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

Subject: -- Geophysical Assistance -- **Date:** 16 May 2000

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Purpose:
The purpose of this investigation was to evaluate the suitability of using electromagnetic induction (EMI) and towed array resistivity methods to help assist soil survey updates and assess soil properties within Winneshiek County, Iowa. In addition, training and practical exposure to five different geophysical tools and survey platforms was provided to soil scientists.

Participants:
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Activities:
All field activities were completed during the period of 1 to 5 May 2000.

Results:
1. Soil scientists from four states participated in this unique study. Never before had 5 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 survey investigations. The participation and efforts of Illinois's "Veris Cadre" added immensely to the success of this study and is deeply appreciated by all.

2. Electrical resistivity and electromagnetic induction methods can be used to create detailed maps showing the spatial distribution of apparent conductivity within soil map units and across units of management. Values of apparent conductivity are seldom diagnostic in themselves, but lateral and vertical variations in these measurements can be used to infer changes in soils and soil properties. Interpretations are based on the identification of spatial patterns within data sets and knowledge of soil parameters. At each site, variations in apparent conductivity were associated with changes in soil moisture and clay contents and soil depth. Patterns of apparent conductivity were visually correlated with soil patterns.

3. Results from different instruments produce do not produce identical results. Differences in measured values and spatial patterns of apparent conductivity are attributed to differences in the frequency, depth of observation, and depth-response functions of the instruments, as well as variations in soil and stratigraphic profiles. Differences in sampling intensity and survey design also affect results.

4. The use of these geophysical tools should be more fully understood and explored by soil scientists and conservationists within this region. To help fulfill this need, an EM31 meter (serial # 9315002; AG0002518477) has been loaned to the Iowa NRCS staff for a period of six months.

5. A dilemma for field soil scientists using these methods will be to understand what these methods do and do not tell us. Soil scientist and conservationists will need to relate soils and soil properties to the spatial patterns appearing on computer graphic simulations, select meaningful isoline intervals on computer simulations, and understand the limitations of these methods.

6. 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.

7. This study provided new information on the sensitivity of the Veris 3100 soil EC mapping system to traffic pans.

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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A New Generation of Soil Mapping Tools:
In a recent article in a popular farm magazine, a sales agronomist states, "Soil EC [electrical conductivity] readings are light years ahead of the soil survey manuals" (Olson, 2000). The agronomist proceeded to note, "The data [EC] gives us a better way to draw in soil boundaries and create management zones by soil types." Later in the article, a precision farming agronomist lauds the use of promising geophysical tools and notes, "Soil EC defines soil differences much better than a soil survey map." Unfortunately, soil EC maps do not define anything they merely show spatial patterns of apparent conductivity. Regrettably, the glitter of new technology often overshadows the required knowledge needed by the interpreter of soils. In the hands of an uninformed user, interpretations and results can be misleading or incorrect.

Precision farming has created a need for more intensive soil surveys and the acceptance of emerging technologies. In recent years, the use of electromagnetic induction (EMI) has increased rapidly. With precision farming, our soil surveys seem to have come under attack. Many involved in these high intensity surveys have overlooked the merits, scales, and design of the soil survey. Some, as those in the referenced article, have unwittingly inflated the strengths while overlooking some of the weaknesses of EMI. Electromagnetic induction is merely a method to help us understand and appraise the variability of some soils and soil properties. Electromagnetic induction is an imperfect tool and does not work equally well in all soils. Results are interpretative and depend on the knowledge of the operator as well as on the physical and chemical properties of soils and their variability across landscapes. Goals of the National Soil Survey Center and the "Veris Cadre" from Illinois are to evaluate innovative geophysical devices, learn their strengths and weaknesses, educate others on their use and interpretations, and develop protocol for field use within NRCS.

Continuous profiling resistivity units, EMI meters and sensors are geophysical tools that are being used for high intensity soil surveys and precision farming initiatives. Sorensen (1994) and Lund and Christy (1998) describe a towed, multi-electrode resistivity unit. The Veris 3100 soil EC mapping system is a towed array, continuous profiling, electrical resistivity unit that injects electrical currents into the soils through coulter-electrodes. With electrical resistivity, current is directly injected into the soil through current electrodes and the potential difference in current flow is measured between the potential electrodes. Profiling is accomplished through an arrangement of electrodes referred to as an "array." Electrical resistivity requires the electrodes to be well grounded in the soil. Poor ground contact can result in erroneous data (negative values). Poor ground contact can be experienced in dry, coarse-textured, fragmental, and frozen soils, or soils having a large cover of plant residue. Compared with EMI, resistivity methods provide better depth resolution and are less susceptible to interference from cultural sources (buildings, fences, utility lines). However, thin layers located near the electrodes can disproportionately influence responses and cause significant errors in measurements (McNeill, 1980).

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). A transmitter produces a magnetic field that induces current to flow through the subsurface. This flow of current sets up a secondary magnetic field in the soil. By comparing the difference in the magnitude and phase of these magnetic fields, the device measures the apparent conductivity of the profiled materials. No ground contact is needed with EMI. Compared with resistivity methods, EMI is noninvasive and data acquisition is generally faster.

Equipment:
A Veris 3100 soil EC mapping system was used in this study. The Veris 3100 implement is a towed, multi-electrode resistivity unit manufactured by Veris Technologies.[1] Operating procedures are described by Veris Technologies (1998). The Veris 3100 implement 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 observation: one for the upper 0 to 30 cm and one for the upper 0 to 90 cm of the soil. The depth of observation is "geometry limited" and is dependent upon the spacing and type of electrode array. The Veris 3100 implement 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 0 to 30 cm depth interval. The Veris EC implement 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 implement.[1]

The electromagnetic induction meters used in this study were the EM38 and the EM31 manufactured by Geonics Limited.[1] These meters are portable and require only one person to operate. McNeill (1980) and Geonics Limited (1998) have described principles of operation for the EM31 and the EM38 meters, respectively. No ground contact is required with these meters. The depth of observation is "geometry limited" and is dependent upon the intercoil spacing, coil orientation, and frequency. Lateral

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

resolution is approximately equal to the intercoil spacing. The EM38 meter has a 1 m intercoil spacing and operates at a frequency of 14,600 Hz. It has theoretical observation depths of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively (Geonics Limited, 1998). The EM31 meter has a 3.66 m intercoil spacing and operates at a frequency of 9,810 Hz. It has theoretical observation depths of about 3.0 and 6.0 meters in the horizontal and vertical dipole orientations, respectively (McNeill, 1980). Values of apparent conductivity are expressed in milliSiemens per meter (mS/m).

Dr Tom Fenton brought and operated Iowa State University's towed EM38 meter platform.

A GEM300 multifrequency sensor, developed by Geophysical Survey Systems, Inc., [2] was also used in this study. This sensor is configured to simultaneously measure up to 16 frequencies between 330 and 19,950 Hz with a fixed coil separation (1.6 m). Won and others (1996) have described the use and operation of this sensor. With the GEM300 sensor, the depth of observation is considered "skin depth limited" rather than "geometry limited". The skin-depth represents the maximum depth of observation and is frequency and soil dependent: low frequency signals travel farther through conductive mediums than high frequency signal. The theoretical observation depth of the GEM300 sensor is dependent upon the bulk conductivity of the profiled earthen material(s) and the operating frequency. Multifrequency sounding with the GEM300 allows multiple depths to be profiled with one pass of the sensor.

The positions of observation points for the EM38 and EM31 meters, and the GEM300 sensor were obtained with Rockwell Precision Lightweight GPS Receivers (PLGR).[2] The 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.,[2] was used to construct two-dimensional simulations. Grids were created using kriging methods with an octant search.

Field Procedures:

Survey grids were established at each site. The grid interval was about 30 meters. Survey flags were inserted at each grid intersection and served as observation points. The coordinates of each observation point were determined with GPS.

The Veris 3100 implement and ISU's EM38 meter platform were towed behind a vehicle along parallel sets of grid lines. Measurements were continuously recorded and geo-referenced with Trimble GPS receivers. As measurements were obtained in both the horizontal and vertical dipole orientations and precise positioning of instruments were required, the EM38 meter, EM31 meter, and GEM300 sensors were operated in a station-to-station rather than a continuous mode. Apparent conductivity measurements were recorded at each observation point with an EM38 meter placed on the ground surface in both the horizontal and vertical dipole orientations. To remove residual signals arising from magnetic susceptibility, the EM38 meter was re-nulled before each measurement (Geonics Limited, 1998). At the first study site, measurements were taken with EM31 meter held at hip-height in both the horizontal and vertical dipole orientations. At the other study sites measurements were taken with the EM31 meter placed on the ground surface in both the horizontal and vertical dipole orientations. Measurements were taken with the GEM300 sensor held at hip-height in both the horizontal and vertical dipole orientations.

Interpretation of Data:

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 increases in soluble salts, water, and clay contents (Kachanoski et al., 1988; Rhoades et al., 1976).

Interpretations of EMI or resistivity 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.

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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.

Discussion:

Site #1

The study site was located in the northwest quarter of Section 27, Township 96 N, Range 10 W, near the town of Jackson Junction. The field was in pasture. The site is in a mapped area of Ostrander loam, 2 to 5 percent slopes; Bassett loam, 5 to 9 percent slopes moderately eroded; and Clyde silt loam, 0 to 4 percent slopes (Kittleson and Dideriksen, 1968). The deep, well-drained Ostrander and the moderately well drained Bassett soil formed in loamy sediments overlying loam glacial till. The Ostrander soil is a member of the fine-loamy, mixed, mesic Typic Hapludolls family. The Bassett soil is a member of the fine-loamy, mixed, mesic Mollic Hapludalfs family. The deep, poorly and very poorly drained Clyde soils formed in loamy glacial outwash and erosional sediments overlying loam glacial till. The Clyde soil is a member of the fine-loamy, mixed, mesic Typic Haplaquolls family.

Figure 1 shows the spatial distribution of apparent conductivity collected with the Veris 3100 soil EC mapping system. The spatial distributions of apparent conductivity within the upper 30 (upper plot) and 90 (lower plot) cm of the soil are shown in the upper and lower plots, respectively. In each plot, the isoline interval is 4 mS/m. The track and the locations of observation points for the Veris 3100 implement are shown in the upper plot. Moving across the field at speeds of about 5 mph, the Veris 3100 implement recorded 1077 observation points in a very short time. An observation (two apparent conductivity measurements with coordinates) is recorded every second. By varying the speed of advance, the number and density of observation points can be varied. Variations in the speed of advance across the field are evident by the spacing of observation points in Figure 1 (note the turn areas at the end of each traverse line).

A general comparison of the two plots shown in Figure 1 reveals that apparent conductivity increased with increasing soil depth. This vertical trend is attributed to increased clay and moisture contents with increasing soil depths. Basic statistics for the Veris data are listed in Table 1. Within Site 1, for the upper 0 to 30 cm of the soil, apparent conductivity averaged 8.3 mS/m with a range of –25.0 to 26.0 mS/m. Half of the observation points had values of apparent conductivity between 5.8 and 10.1 mS/m. For the upper 0 to 90 cm of the soil, apparent conductivity averaged 19.9 mS/m with a range of –27.0 to 60.9 mS/m. Half of the observation points had values of apparent conductivity between 12.1 and 26.1 mS/m. Negative values are attributed poor ground contact of coulter-electrodes.

Table 1
Basic Statistics
Veris 3100 Survey
Study Site #1
(All values are in mS/m)

	Shallow	Deep
AVERAGE	8.29	19.91
MINIMUM	-25.00	-27.00
MAXIMUM	26.00	60.90
FIRST	5.80	12.10
MEDIAN	7.40	18.20
THIRD	10.10	26.10

Based on seven soil observations, the spatial patterns evident in Figure 1 are believed to principally reflect differences in moisture and clay contents and correspond with changes in soil types. Areas of higher conductivity closely mimic patterns of included soils (Clyde) associated with lower-lying, intermittent drainageways that extend into the survey area from the north. In the western part of the survey area, areas of higher conductivity correspond to areas of Bassett soils. Areas of lower conductivity correspond with higher-lying, better drained, convex surfaces that extend in a northwest direction across the site.

In the extreme southeastern corner of the site, an area of exceptionally low (<4 mS/m) conductivity corresponds to an included area of coarser textured soil (Flagler till substratum).

Figures 2, 3, and 4 show the results of the survey conducted with the GEM300 sensor. In each figure, measurements of apparent conductivity obtained in the horizontal and vertical dipole orientations are shown in the upper and lower plots, respectively. The isoline interval is 4 mS/m. In each Figure, the locations of the 102 observation points recorded with the GEM300 sensor are shown in the upper plot.

At Site 1, three frequencies were selected on the GEM300 sensor. These frequencies were: 6030 (Figure 2), 9810 (Figure 3), and 14610 (Figure 2) Hz. The depth of observation or the "skin depth" can be estimated with the following formula given by McNeill (1996):

$$D = 500/(s*f)^{-2} \qquad [1]$$

Where s is the ground conductivity (mS/m) and f is the frequency (kHz). At Site 1, with the GEM300 sensor held at hip height in the vertical dipole orientation, apparent conductivity averaged 26.15, 27.60, and 30.15 mS/m at frequencies of 6030, 9810, and 14610 Hz, respectively. Based on equation [1], the selected frequencies and these averaged conductivities, the estimated skin depths (observation depths) were 39.8 m at 6030 Hz, 30.4 m at 9,810 Hz, and 23.8 m at 14,610 Hz. With the frequencies used in this survey, the GEM300 sensor profiled greater depths than the other devices. However, these depths are hypothetical and unconfirmed by field research. While the induced magnetic fields may achieve these depths, the strengths of the response from these depths are probably too weak to be sensed by the GEM300. As no depth-weighting functions are presently available for the GEM300 sensor, it is unclear what feature(s) or depth is providing the observed response.

Although no depth-weighting functions are available for the GEM300, 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. At each frequency, measurements obtained in the vertical dipole orientation were generally higher than those obtained in the horizontal dipole orientation. This indicates the presence of a more conductive layer in the subsurface than near the surface. However, apparent conductivity decreased with increasing observation depths (lower frequency). This trend suggests that with increasing observation depths the materials become more resistive.

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

	Frequency (Hz)					
	6030H	**6030V**	**9810H**	**9810V**	**14610H**	**14610V**
AVERAGE	23.68	26.15	24.93	27.60	27.58	30.15
MINIMUM	5.01	12.90	7.23	14.53	9.26	17.57
MAXIMUM	48.48	68.72	51.16	57.32	54.70	52.36
FIRST	14.51	19.18	14.86	21.20	17.40	24.25
MEDIAN	20.18	24.33	19.71	26.40	22.30	29.43
THIRD	34.45	31.75	36.40	36.62	30.04	35.02

Table 2 summarizes the GEM300 data collected at Site 1. At each frequency, measurements taken in the deeper sensing vertical dipole orientation were higher than those obtained in the shallower horizontal dipole orientation. With a frequency of 6030 Hz, apparent conductivity ranged from about 5.0 to 48.5 mS/m in the horizontal dipole orientation and from about 12.9 to 68.7 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observation points had values of apparent conductivity between 14.5 and 34.4 mS/m. In the vertical dipole orientation, half of the observation points had values of apparent conductivity between 19.2 and 31.8 mS/m. With a frequency of 9810 Hz, apparent conductivity ranged from 7.2 to 51.2 mS/m in the horizontal dipole orientation and from 14.5 to 57.3 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observation points had values of apparent conductivity between 14.9 and 36.4 mS/m. In the vertical dipole orientation, half of the observation points had values of apparent conductivity between 21.2 and 36.6 mS/m. With a frequency of 14610 Hz, apparent conductivity ranged from 9.3 to 54.7 mS/m in the horizontal dipole orientation and from 17.6 to 52.4 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observation points had values of apparent conductivity between 17.4 and 30.0 mS/m. In the vertical dipole orientation, half of the observation points had values of apparent conductivity between 24.2 and 35.0 mS/m.

At this site, spatial patterns obtained with the GEM300 sensor did not mimic soil patterns. Spatial patterns evident in figures 2, 3, and 4 do not reflect soil or topographic patterns observed in the field. The spatial patterns evident in these figures are believed to principally reflect differences in the underlying lithology. Similar spatial patterns were obtained for each frequency. The most conspicuous variation in spatial patterns occurs with changes in the dipole orientation rather than with changes in frequency.

Figure 5 shows the results of the survey conducted with the EM38 meter. In this figure, measurements of apparent conductivity obtained in the horizontal and vertical dipole orientations are shown in the upper and lower plots, respectively. The locations of the 102 observation points recorded with the EM38 meter are shown in the upper plot. The isoline interval is 4 mS/m.

Table 3 summarizes the apparent conductivity measurements collected with the EM38 and EM31 meters at Site 1. The apparent conductivity of the upper 0.75 meter (measured with the EM38 meter in the horizontal dipole orientation) averaged 14.9 mS/m with a range of 5.0 to 30.6 mS/m. Half of the observations had values of apparent conductivity between 11.2 and 17.7 mS/m. The apparent conductivity of the upper 1.5 meters (measured with the EM38 meter in the vertical dipole orientation) averaged 20.4 mS/m with a range of 7.4 to 37.7 mS/m. Half of the observations had values of apparent conductivity between 16.0 and 24.1 mS/m.

Table 3
Basic Statistics
Geonic Limited Meters
Study Site #1
(All values are in mS/m)

	AVERAGE	MINIMUM	MAXIMUM	FIRST	MEDIAN	THIRD
EM38H	14.91	5.0	30.6	11.2	14.5	17.7
EM38V	20.37	7.4	37.7	16.0	20.5	24.1
EM31H	17.96	10.5	28.8	15.8	18.1	20.1
EM31V	28.18	18.5	34.4	26.1	28.8	30.6

Spatial patterns in both plots (Figure 5) mimic soil and topographic patterns and are believed to principally reflect differences in clay and moisture contents and changes in soil types. Areas of Clyde soils have higher conductivity than areas of Bassett or Ostrander soils. Measurements and spatial patterns obtained with the EM38 meter in the vertical dipole orientation were similar to the "deep" measurements obtained with the Veris 3100 system.

Figure 6 shows the results of the survey conducted with the EM31 meter. In this figure, measurements of apparent conductivity obtained in the horizontal and vertical dipole orientations are shown in the upper and lower plots, respectively. The locations of the 102 observation points recorded with the EM31 meter are shown in the upper plot. In Figure 6, the isoline interval is 4 mS/m.

For this survey, the EM31 meter was operated at hip-height (90 cm). The apparent conductivity of the upper 3 meters (measured with the EM31 meter in the horizontal dipole orientation and including the air column beneath the meter) averaged 18.0 mS/m with a range of 10.5 to 28.8 mS/m. Half of the observations had values of apparent conductivity between 15.8 and 20.1 mS/m. The apparent conductivity of the upper 6 meters (measured with the EM31 meter in the vertical dipole orientation and including the air column beneath the meter) averaged 28.2 mS/m with a range of 18.5 to 34.4 mS/m. Half of the observations had values of apparent conductivity between 26.1 and 30.6 mS/m.

Measurements and spatial patterns obtained with the EM31 meter did not conform to observed soil and topographic features. Isolines were aligned in a more east-to-west orientation similar to patterns observed with the GEM300 sensor. It is believed that the EM31 was more sensitive to changes in the underlying strata or lithology than to variations in soil properties.

At Site 1, data obtained with the GEM300 sensor, though comparable, were slightly higher and more variable than those collected with the Veris 3100 soil EC mapping system, EM38 and EM31 meters. The dissimilarity in apparent conductivity measured among these devices is attributed to differences in system calibration by manufacturers, intercoil and electrode spacing, depth and volume of soil profiled, and frequencies. Spatial patterns obtained with the Veris 3100 system and the EM38 meter appear to conform to changes in soil types and topography. Spatial patterns obtained with the deeper-sensing GEM300 sensor and the EM31meter do not appear to mimic observed soil or topographic patterns. These patterns are assumed to reflect underlying stratigraphic or lithologic features.

