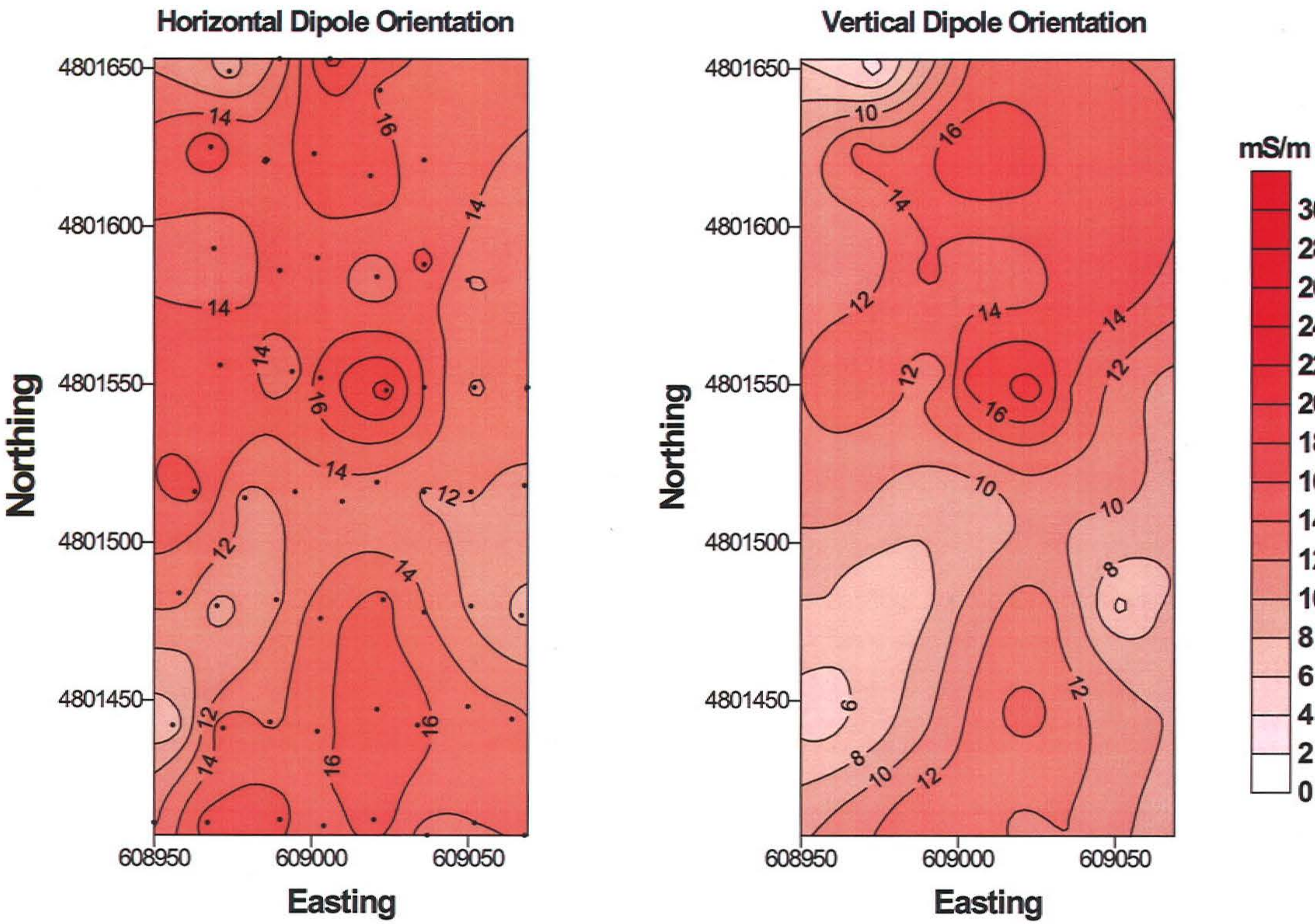

Figure 11

EMI SURVEY
SITE #3
EM38 METER

12

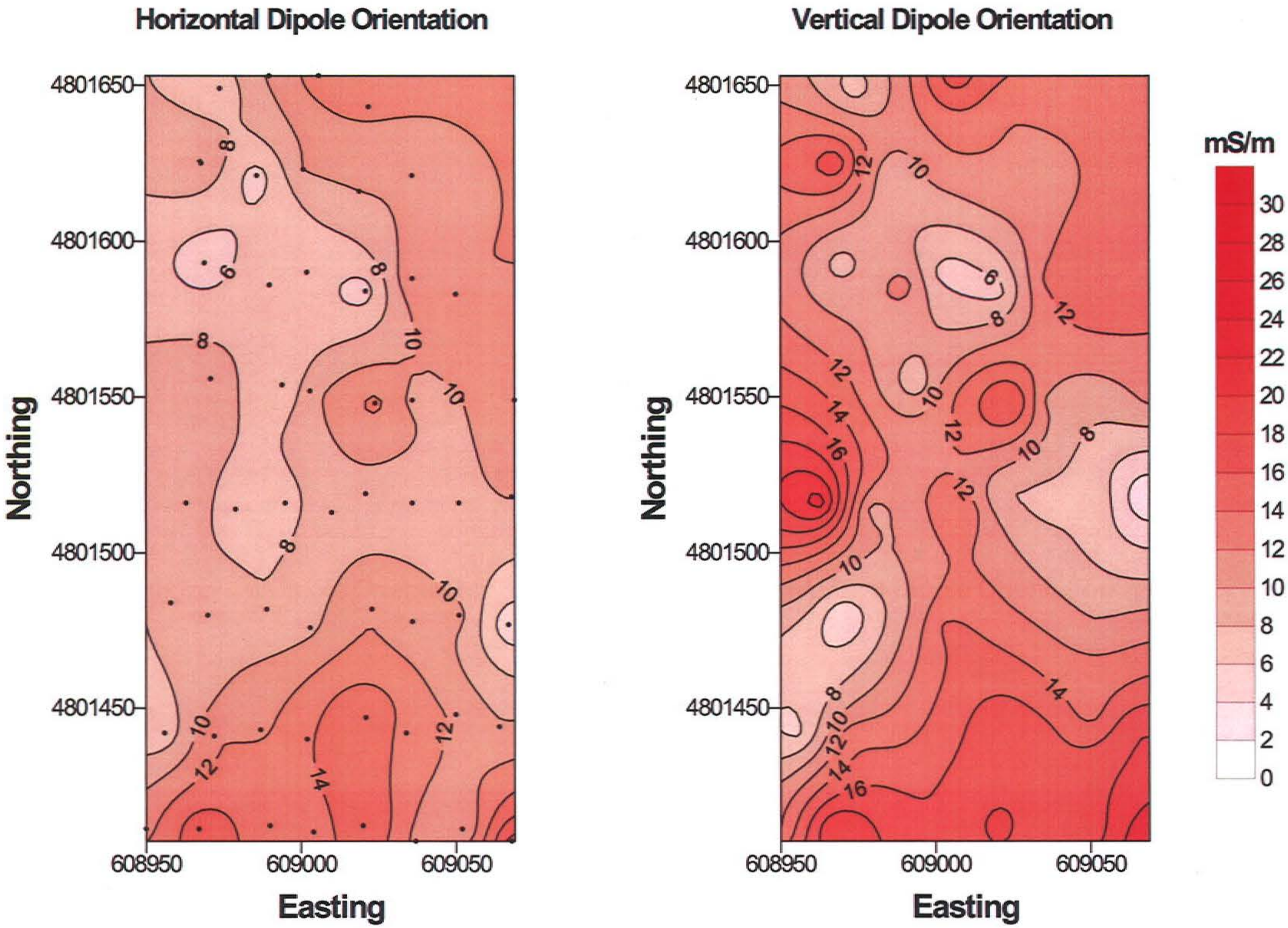