Site #2

The study site was located in southeast ¼ of Section 34, Township 98 N, Range 9 W. The site was in pasture and had not been recently tilled. A series of north-south orientated trails crossed the site. Along these trails, vehicular traffic had compacted the soil. Various phases of Marlean soils have been mapped within the site. Map units include Marlean loam, 2 to 5 percent slopes; Marlean loam 5 to 9 percent slopes, moderately eroded; and Marlean loam, 9 to 14 percent slopes, moderately eroded (Kittleson and Dideriksen, 1968). The well drained Marlean soil is shallow over residium weathered from limestone bedrock. The overlying sediments are of glacial or eolian origins. Marlean is a member of the loamy-skeletal, mixed, mesic Typic Hapludolls family.

Comparative studies were conducted with the Veris 3100 implement, the GEM300 sensor, and the EM38 and EM31 meters. The observation depth, area coverage, number of observations, and survey times varied with each method. The mobile Veris 3100 implement had the shallowest observation depth, covered the site in the shortest period of time, and collected the largest number of observations (1247). The hand-held GEM300 sensor provided the deepest observation depth and recorded 90 observations in the second fastest time. The hand-held EM38 and EM31meters covered the site at slower speeds.

Figure 7 shows the track and the locations of the 1247 observation points obtained with the Veris 3100 implement within Site 2. In Figure 7, spatial patterns of apparent conductivity within the upper 30 and the upper 90 cm of the soil are shown in the left-hand and right-hand plots, respectively. In each plot, the isoline interval is 5 mS/m. A closer isoline interval (1 to 5 mS/m) would provide more intricate patterns, but would add little to the interpretability of these plots.

Basic statistics for the Veris data collected at Site 2 are listed in Table 4. Apparent conductivity increased and became more variable with increasing soil depth. This vertical trend was attributed to higher conductivity within the underlying residuum that is weathered from limestone bedrock and increased moisture and carbonate contents with increasing soil depths. For the upper 0 to 30 cm of the soil, apparent conductivity averaged 10.8 mS/m with a range of –25.0 to 21.7 mS/m. Negative values are attributed to poor ground contact of coulter-electrodes (caused by rock fragments). When contact is lost, a measurement of about –25 mS/m is typically recorded with the Veris system. Half of the observations had values of apparent conductivity between 8.0 and 13.1 mS/m. For the upper 0 to 90 cm of the soil, apparent conductivity averaged 16.9 mS/m with a range of -27.0 to 63.5 mS/m. Half of the observations had values of apparent conductivity between 11.7 and 21.7 mS/m.

Table 4
Basic Statistics
Veris 3100 Survey
Site #2
(All values are in mS/m)

	Shallow	Deep
AVERAGE	10.8	16.9
MINIMUM	-25.0	-27.0
MAXIMUM	21.7	63.5
FIRST	8.0	11.7
MEDIAN	10.6	16.1
THIRD	13.1	21.7

In Figure 7, several small, anomalous features appear on each plot. These anomalies are aligned in a north-south direction and are confined to the track of the Veris system. Negative values are assumed to indicate poor electrode contact caused by rock fragments or surface debris. Positive values are believed to reflect areas of compacted soil conditions. The effects of soil compaction have not been widely reported with the Veris 3100 system (Eric Lund, Veris Technologies, personal communication, 2000). However, in low conductivity (< 20 mS/m) soils, differences in EMI responses caused by soil compaction can be sufficient to be detectable. Under dry soil conditions and with low conductivity, compaction appears to increase the electrical response of the Veris 3100 implement. The effects of soil compaction were not observed in measurements taken with the EM31and EM31 meters and the GEM300 sensor. However, these instruments were operated in the station-to-station mode and sampling was not as intense as that of the Veris system.

A second survey of the site was conducted in order to more fully evaluate the effects of soil compaction on the response of the Veris implement. This survey was conducted at a closer line spacing with alternate traverses "on" and "off" the trails. The results of the second survey are shown in Figure 8. In Figure 8, the spatial distributions of apparent conductivity within the upper 30 and 90 cm of the soil are shown in the left-hand and right-hand plots, respectively. In each plot, the isoline interval is 5 mS/m. The more intensive sampling has resulted in more intricate patterns. For the shallow measurements (left-hand plot), alternating lines with intermittent high values of soil conductivity bear witness to the instrument's sensitivity of the traffic pan. The effects of this compacted layer are, as should be expected, more distinguishable in the shallower (0 to 30 cm) than in the deeper (0 to 90 cm) measurements.

In the shallow mode, the average conductivity of the 0 to 30 cm layer was 10.8 mS/m. Areas of compacted soil typically had values greater than 25 mS/m and as high as 125 mS/m (about 2 to 12 times higher than background levels). The soils were very dry at the time of this survey. As traffic pans had not been previous observed in studies conducted in Illinois and Missouri, the effects of soil moisture content on the recognition of traffic pans should be evaluated.

Unwanted responses caused by soil compaction (positive values) and rock fragments (negative values), unless removed from data sets can obscure spatial patterns relating to soil and soil properties. As apparent in figures 7 and 8, background noise caused by soil compaction can produce survey design and replication problems. It may be necessary to conduct surveys in two mutually perpendicular directions and compare the plots for each direction.

Figures 9, 10, and 11 show the results of the survey conducted with the GEM300 sensor. In each Figure, the locations of the 90 observation points recorded with the GEM300 sensor are shown in the left-hand plot. The isoline interval is 4 mS/m. For this study site, three frequencies were selected: 9810 (Figure 9), 14610 (Figure 10), and 19950 (Figure 11) Hz. The latter frequency is the highest obtainable with the GEM300 sensor.

With the GEM300 sensor held at hip height in the vertical dipole orientation, apparent conductivity averaged 16.8, 16.4, and 19.2 mS/m at frequencies of 9810, 14610, and 19950 Hz, respectively. Based on equation [1], the selected frequencies and these averaged conductivities, the estimated skin depths (observation depths) were about 38.9 m at 9,810 Hz, 32.3 m at 14,610 Hz and 25.5 m at 19950 Hz. These depths are theoretical and represent maximums. These depths do not account for the sensitivity of the sensor and as no depth-weighting functions are presently available, it is uncertain what layers or depths are actually being distinguished.

Table 5 summarizes the GEM300 data collected at Site 2. In general, conductivity decreased with increasing frequency and depth of observation. As conductivity increased with increasing observation depth with the Veris system, this trend is believed to reflect, in part, the GEM300's deeper depth of observation. This conductivity profile does not suggest the typical Marlean with more resistive loamy sediment overlying more conductive loam, clay loam or sandy clay loam residium weathered from limestone bedrock.

Table 5
Basic Statistics
GEM300 Survey
Study Site #2
(All values are in mS/m)

	Frequency (Hz)					
	9810H	9810V	14610H	14610V	19950H	19950V
AVERAGE	14.4	16.8	17.1	16.4	22.2	19.2
MINIMUM	6.8	4.7	-6.0	8.7	14.0	11.5
MAXIMUM	26.6	28.3	28.2	26.6	34.6	29.5
FIRST	10.7	14.2	13.8	13.6	19.0	16.4
MEDIAN	13.7	16.8	17.1	16.4	22.2	19.1
THIRD	16.6	18.9	20.0	18.3	25.2	22.0

With a frequency of 9810 Hz, apparent conductivity ranged from 6.8 to 26.6 mS/m in the horizontal dipole orientation and from 4.7 to 28.3 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observation points had values of apparent conductivity between 10.7 and 16.6 mS/m. In the vertical dipole orientation, half of the observation points had values of apparent conductivity between 14.2 and 18.9 mS/m. With a frequency of 14610 Hz, apparent conductivity ranged from –6.0 to 28.2 mS/m in the horizontal dipole orientation and from 8.7 to 26.6 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observation points had values of apparent conductivity between 13.8 and 20.0 mS/m. In the vertical dipole orientation, half of the observation points had values of apparent conductivity between 13.6 and 18.3 mS/m. With a frequency of 19950 Hz, apparent conductivity ranged from 14.0 to 34.6 mS/m in the horizontal dipole orientation and from 11.5 to 29.5 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observation points had values of apparent conductivity between 19.0 and 25.2 mS/m. In the vertical dipole orientation, half of the observation points had values of apparent conductivity between 16.4 and 22.0 mS/m.

Spatial patterns evident in figures 9, 10, and 11 appear to mimic soil patterns. However, in the vertical dipole orientation, high values of apparent conductivity adjacent to the eastern (right-hand) border of the study site represents interference caused by metal fence posts and a barbed wire fence. Regardless of frequency, spatial patterns are similar for each dipole orientation. These patterns are believed to reflect differences in clay contents, changes in soil types, and/or depths to limestone bedrock. Higher values of apparent conductivity were obtained on lower-lying, concave surfaces. Lower values of apparent conductivity were obtained on higher-lying, better-drained, convex surfaces.

Figure 12 shows the results of the survey conducted with the EM38 meter. The locations of the 90 observation points at which measurements were obtained with the EM38 meter are shown in the left-hand plot. The isoline interval is 4 mS/m.

Table 6 summarizes the apparent conductivity measurements collected with the EM38 and EM31 meters at Site 2. The apparent conductivity of the upper 0.75 meter (measured with the EM38 meter in the horizontal dipole orientation) averaged 11.0 mS/m with a range of 4.0 to 19.6 mS/m. Half of the observations had values of apparent conductivity between 8.2 and 13.5 mS/m. The apparent conductivity of the upper 1.5 meters (measured with the EM38 meter in the vertical dipole orientation) averaged 10.9 mS/m with a range of 3.6 to 19.2 mS/m. Half of the observations had values of apparent conductivity between 8.7 and 12.4 mS/m.

Table 6
Basic Statistics
Geonic Limited Meters
Study Site #2
(All values are in mS/m)

	AVERAGE	MINIMUM	MAXIMUM	FIRST	MEDIAN	THIRD
EM38H	11.0	4.0	19.6	8.2	10.3	13.5
EM38V	10.9	3.6	19.2	8.7	10.2	12.4
EM31H	13.3	9.0	21.9	11.1	12.7	15.3
EM31V	14.4	9.7	111.7	11.6	12.6	14.3

Figure 13 shows the results of the survey conducted with the EM31 meter. The locations of the 90 observation points at which measurements were obtained with the EM31 meter are shown in the left-hand plot. In Figure 13, the isoline interval is 4 mS/m. The anomalously high values adjacent to the eastern (right-hand) border of the study site reflect interference caused by metal fence posts and a barbed wire fence.

For this survey, measurements were taken with the EM31 meter placed on the ground surface. The apparent conductivity of the upper 3 meters (measured with the EM31 meter in the horizontal dipole orientation) averaged 13.3 mS/m with a range of 9.0 to 21.9 mS/m. Half of the observations had values of apparent conductivity between 11.1 and 15.3 mS/m. The apparent conductivity of the upper 6 meters (measured with the EM31 meter in the vertical dipole orientation) averaged 14.4 mS/m with a range of 9.7 to 111.7 mS/m. Half of the observations had values of apparent conductivity between 11.6 and 14.3 mS/m.

Spatial patterns obtained with the EM31 meter in the horizontal dipole orientation were similar to those obtained with the EM38 meter in the horizontal dipole orientation. However, measurements obtained with the EM31 meter were slightly higher than those obtained with the EM38 meter, suggesting that conductivity increased with increasing depth of observation. Spatial patterns collected with both the EM38 and the EM31 meters were similar to those obtained with the GEM300 system and closely replicate topographic and soil patterns observed in the field. Soil observations were obtained at three observation points within Site 2. Brief profile descriptions of these soils were described. Differences in soil type, depth, and moisture and clay contents were associated with EMI responses.

Figure 14 contains two-dimensional plots showing the distribution of apparent conductivity collected with the EM38 meter overlaid on two, three-dimensional surface plots of the study site. In each plot, the isoline interval is 4 mS/m. These plots may help to better visualize the relationship of apparent conductivity patterns with soil and landscape patterns. Within the site, relief is about 25.3 feet. Areas of higher apparent conductivity appear to be confined to lower-lying swales and draws. Higher-lying convex surfaces have low values of apparent conductivity.

Site #3

The study site was located in northeast quarter of Section 2, Township 96 N, Range 9 W. The field had been recently planted to corn. The site included mapped areas of Fayette silt loam, 5 to 9 percent slopes, moderately eroded; and Fayette silt loam, 14 to 18 percent slopes, severely eroded (Kittleson and Dideriksen, 1968). The deep, well drained Fayette soil form in loess on uplands and high stream benches. Fayette is a member of the fine-silty, mixed, superactive, mesic Typic Haludalfs family.

Once again, comparative studies were conducted with the Veris 3100 implement, the GEM300 sensor, and the EM38 and EM31 meters. However, because of the terrain, vision was obscured and the highly irregular grid design resulted in the measurements obtained with the GEM300 sensor and the EM meters not being correctly geo-referenced. As a consequence the data were not plotted or included in this report.

Basic statistics for the Veris data collected at Site 3 are listed in Table 7. Apparent conductivity increased with increasing soil depth. This vertical trend is attributed to increased clay and moisture contents with increasing soil depths. For the upper 0 to 30 cm of the soil, apparent conductivity averaged 31.7 mS/m with a range of 14.6 to 115.2 mS/m. Half of the observations had values of apparent conductivity between 27.8 and 35.3 mS/m. For the upper 0 to 90 cm of the soil, apparent conductivity averaged 45.1 mS/m with a range of –25.0 to 163.2 mS/m. Negative values are attributed to poor ground contact of coulter-electrodes. Half of the observations had values of apparent conductivity between 38.2 and 50.5 mS/m.

Table 7
Basic Statistics
Veris 3100 System and Towed EM38 Meter
Study Site #3
(All values are in mS/m)

	Veris 3100 System		Towed EM38 Meter
	Shallow	Deep	0 to 150 cm
AVERAGE	31.7	45.1	35.1
MINIMUM	14.6	–25.0	21.2
MAXIMUM	115.2	163.2	47.6
FIRST	27.8	38.2	32.4
MEDIAN	31.9	43.9	35.6
THIRD	35.3	50.5	38.0

Plots of data collected within Site 3 with the Veris system are shown in Figure 15. In each plot, the isoline interval is 10 mS/m. In the upper plot shows the track of the Veris 3100 implement and the locations of the 907 observation points. The upper two plots show the spatial distribution of apparent conductivity measured with the Veris 3100 implement for the upper 30 and the upper 90 cm of the soil.

In the plot of the 0 to 90 cm data (second plot from top), a line of anomalously high values bisects the study site in an east to west direction. This line is believed to represent a former undisturbed grass strip that separated two fields and received greater traffic. As at Site 2, these anomalously high values are believed to represent the effects of soil compaction. However, unlike Site 2, Site 3 was recently tilled and the effects of this compacted layer are not distinguishable in the shallower (0 to 30 cm) depth measurements. However, the effects of the traffic pan are evident in the deeper (0 to 90 cm) measurements.

In the lower two plots of Figure 15, most of the unwanted responses caused by soil compaction (positive values) and poor ground contact (negative values) have been removed from the data set. In these plots apparent conductivity values less than 0 mS/m or greater than 60 mS/m have been removed. These cutoff values, though arbitrary, reflect slightly more than the observed inter-quartile ranges. The spatial patterns evident in the lower two plots are believed to more closely represent variations in soil and soil properties.

Basic statistics for measurements obtained at Site 3 with the Iowa State University's towed EM38 meter are listed in Table 7. A total of 463 measurements were taken with this unit. Measurements were taken in only the vertical dipole orientation. For the upper 0 to 150 cm of the soil, apparent conductivity averaged 35.1 mS/m with a range of 21.2 to 47.6 mS/m. Half of the observations had values of apparent conductivity between 32.4 and 38.0 mS/m.

Data collected with Iowa State University's towed EM38 meter are shown in Figure 16. The isoline interval is 5 mS/m. The track of the unit and the locations of the 463 observation points are shown. Compared to the data collected with the Veris 3100 implement, spatial patterns are more uniform, more expansive, and less noisy with the EM38 unit. Values of apparent conductivity appear higher on level, more stable segments of the landscape. Values are lower in lower-lying, more sloping areas that receive colluvium.

A nearby field was surveyed with the Veris 3100 system. Results of this survey are shown in Figure 17. In this figure the isoline interval is 10 mS/m. The left-hand plot shows the track of the Veris 3100 implement and the locations of the 360observation points. The left-hand and right-hand plots show the spatial distribution of apparent conductivity for the upper 30 and the upper 90 cm of the soil. As I did not view this field, am uninformed as to the soils, and made no soil observations, no interpretations will be provided at this time. Bob Vobora is conducting a high intensity soil survey of the site and will use these plots to assist his mapping and soil sampling.

References

Doolittle, J., R. Murphy, G. Parks, and J. Warner. 1996. Electromagnetic induction investigations of a soil delineation in Reno County, Kansas. Soil Survey Horizons 37:11-20.

Doolittle, J. A., K. A. Sudduth, N. R. Kitchen, and S. J. Indorante. 1994. Estimating depth to claypans using electromagnetic inductive methods. J. Soil and Water Conservation 49(6):552-555.

Geonics Limited. 1998. EM38 ground conductivity meter operating manual. Geonics Ltd., Mississauga, Ontario. 33 pp.

Greenhouse, J. P., and D. D. Slaine. 1983. The use of reconnaissance electromagnetic methods to map contaminant migration. Ground Water Monitoring Review 3(2):47-59.

Hoekstra, P., R. Lahti. J. Hild, R. Bates, and D. Phillips. 1992. Case histories of shallow time domain electromagnetics in environmental site assessments. Ground Water Monitoring Review. 12(4):110-117.

Jaynes, D. B. 1995. Electromagnetic induction as a mapping aid for precision farming. pp. 153-156. IN: Clean Water, Clean Environment, 21st Century: Team Agriculture. Working to Protect Water Resources. Kansas City, Missouri. 5 to 8 March 1995.

Jaynes, D. B., T. S. Colvin, J. Ambuel. 1993. Soil type and crop yield determination from ground conductivity surveys. 1993 International Meeting of American Society of Agricultural Engineers. Paper No. 933552. ASAE, St. Joseph, MI. pp. 6.

Jaynes, D. B., J. M. Novak, T. B. Moorman, and C. A. Cambardella. 1995. Estimating herbicide partition coefficients from electromagnetic induction measurements. J. Environmental Quality. 24:36-41.

Kachanoski, R. G., E. G. Gregorich, and I. J. Van Wesenbeeck. 1988. Estimating spatial variations of soil water content using noncontacting electromagnetic inductive methods. Can. J. Soil Sci. 68:715-722.

Kittleson, K. K., and R. L. Dideriksen. 1968. Soil Survey of Winneshiek County, Iowa. USDA-Soil Conservation Service and the Iowa Agricultural Experiment Station. U. S. Government Printing Office, Washington, DC 225 p.

Lund, E. D. and C. D. Christy. 1998. Using electrical conductivity to provide answers to precision farming. P. I-327 to I-334. IN: First International Conference on Geospatial Information in Agriculture and Forestry. ERIM International, Ann Arbor, MI.

McBride, R. A., A. M. Gordon, and S. C. Shrive. 1990. Estimating forest soil quality from terrain measurements of apparent electrical conductivity. Soil Sci. Soc. Am. J., 54:290-293.

McNeill, J. D. 1980. Electrical Conductivity of soils and rocks. Technical Note TN-5. Geonics Ltd., Mississauga, Ontario. p. 22.

McNeill, J. D. 1996. Why doesn't Geonics Limited build a multifrequency EM31 or EM38 meter? Technical Note TN-30. Geonics Limited, Mississauga, Ontario. 5 p.

Olson, J. 2000. New soils maps spark change, mapping electrical conductivity in soil shows soil-to-yield relationship. Farm Industry News. March 200: 78-80.

Rhoades, J. D., P. A. Raats, and R. J. Prather. 1976. Effects of liquid-phase electrical conductivity, water content, and surface conductivity on bulk soil electrical conductivity. Soil Sci. Soc. Am. J. 40:651-655.

Slavich, P.G. and J. Yang. 1990. Estimation of field scale leaching rates from chloride mass balance and electromagnetic induction measurements. Irrig. Sci. 11:7-14.

Sorensen, K. 1994. Pulled array continuous electrical profiling. pp. 977-983. IN: Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems. Boston, MA.

Stroh, J., S. R. Archer, L. P. Wilding, and J. Doolittle. 1993. Assessing the influence of subsoil heterogeneity on vegetation patterns in the Rio Grande Plains of south Texas using electromagnetic induction and geographical information system. College Station, Texas. The Station (Mar 93): 39-42.

Sudduth, K. A. and N. R. Kitchen, 1993. Electromagnetic induction sensing of claypan depth. Paper No. 93-1550. Presented at the December 1993, Winter Meetings of the American Society of Agricultural Engineers. St. Joseph, Michigan. pp. 18.

Sudduth, K. A., N. R. Kitchen, and S. T. Drummond. 1999. Soil conductivity sensing on claypan soils: Comparison of electromagnetic induction and direct methods. pp. 3-14. IN: Applications of Electromagnetic methods, Agriculture. Geonics Ltd., Mississauga, Ontario.

Sudduth, K. A., N. R. Kitchen, D. H. Hughes, and S. T. Drummond. 1995. Electromagnetic induction sensing as an indicator of productivity on claypan soils. pp. 671-681. IN: Robert, P. C., R. H. Rust, and W. E. Larson (editors). Proceedings of Second International Conference on Precision Management for Agricultural Systems. Minneapolis, Minnesota. March 27-30, 1994. American Society of Agronomy, Madison, Wisconsin.

Veris Technologies. 1998. 3100 Soil EC Mapping System Operations Manual. Publication No. AN 1CM02-02. Veris Technologies, Salina, KS.

Won, I. J., Dean A. Keiswetter, George R. A. Fields, and Lynn C. Sutton. 1996. GEM-2: A new multifrequency electromagnetic sensor. Journal of Environmental & Engineering Geophysics 1:129-137.