Figure 12

13

EMI SURVEY
SITE #3
GEM300 SENSOR

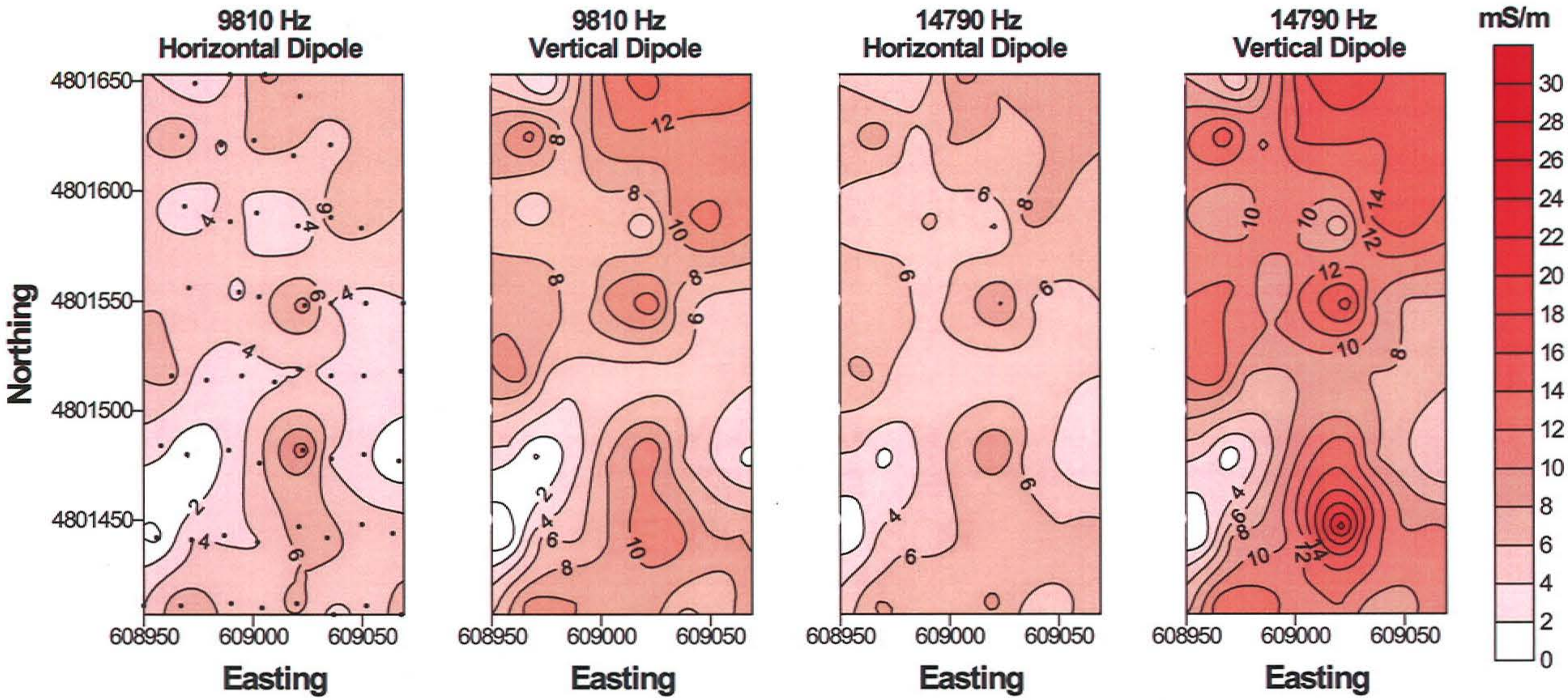

Figure 13

EMI SURVEY
SITE #3
DUALEM-2 & -4

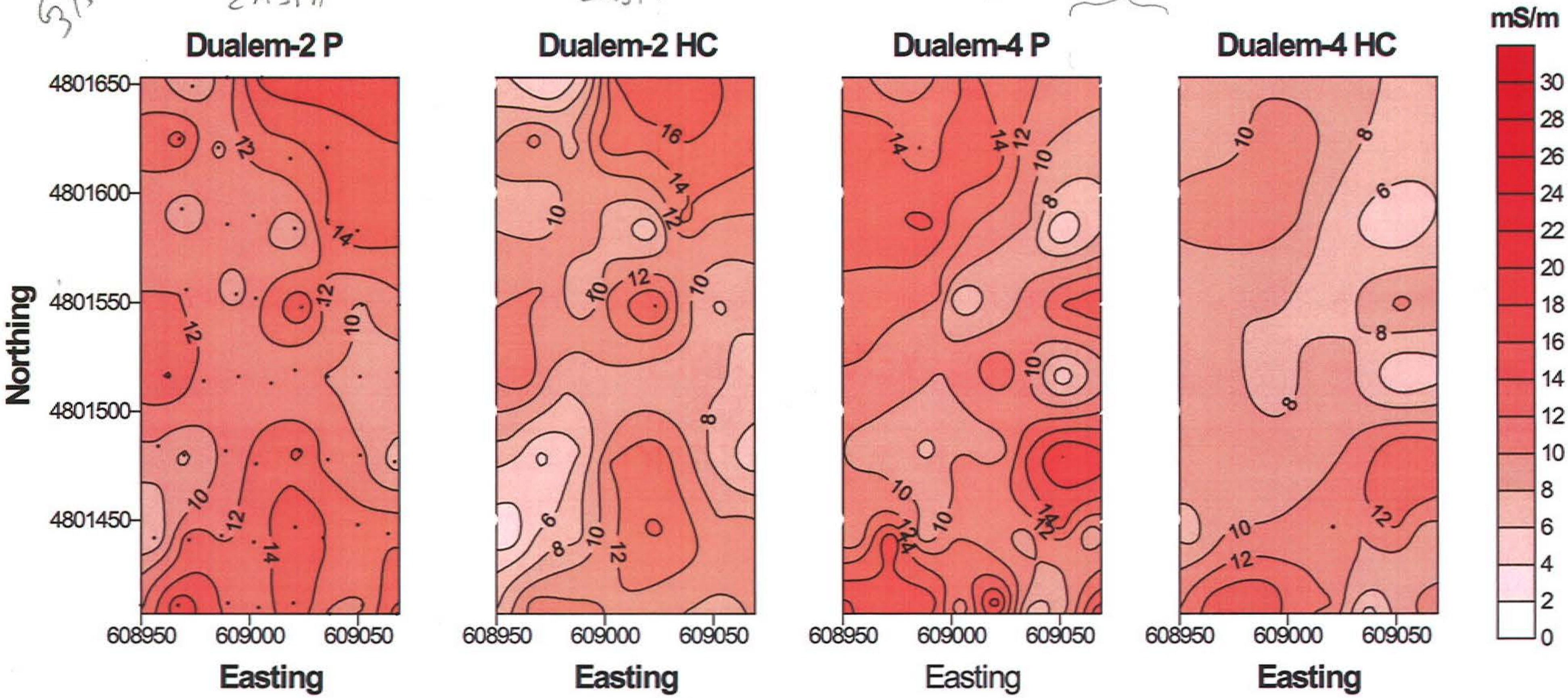

Figure 14

15

Shallow 23.5
Deep 35.3

EMI SURVEY
SITE #3
VERIS 3100 SYSTEM