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #1
VERIS 3100 SYSTEM

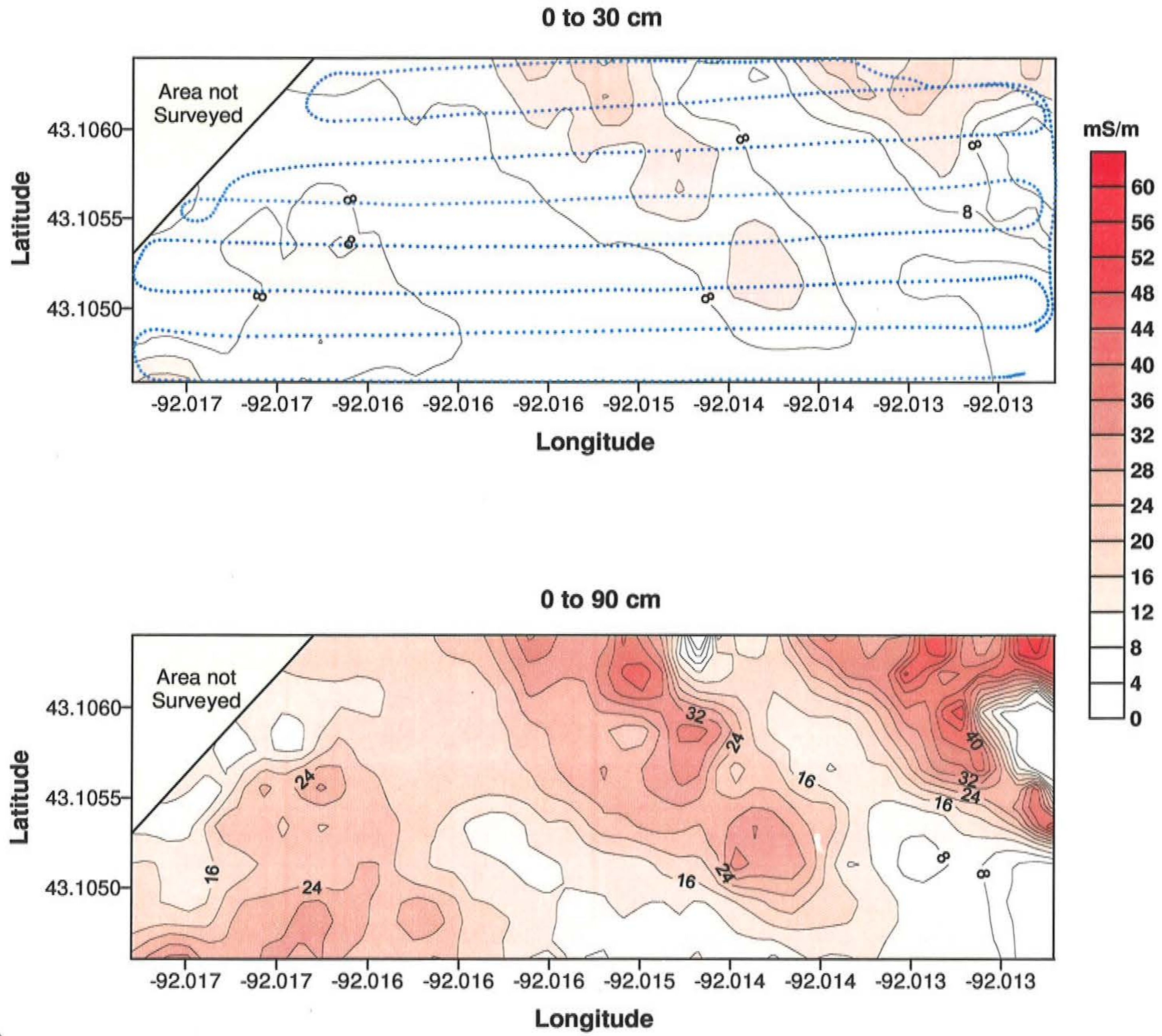


Figure 1

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #1
GEM300 SENSOR
6030 Hz

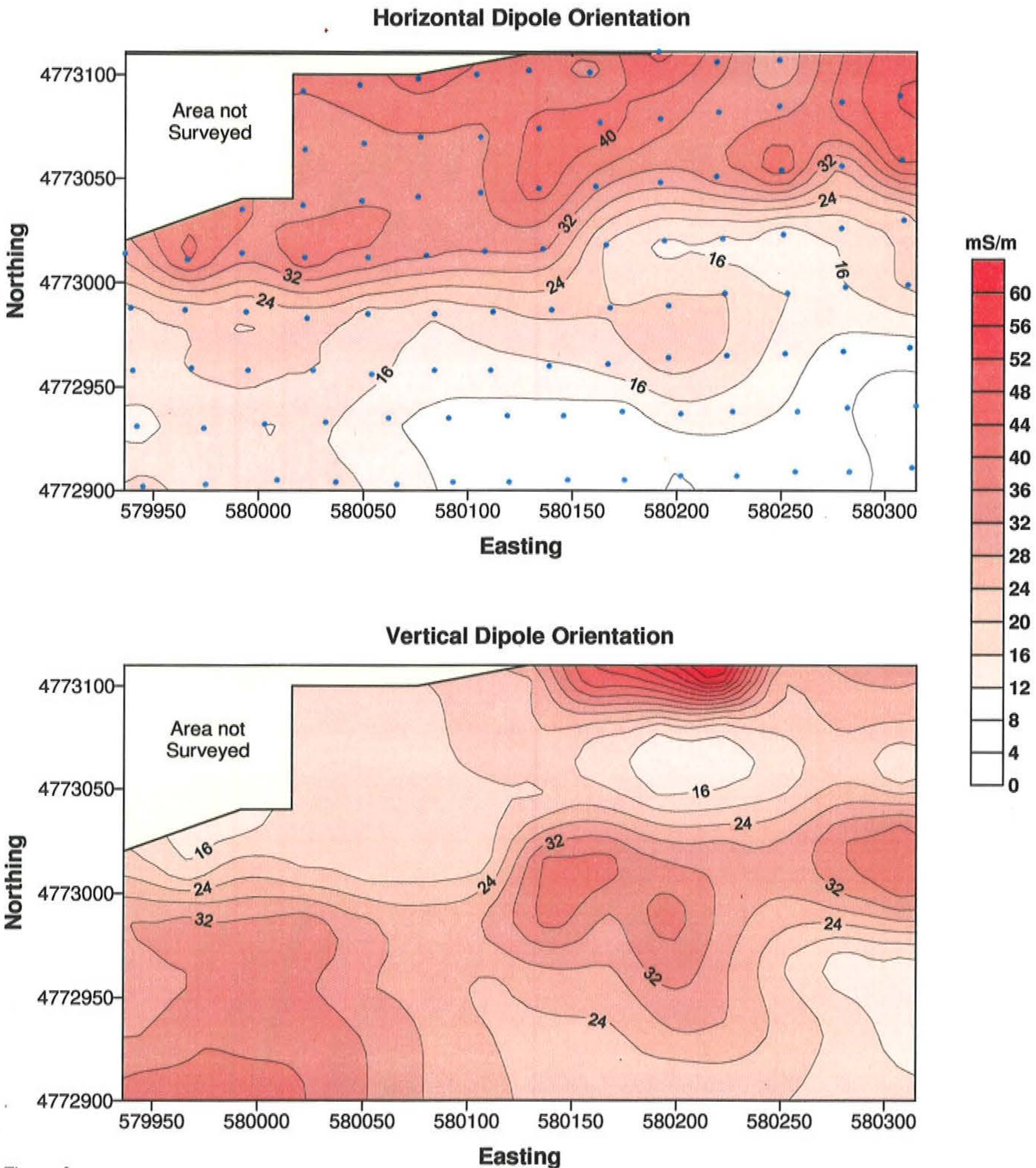


Figure 2

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #1
GEM300 SENSOR
9810 Hz

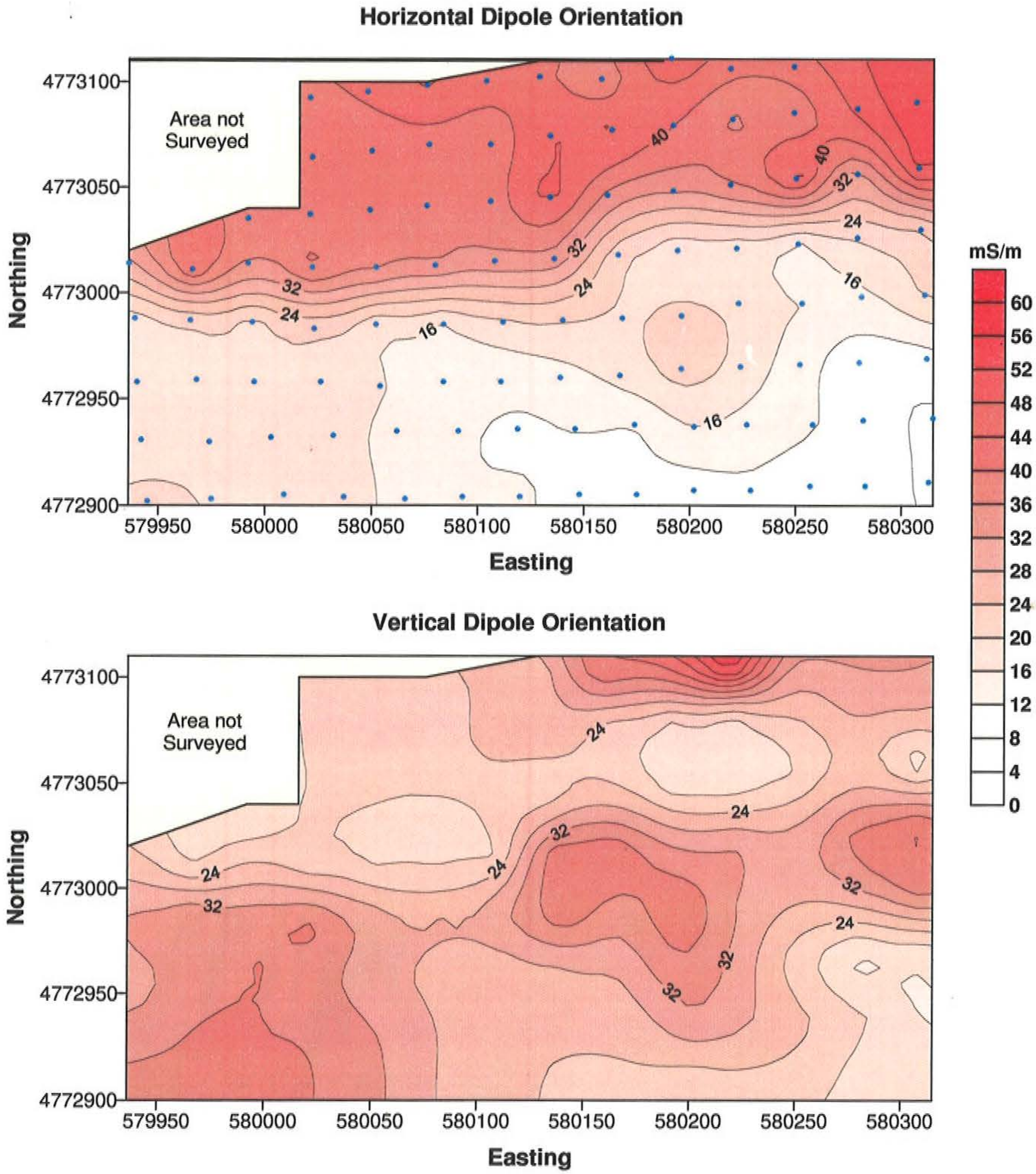


Figure 3

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #1
GEM300 SENSOR
14610 Hz

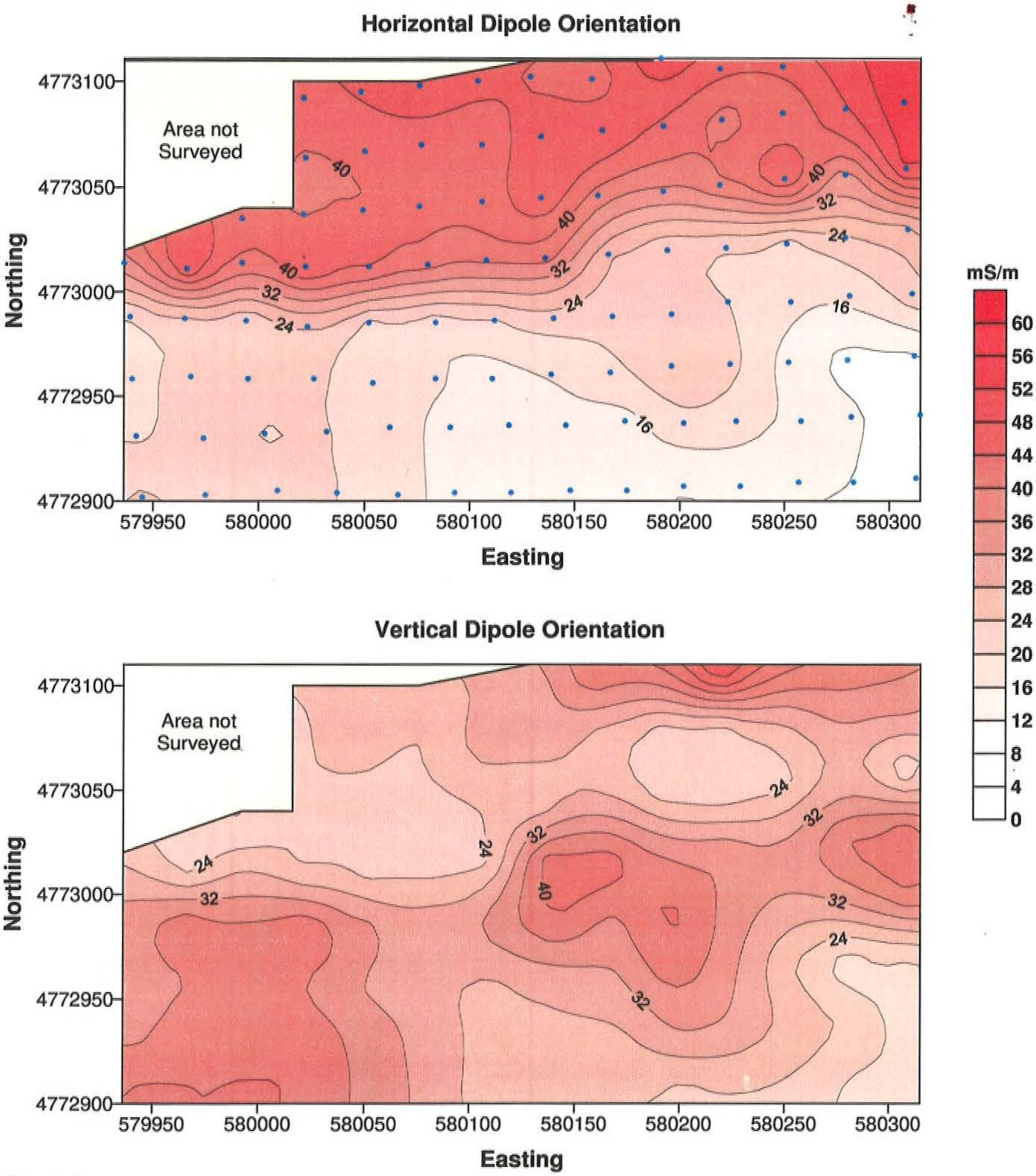


Figure 4

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #1
EM38 METER

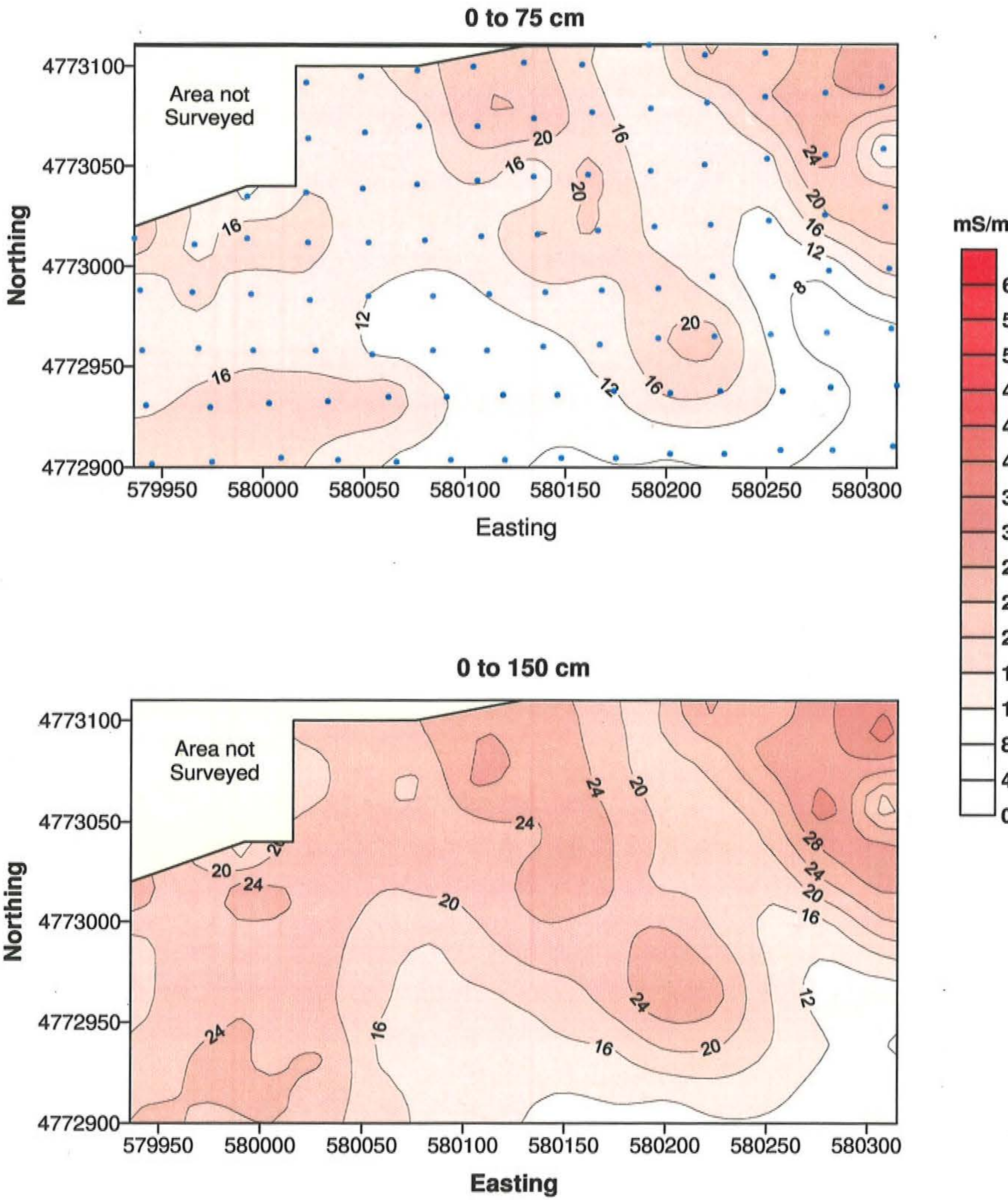


Figure 5

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #1
EM31 METER

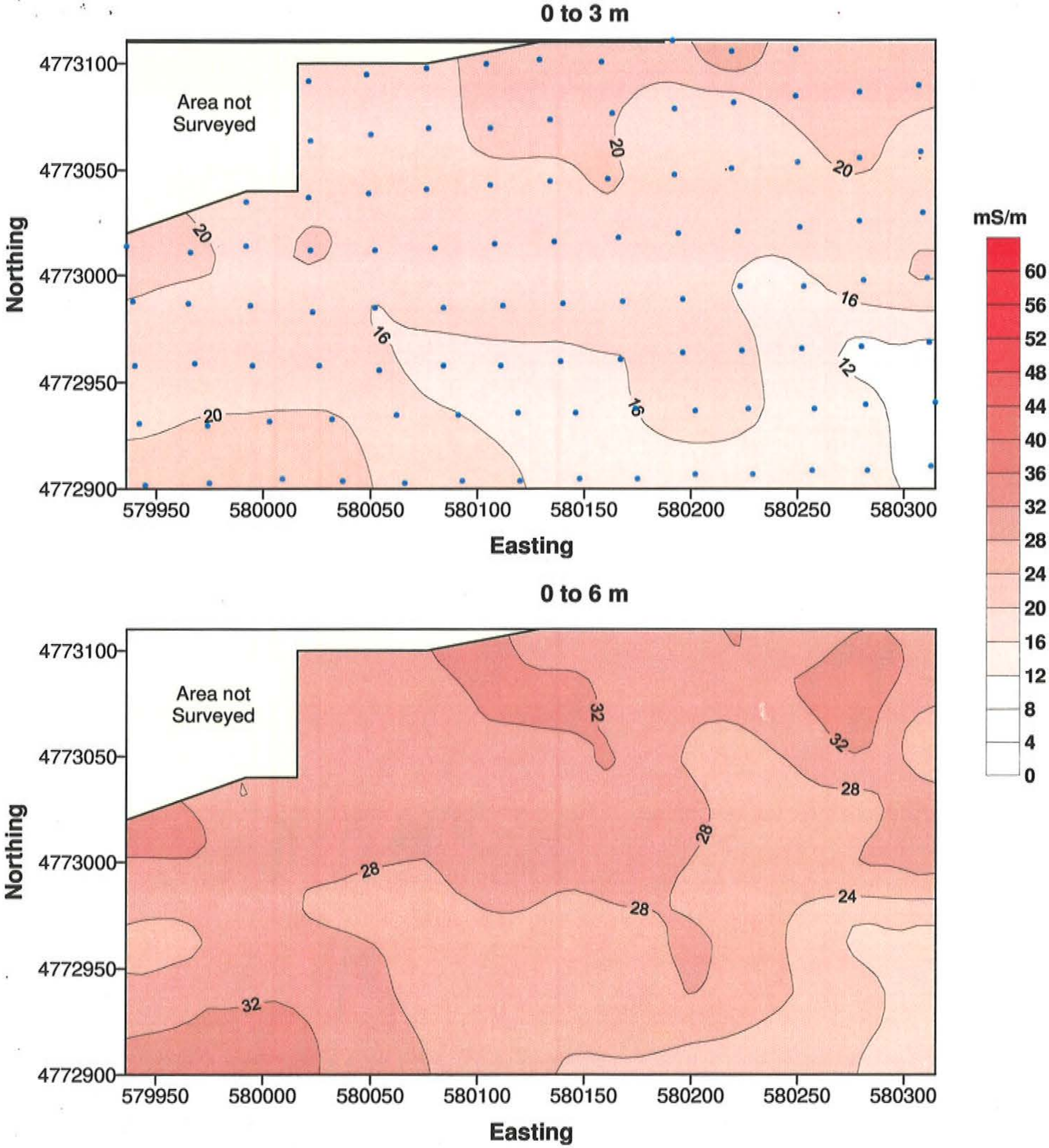


Figure 6

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #2
VERIS 3100 SYSTEM

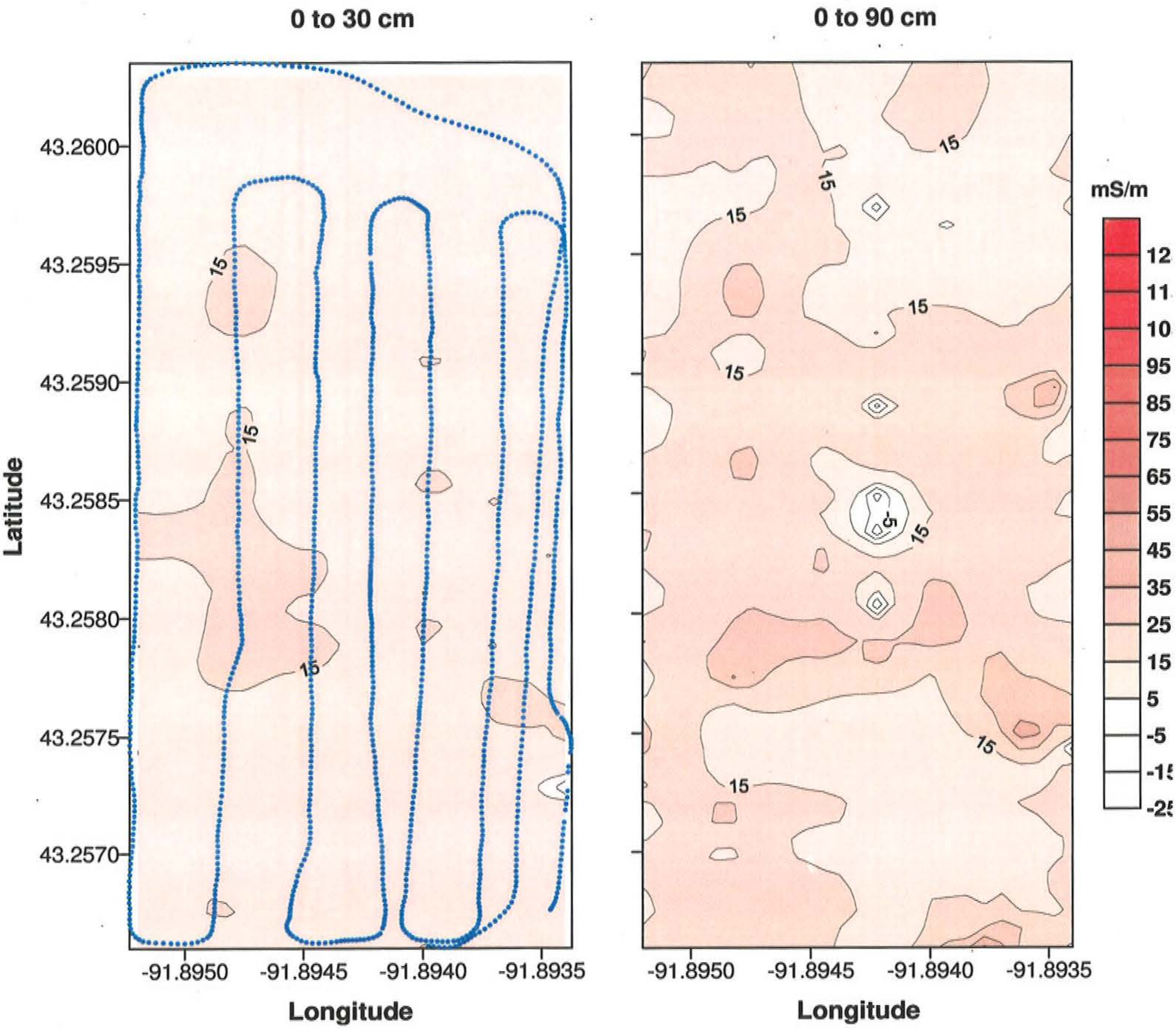


Figure 7

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #2
VERIS 3100 SYSTEM

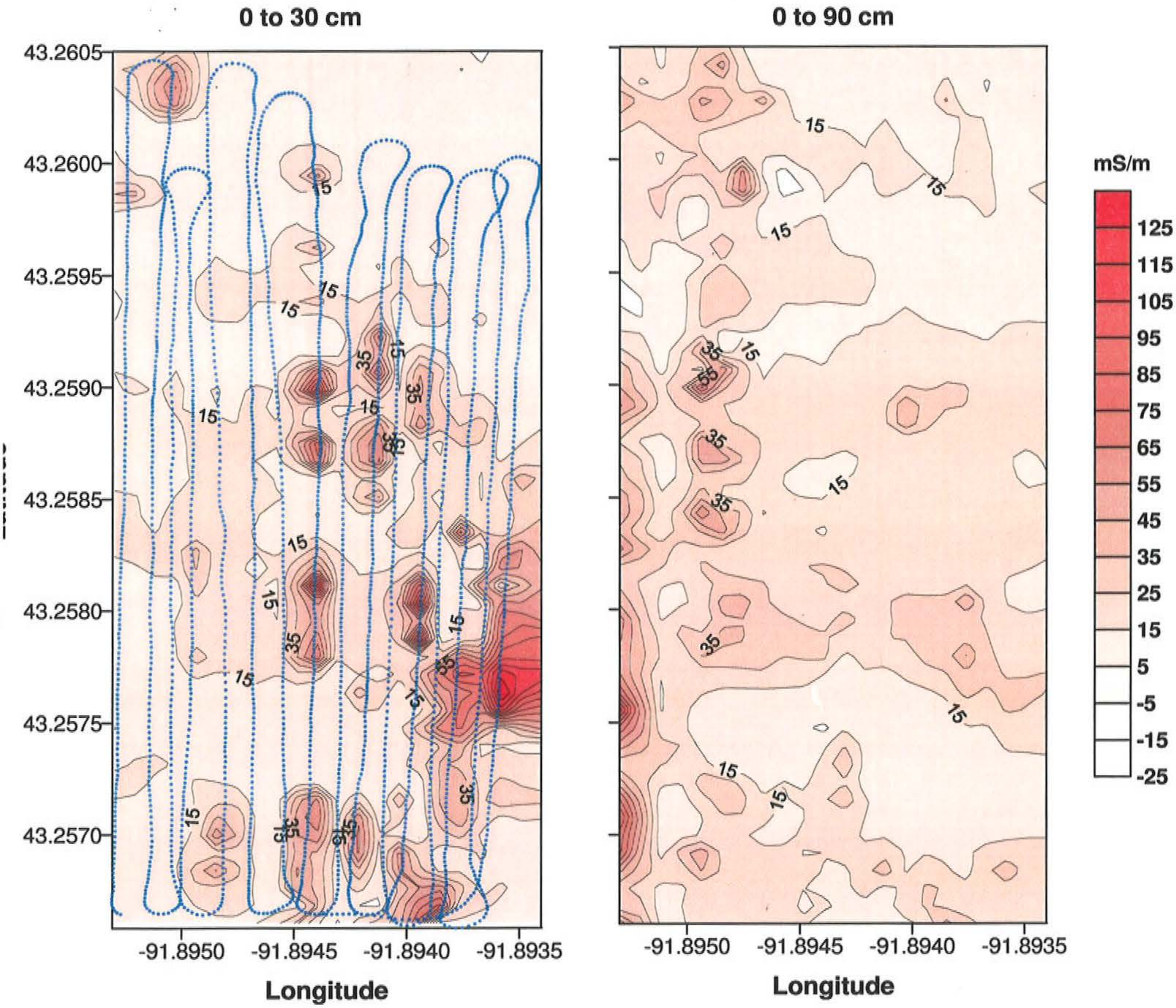


Figure 8

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #2
GEM300 SENSOR
9810 Hz

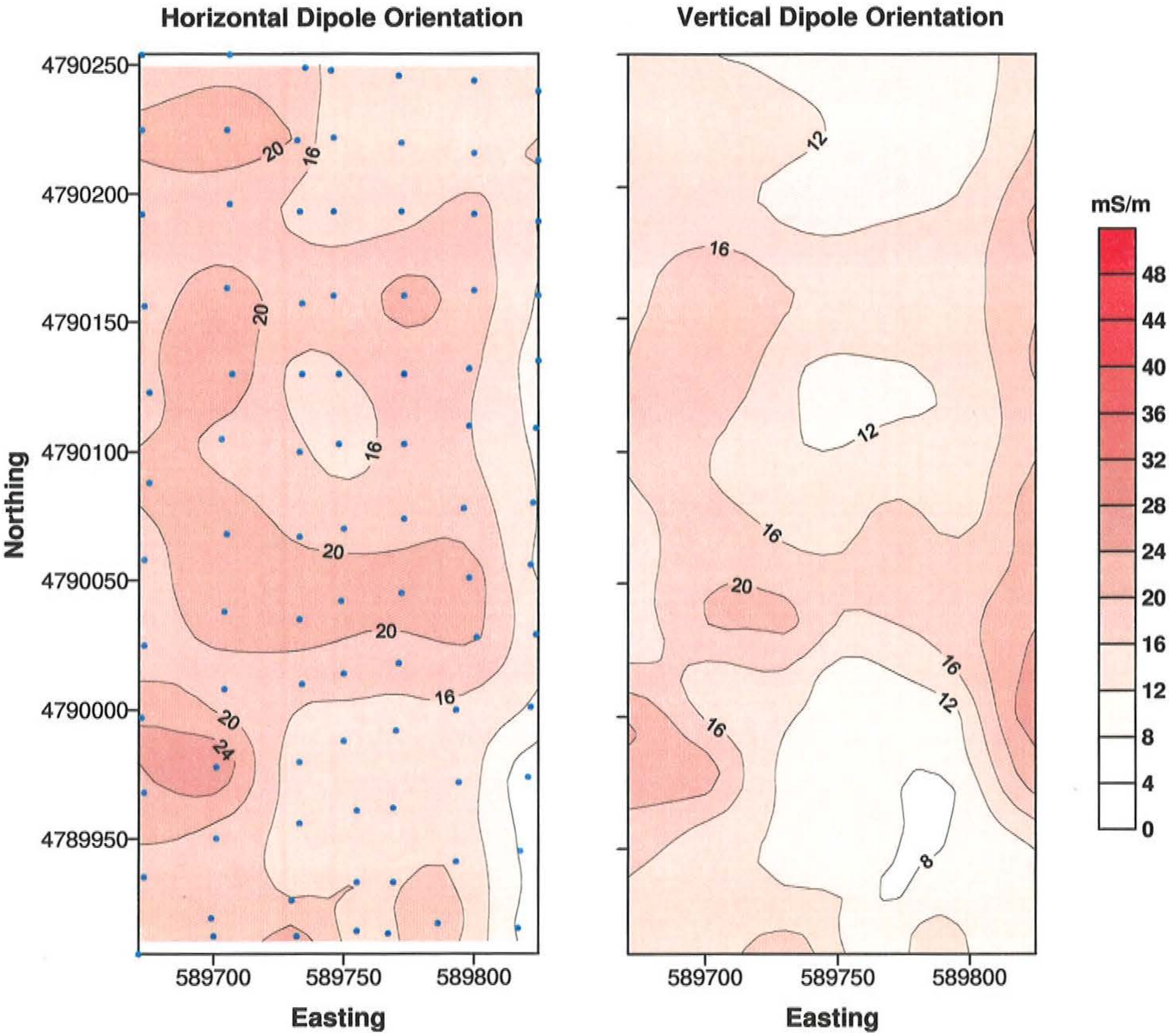


Figure 9

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #2
GEM300 SENSOR
14610 Hz

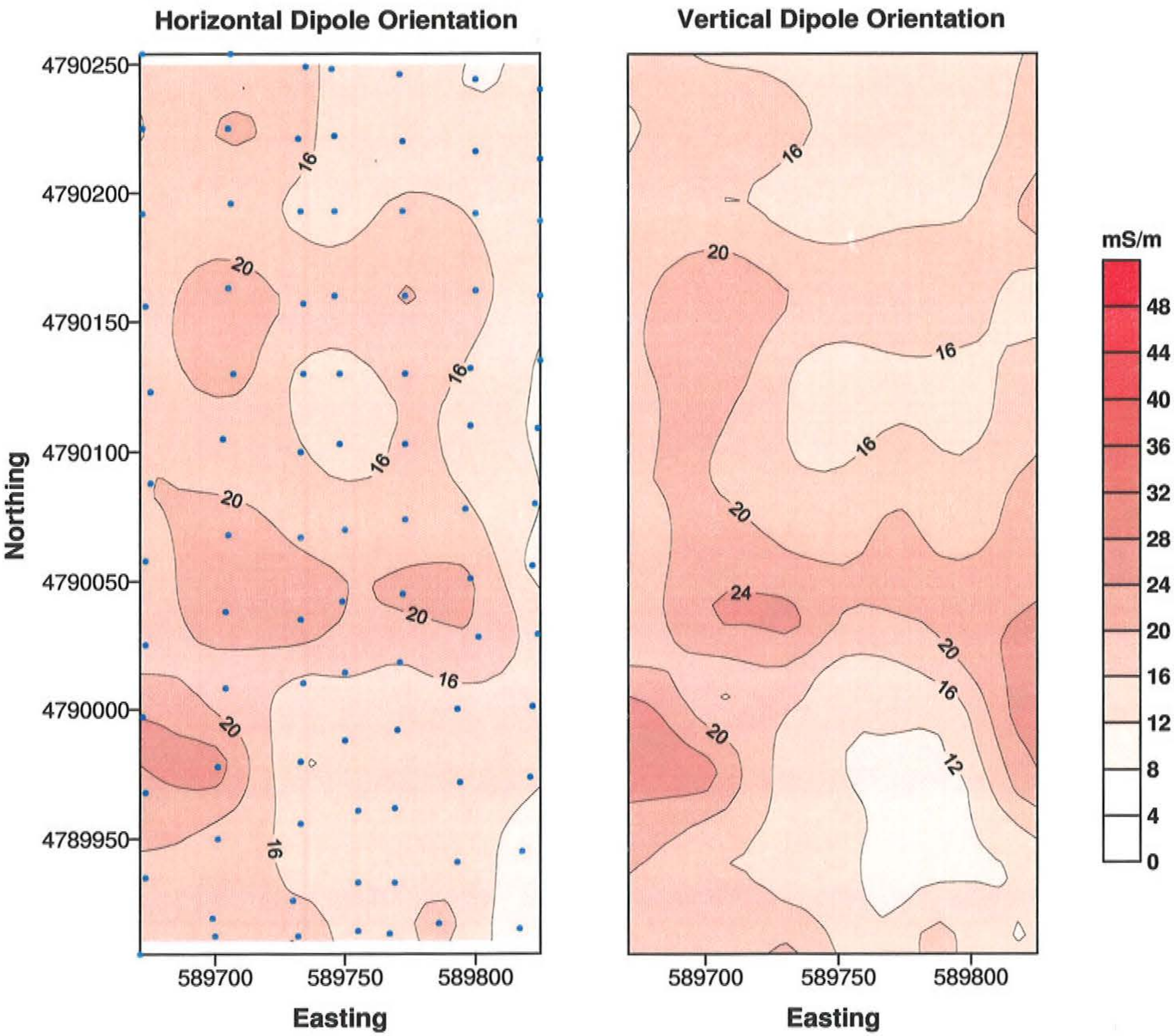


Figure 10

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #2
GEM300 SENSOR
19950 Hz

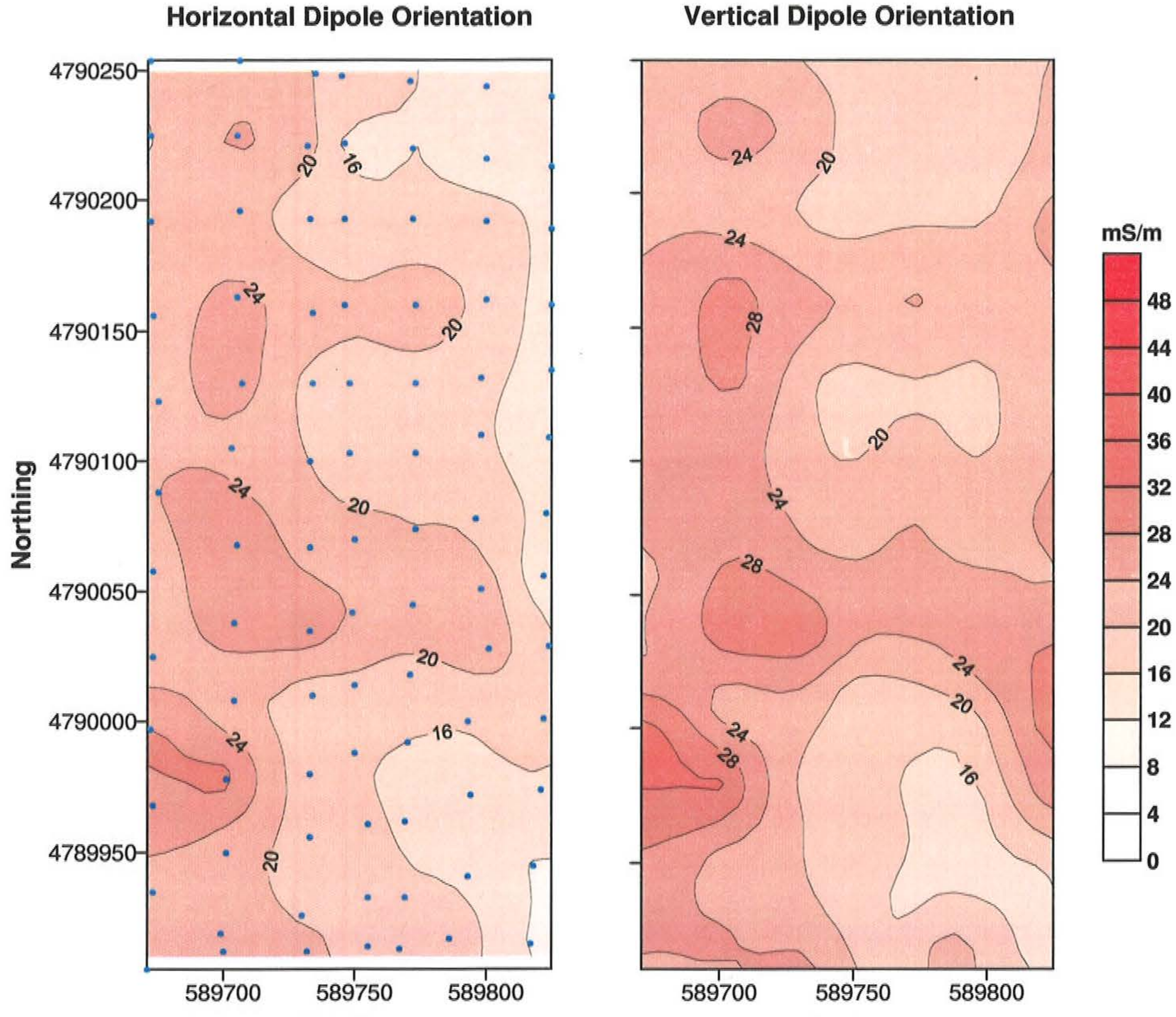


Figure 11

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #2
EM38 METER

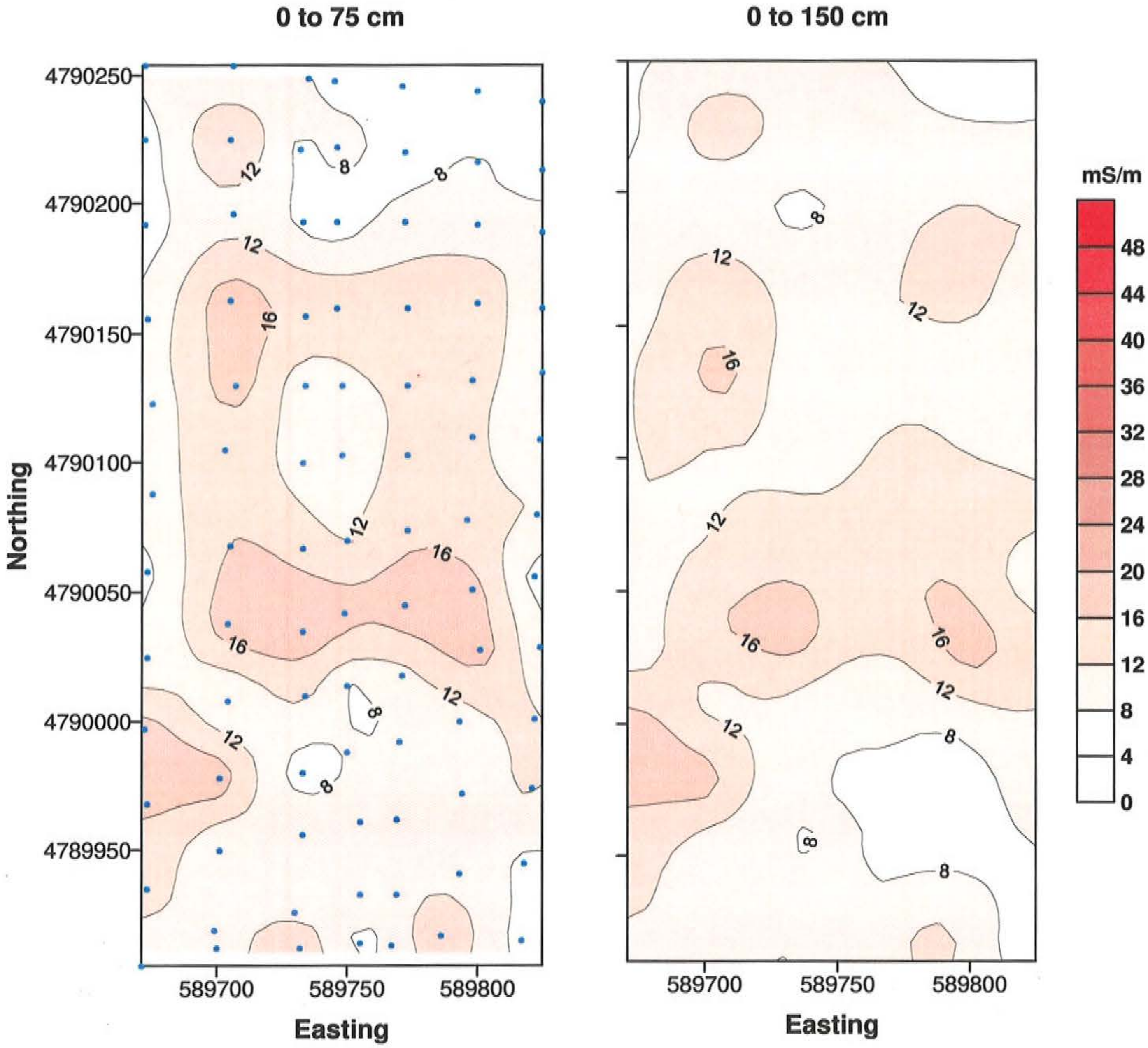


Figure 12

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #2
EM31 METER

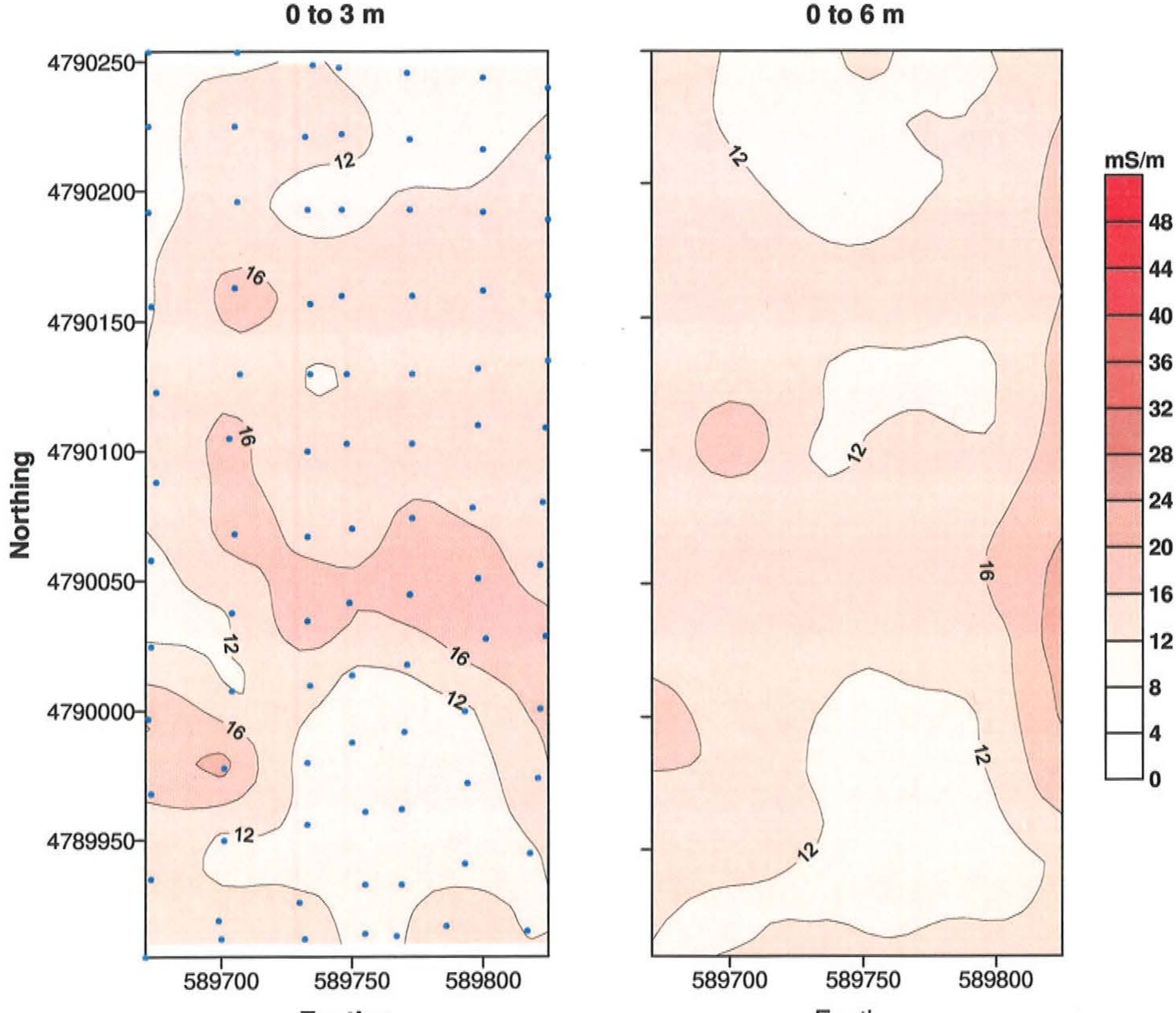
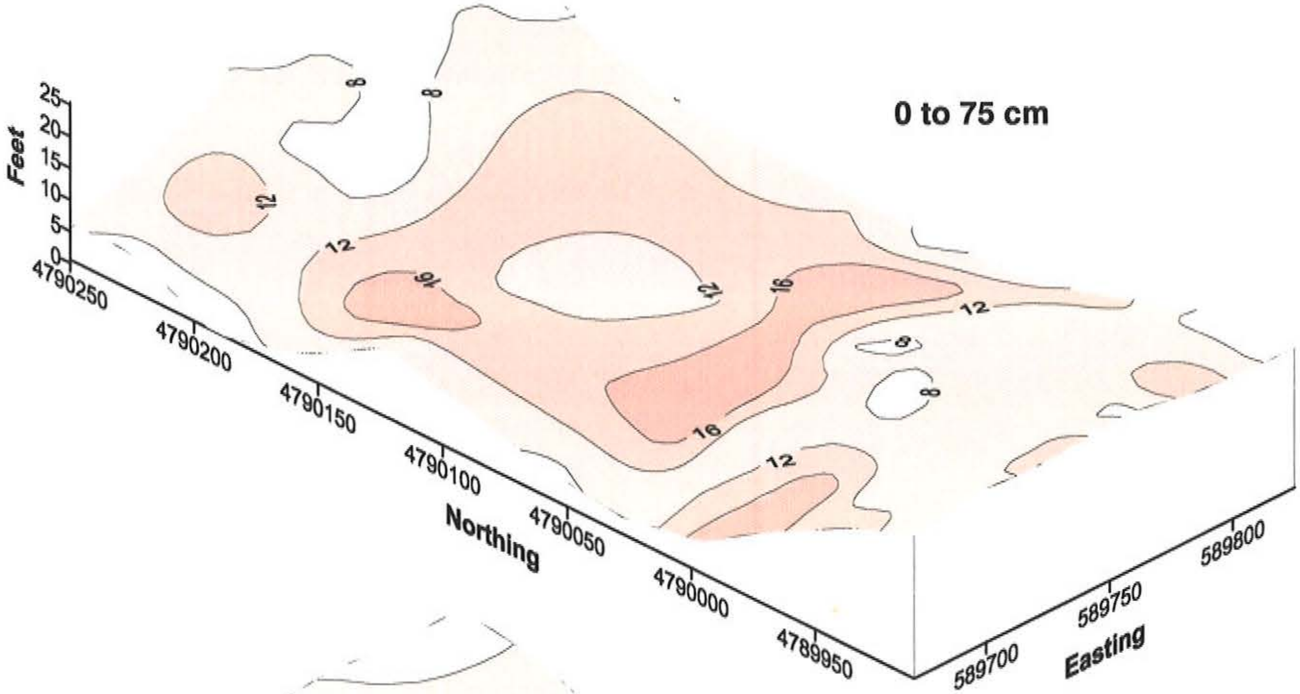
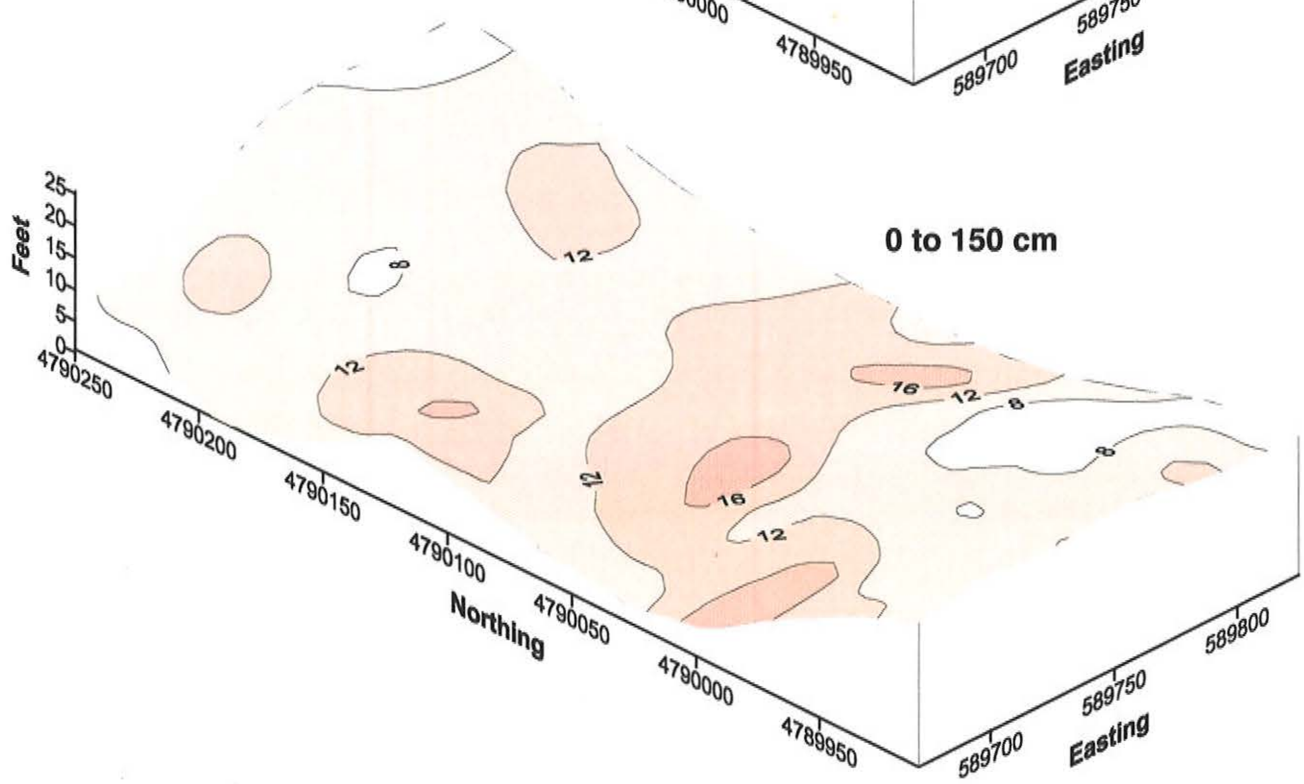


Figure 13

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #2
EM38 METER





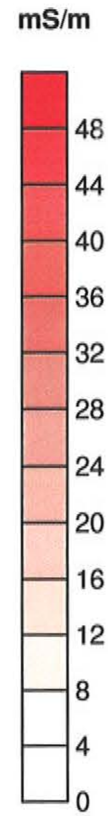


Figure 14

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #3
VERIS 3100 SYSTEM

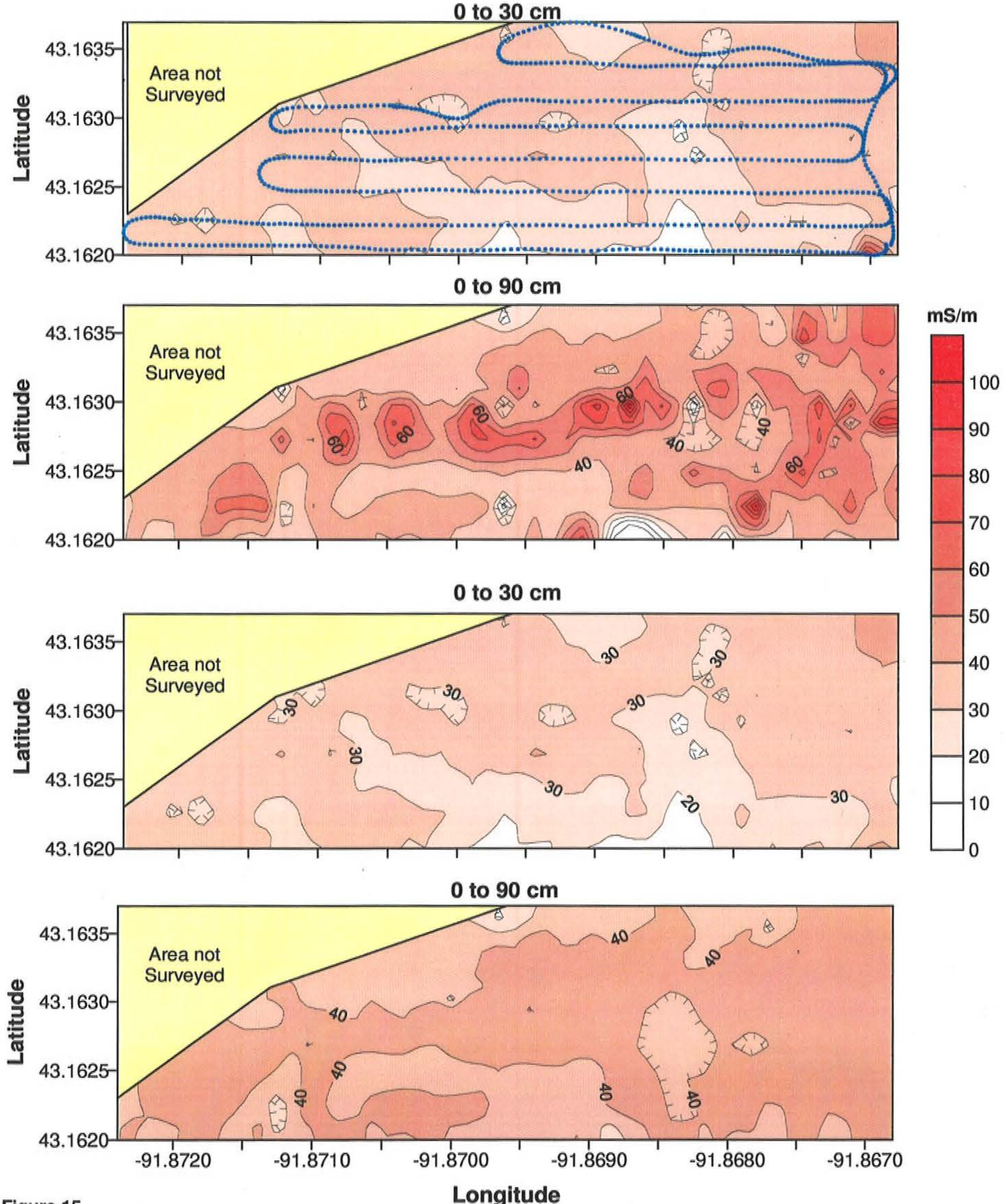


Figure 15

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #2
ISU's TOWED EM38 METER

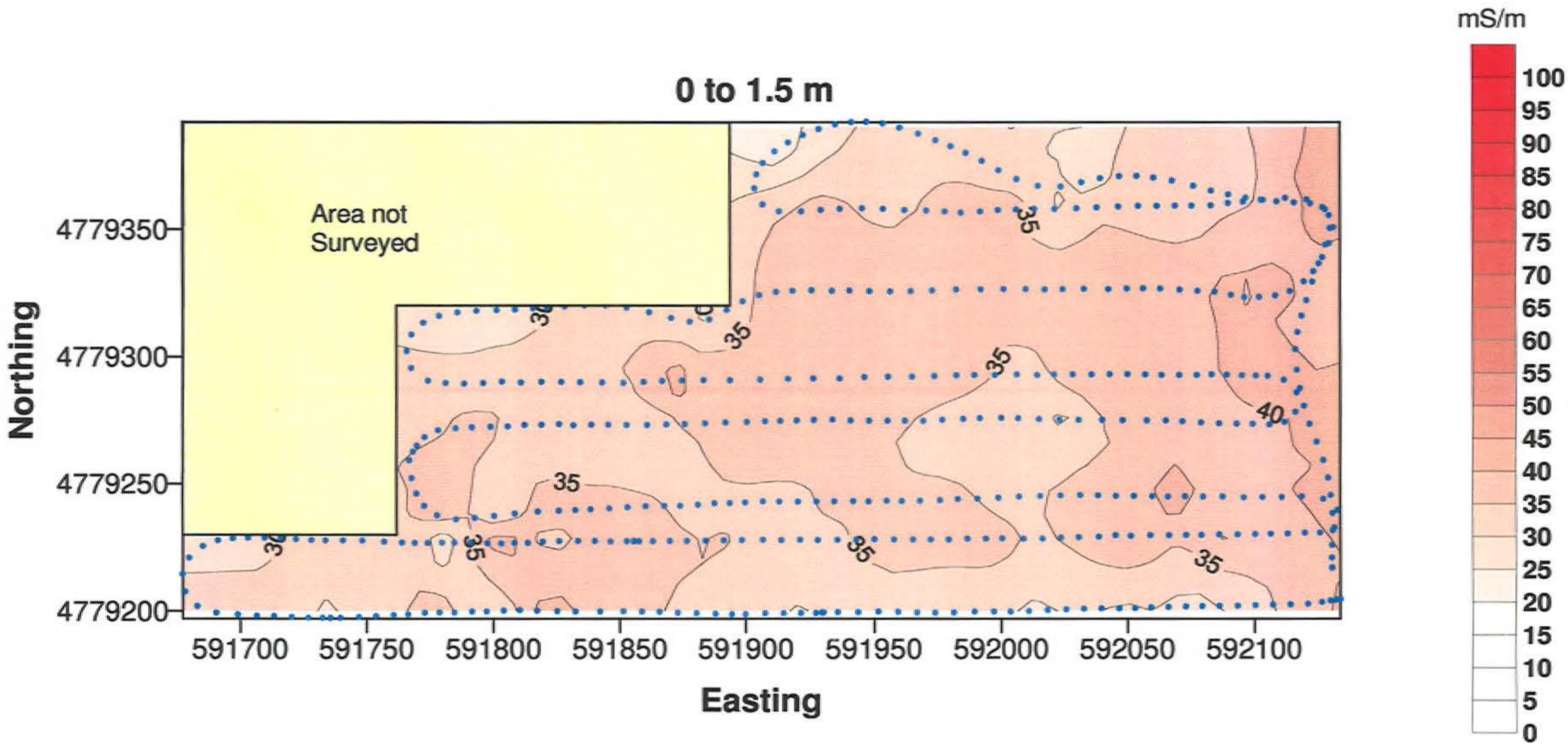


Figure 16

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #3B
VERIS 3100 SYSTEM

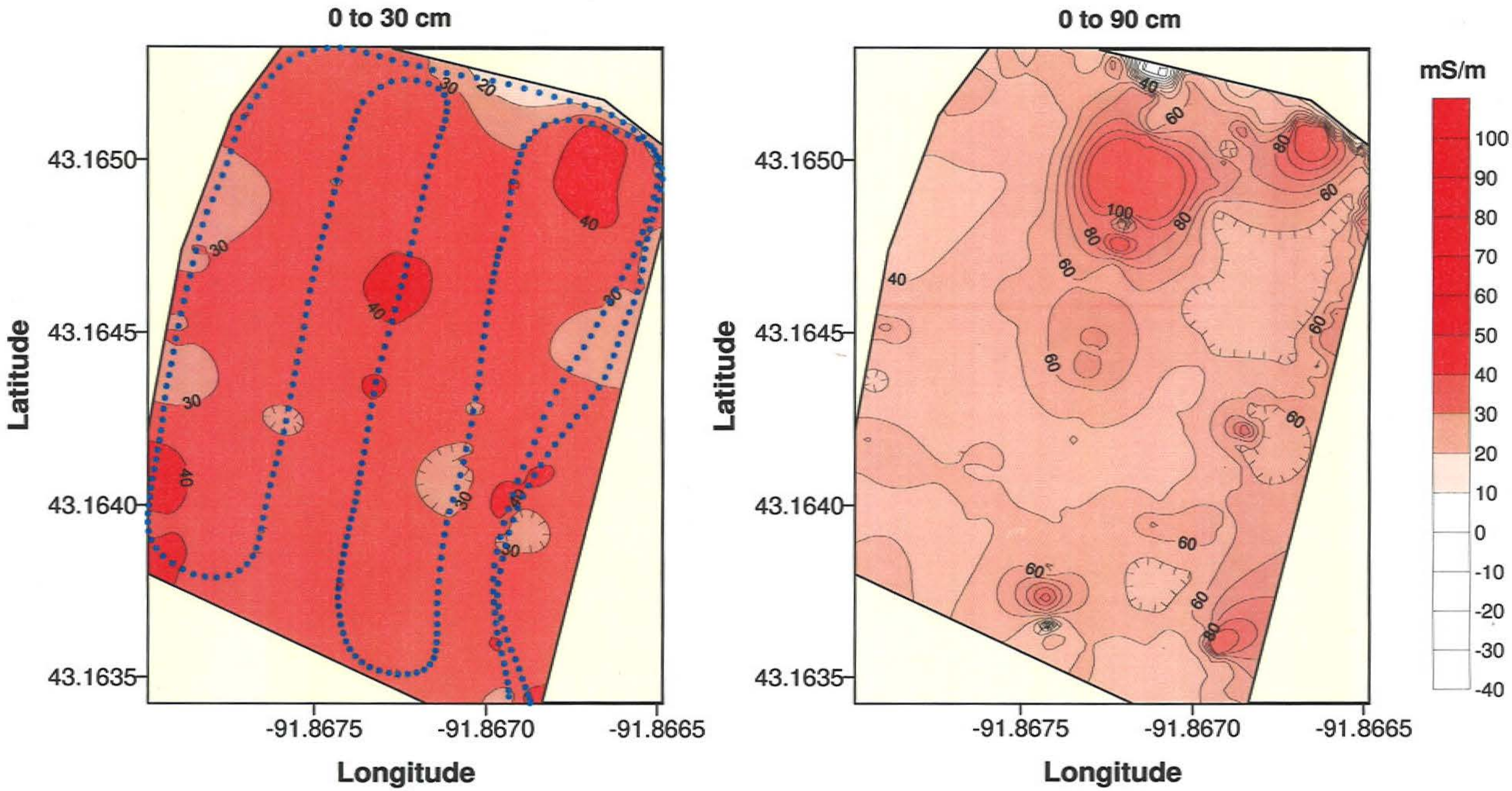


Figure 17

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #1
VERIS 3100 SYSTEM

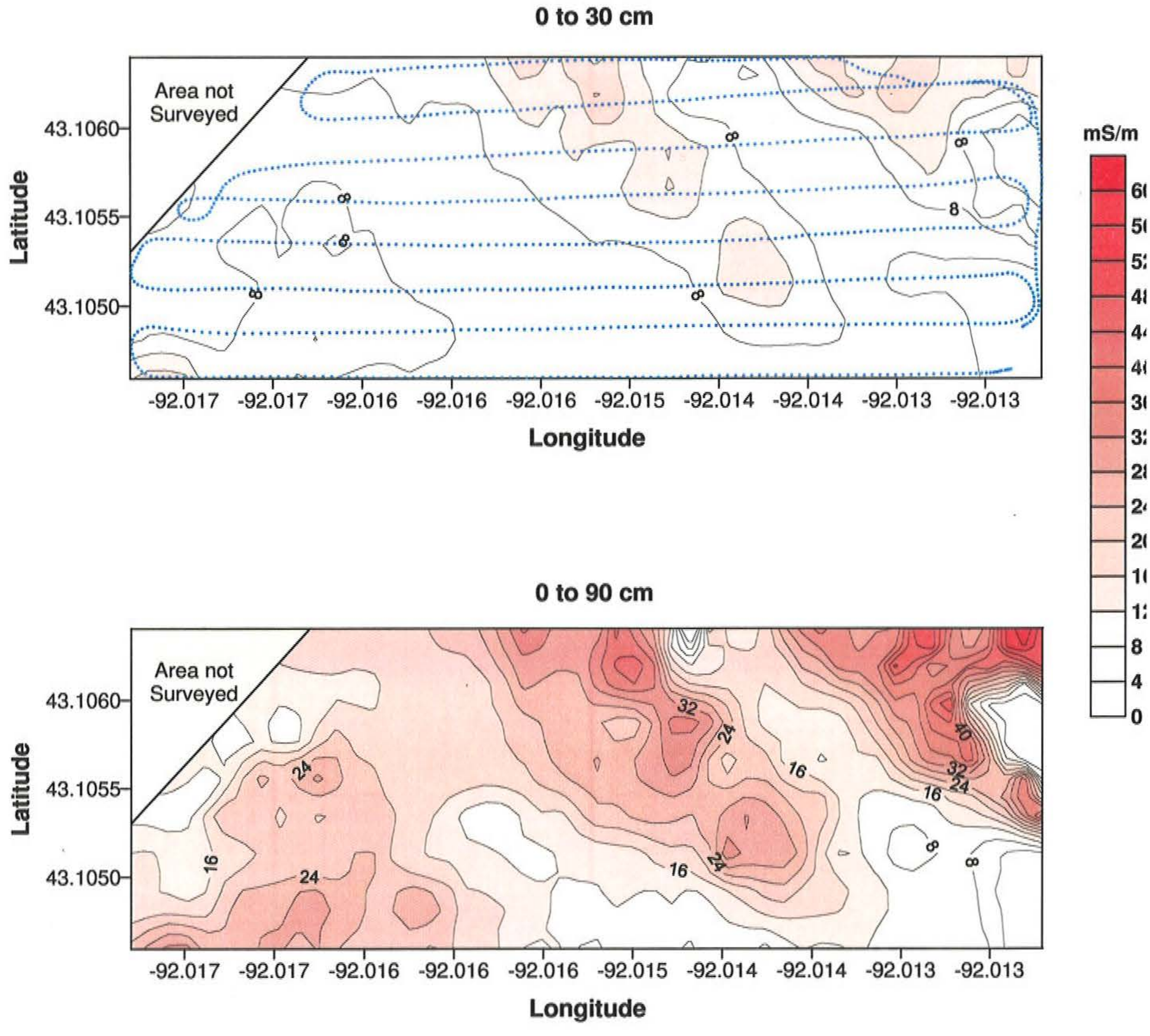


Figure 1

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #1
GEM300 SENSOR
6030 Hz

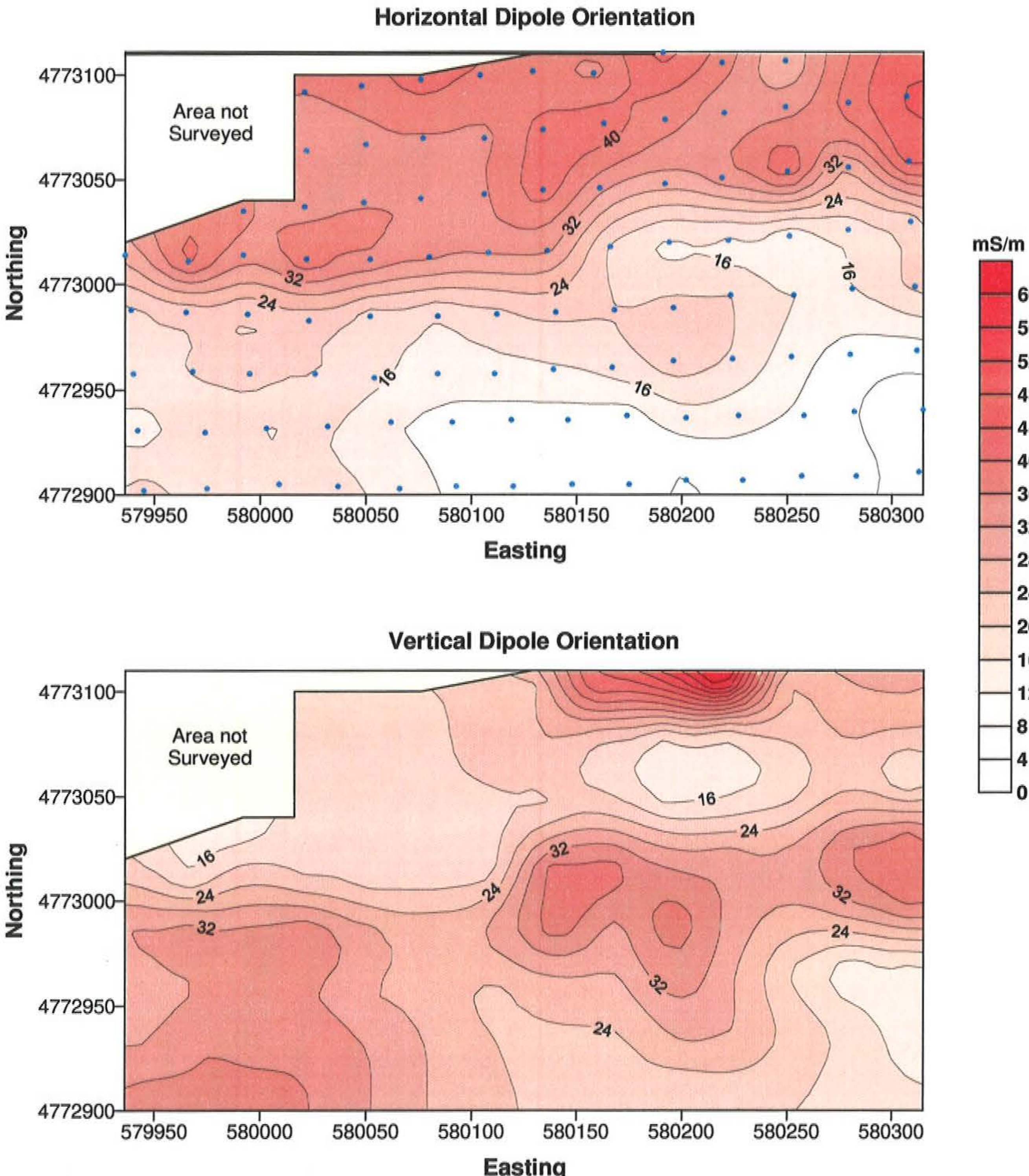


Figure 2

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #1
GEM300 SENSOR
9810 Hz

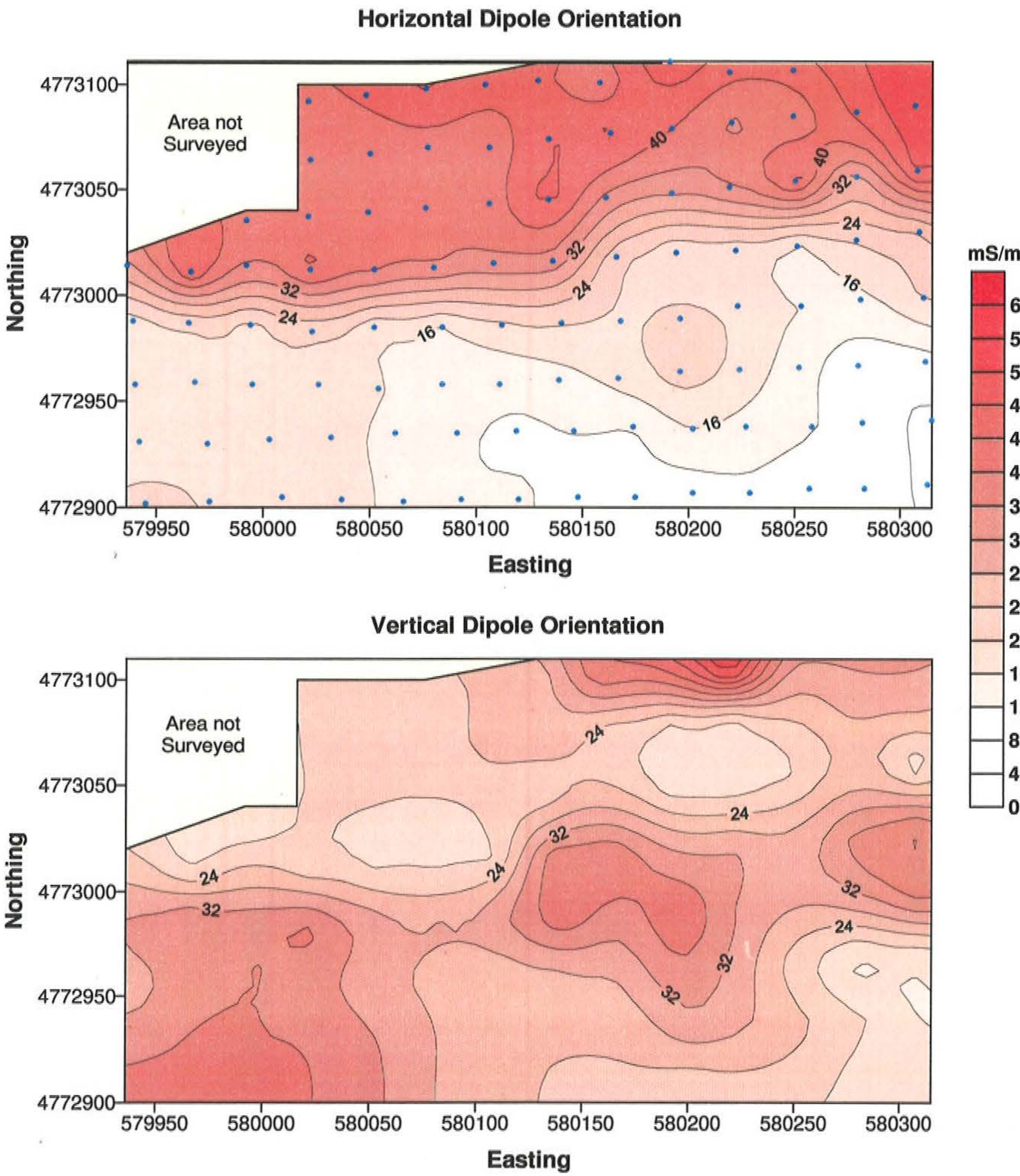


Figure 3

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #1
GEM300 SENSOR
14610 Hz

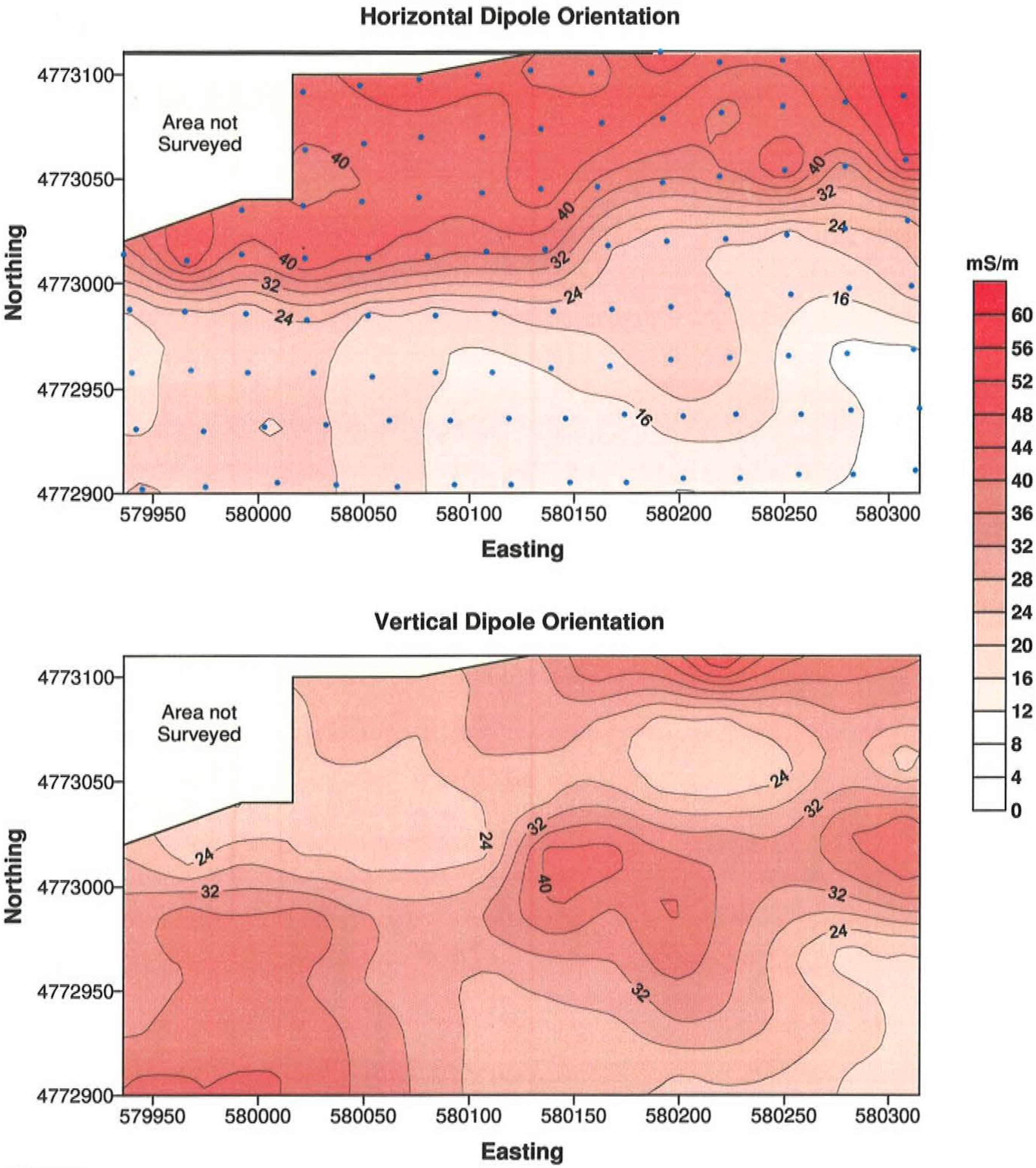


Figure 4

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #1
EM38 METER

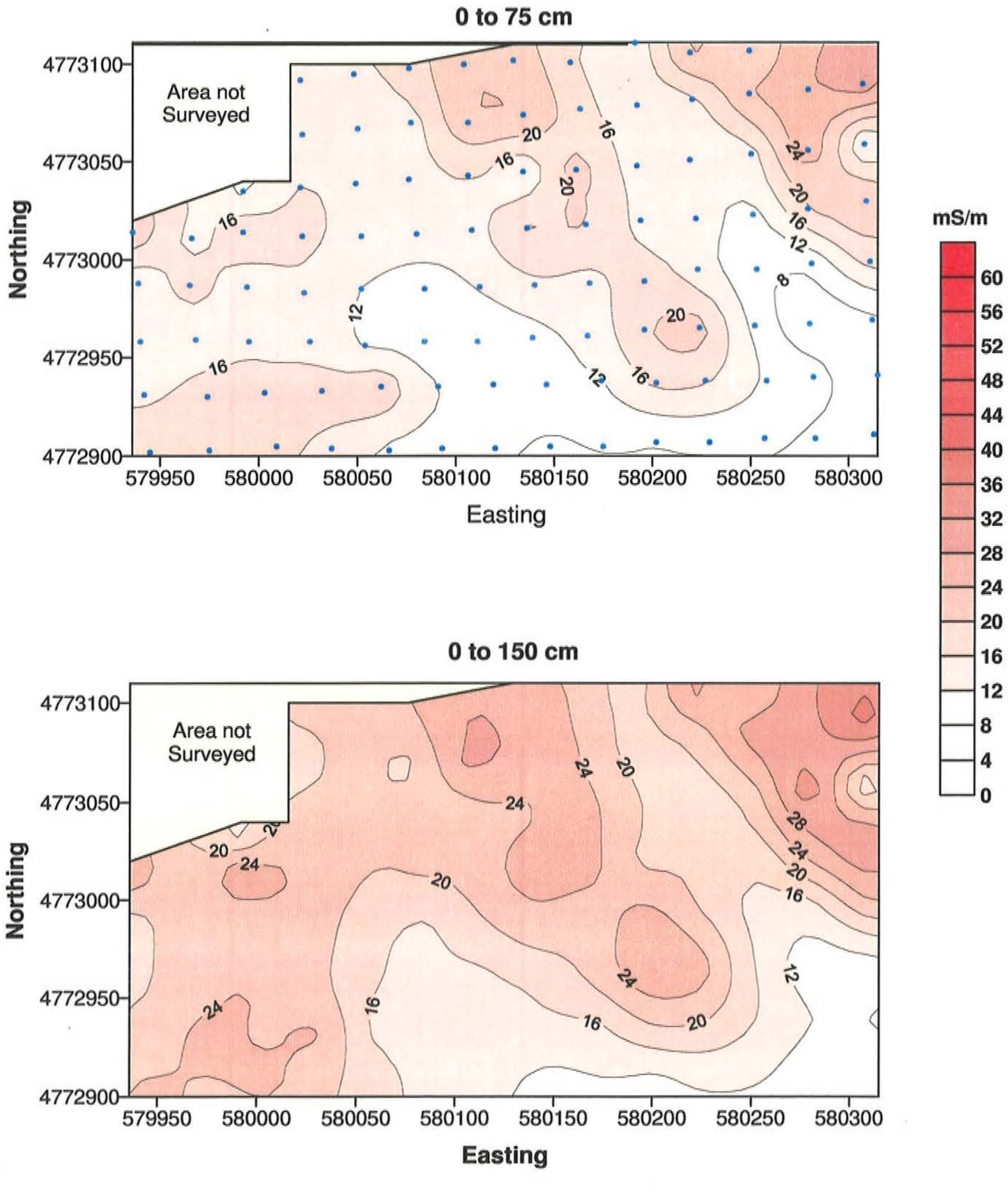


Figure 5

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #1
EM31 METER

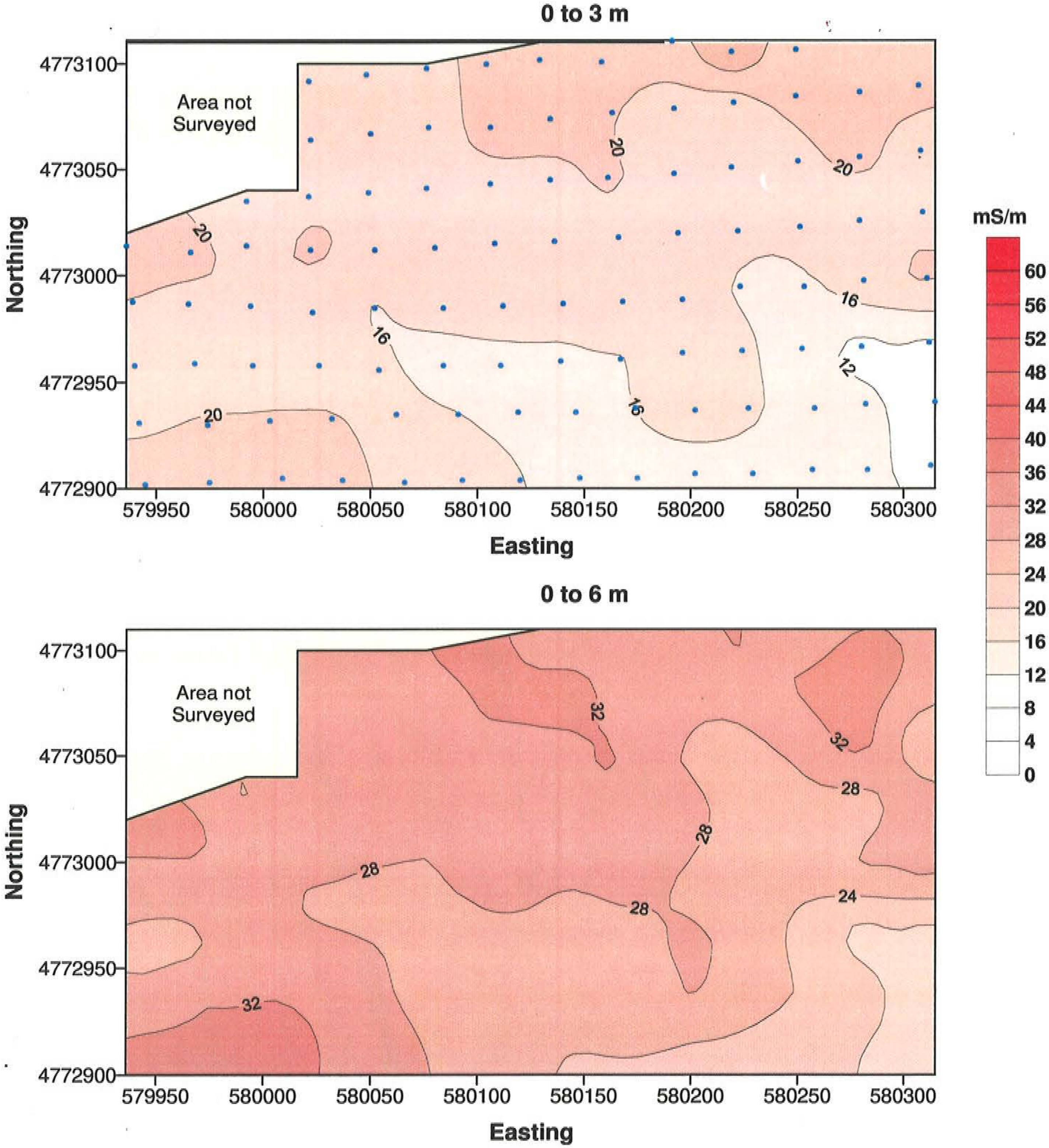


Figure 6

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #2
VERIS 3100 SYSTEM

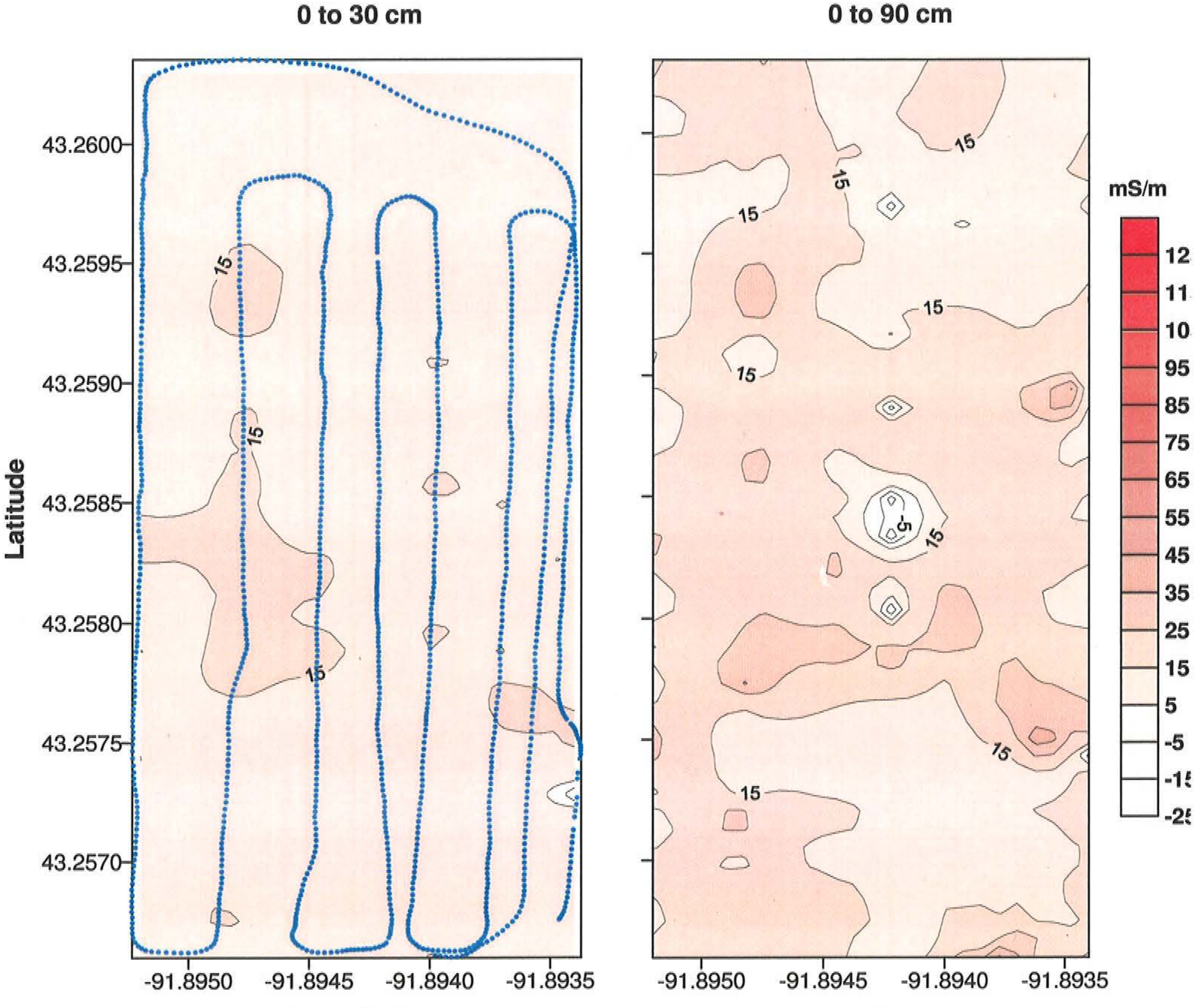


Figure 7

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #2
VERIS 3100 SYSTEM

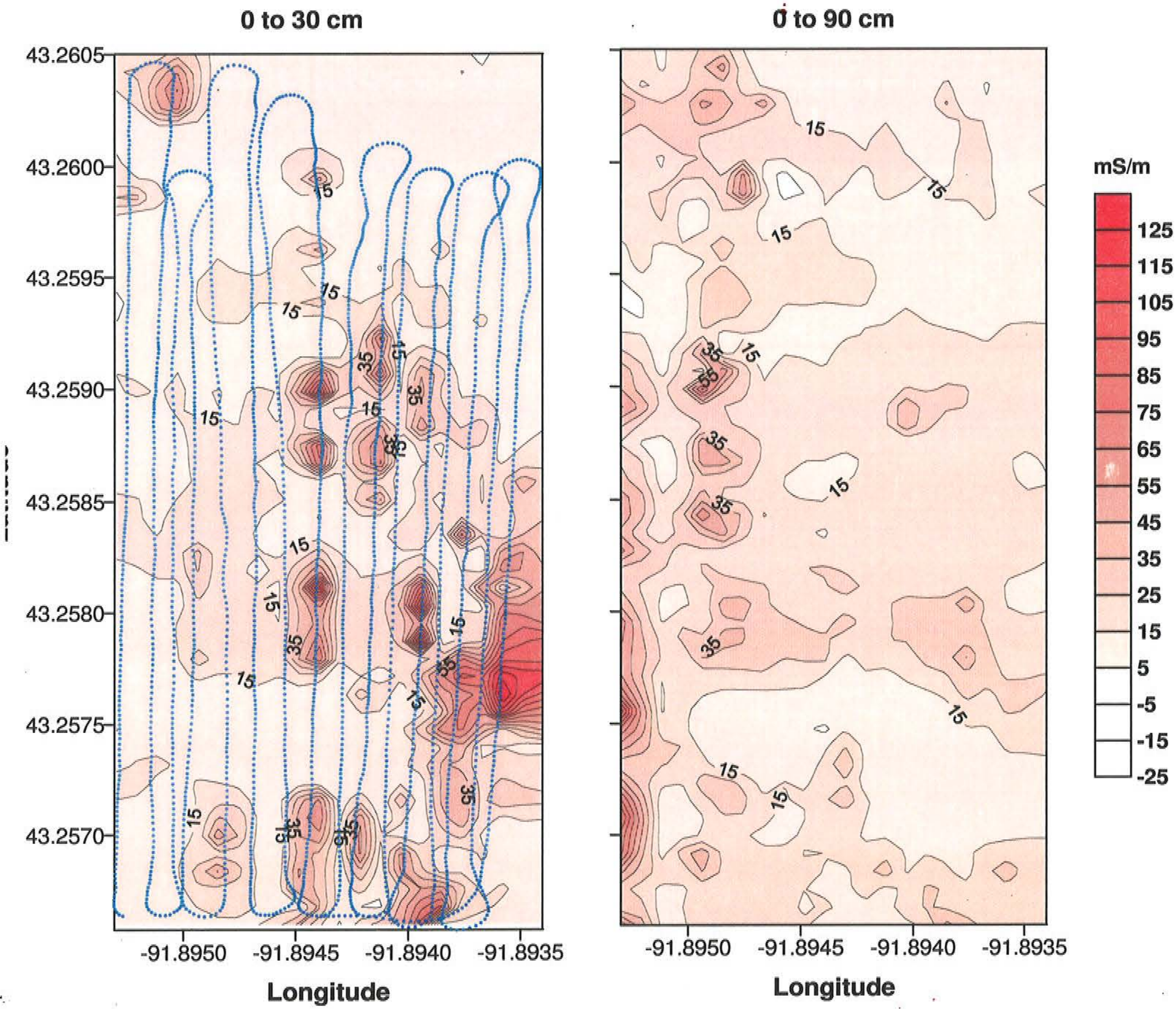


Figure 8

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #2
GEM300 SENSOR
9810 Hz

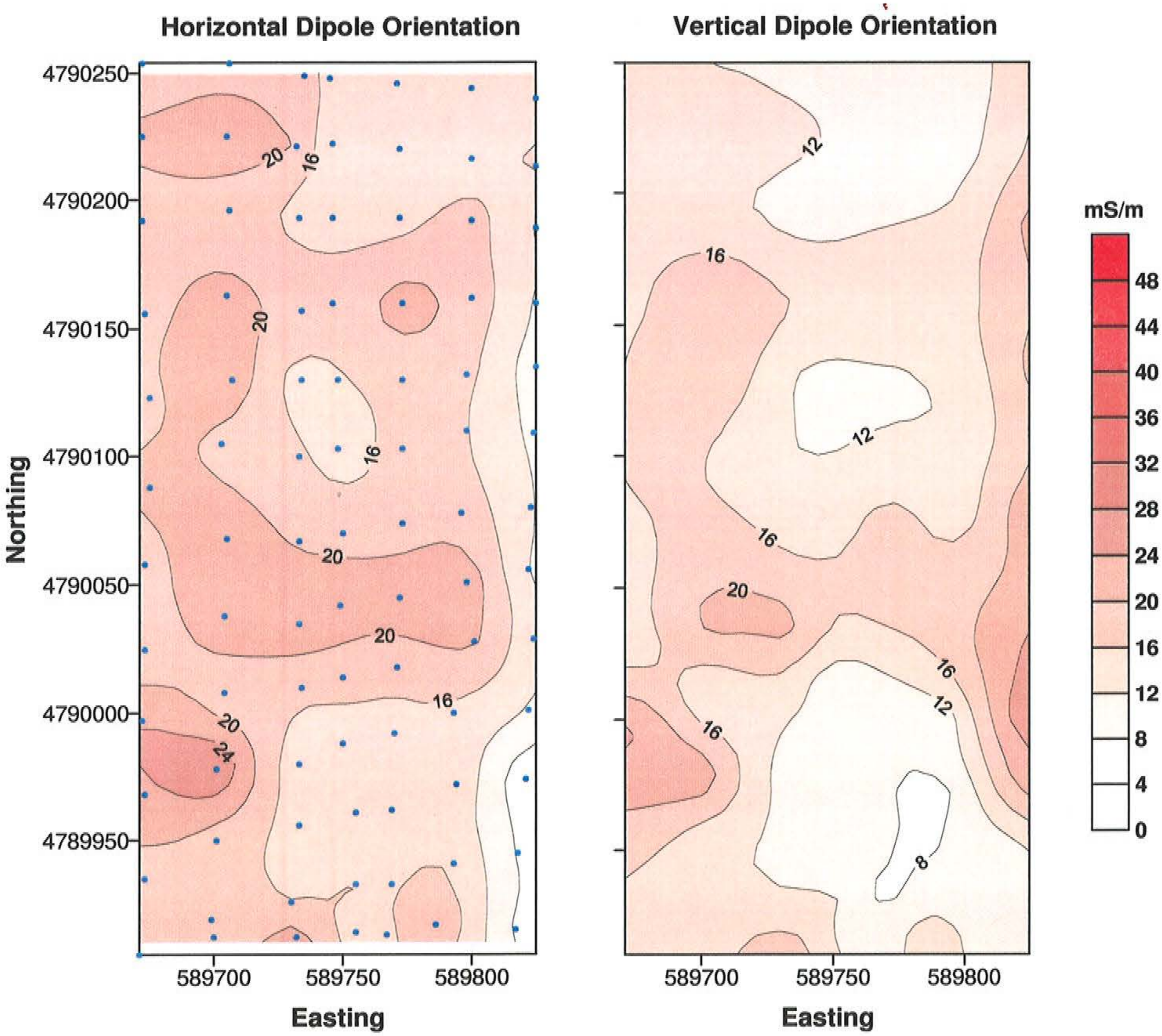


Figure 9

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #2
GEM300 SENSOR
14610 Hz

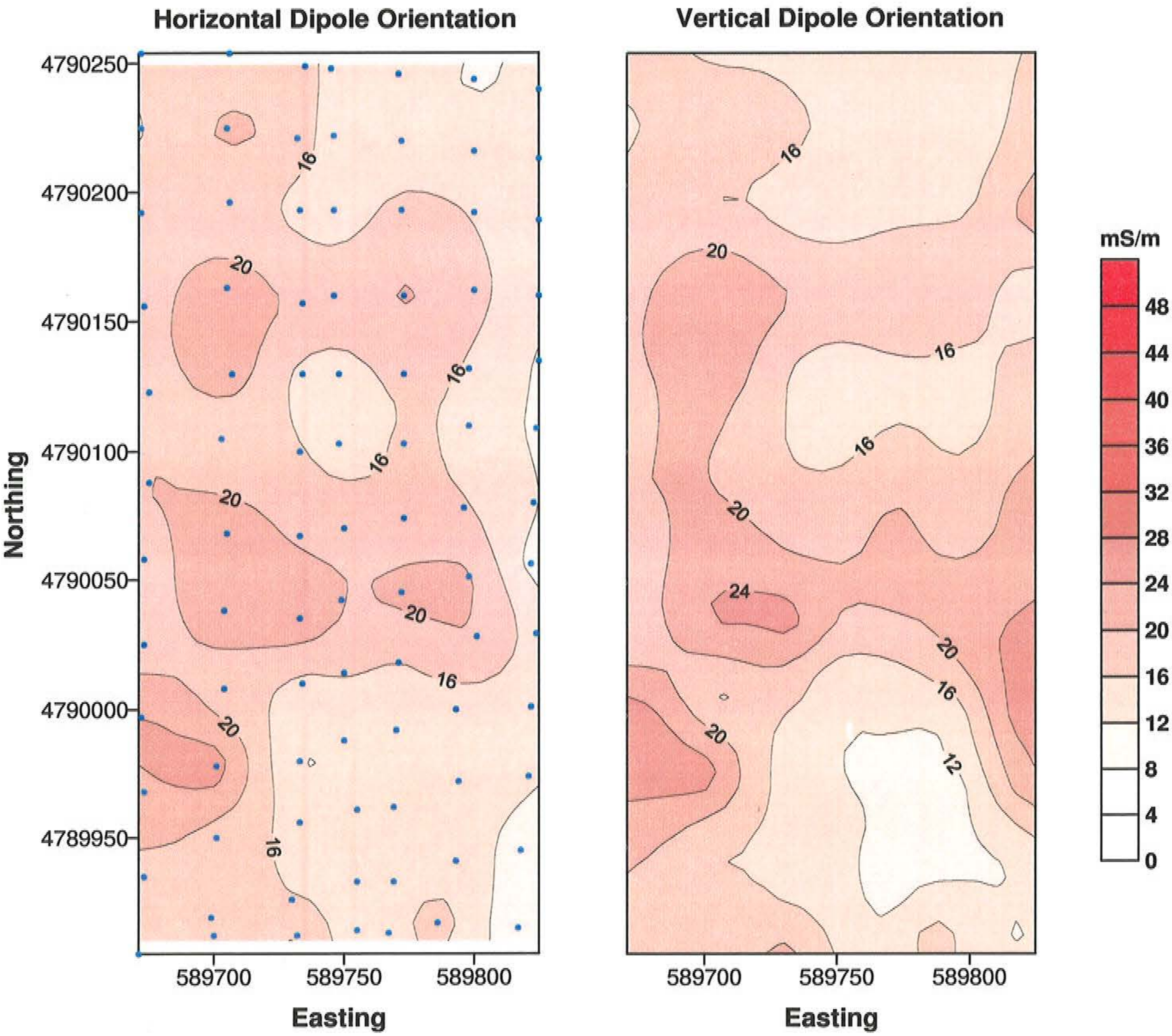


Figure 10

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #2
GEM300 SENSOR
19950 Hz

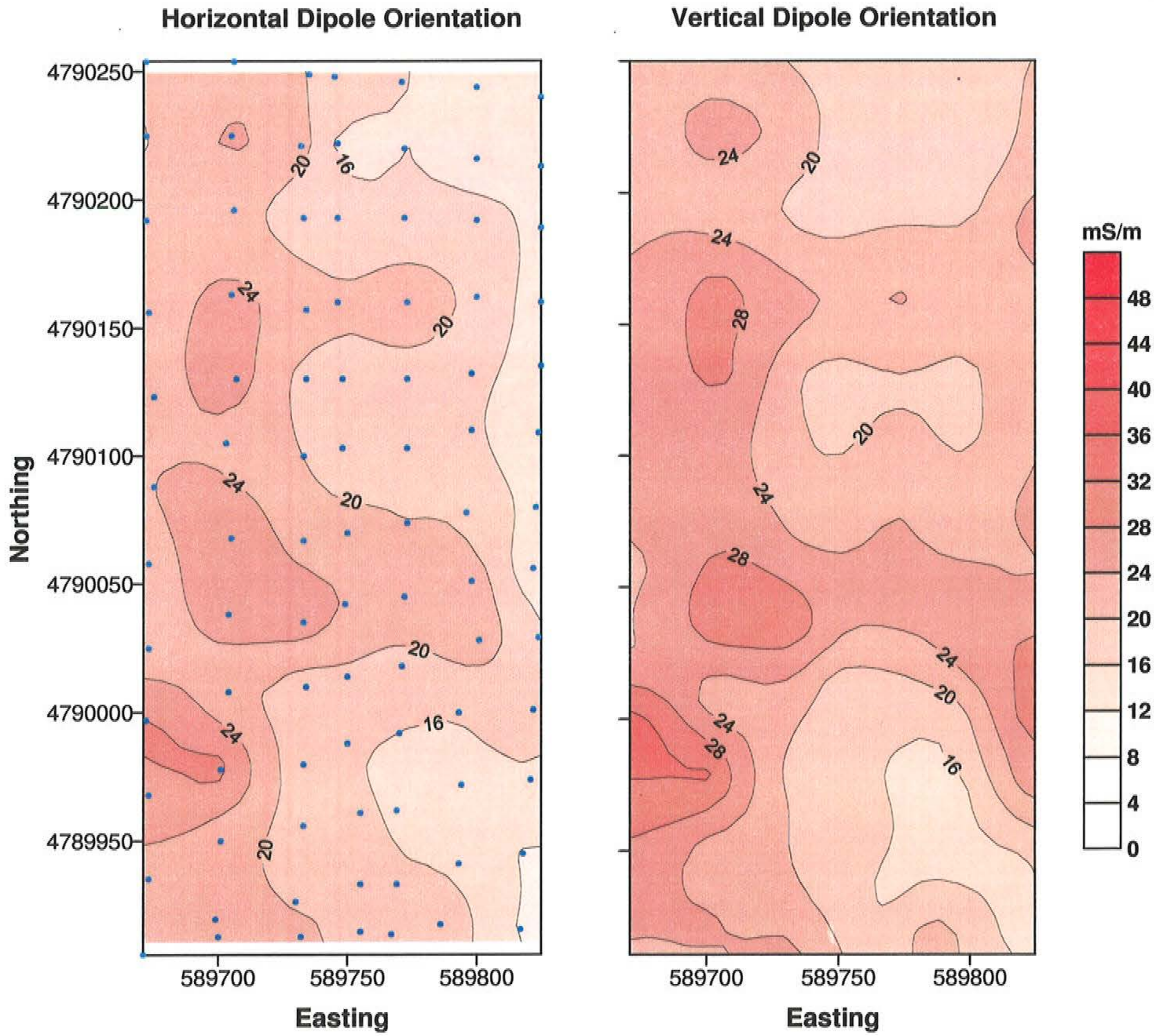


Figure 11

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #2
EM38 METER

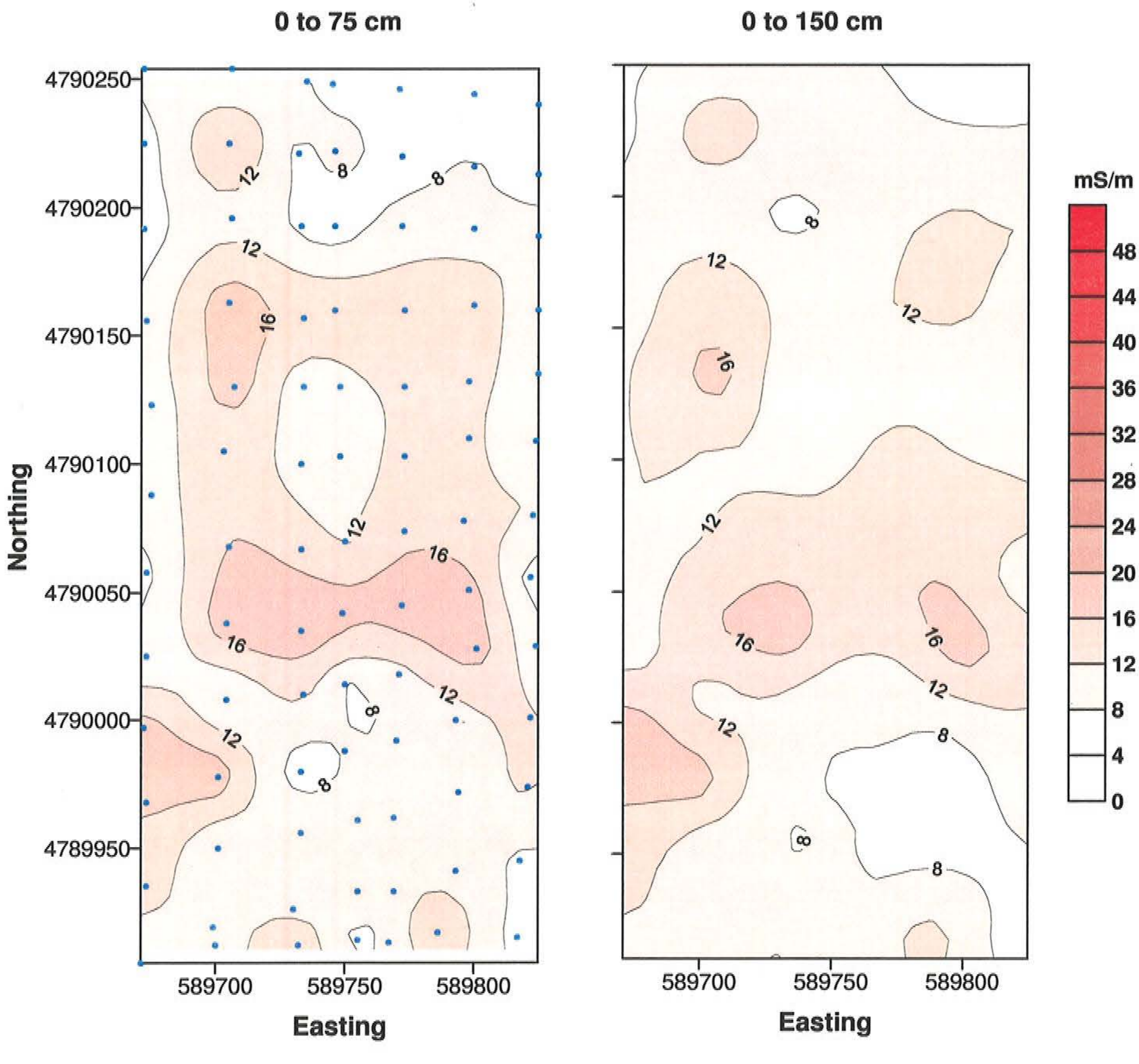


Figure 12

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #2
EM31 METER

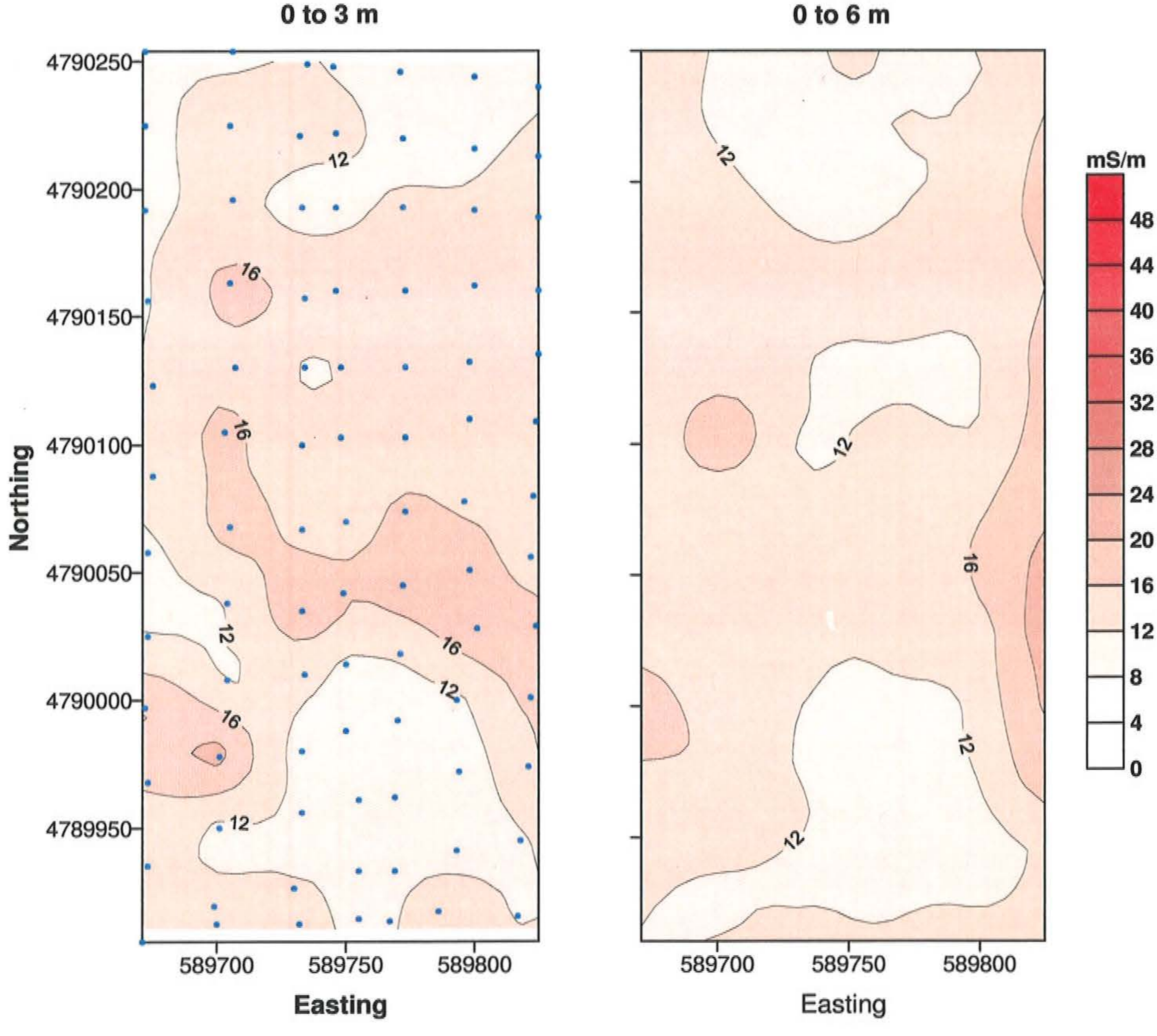


Figure 13

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #2
EM38 METER

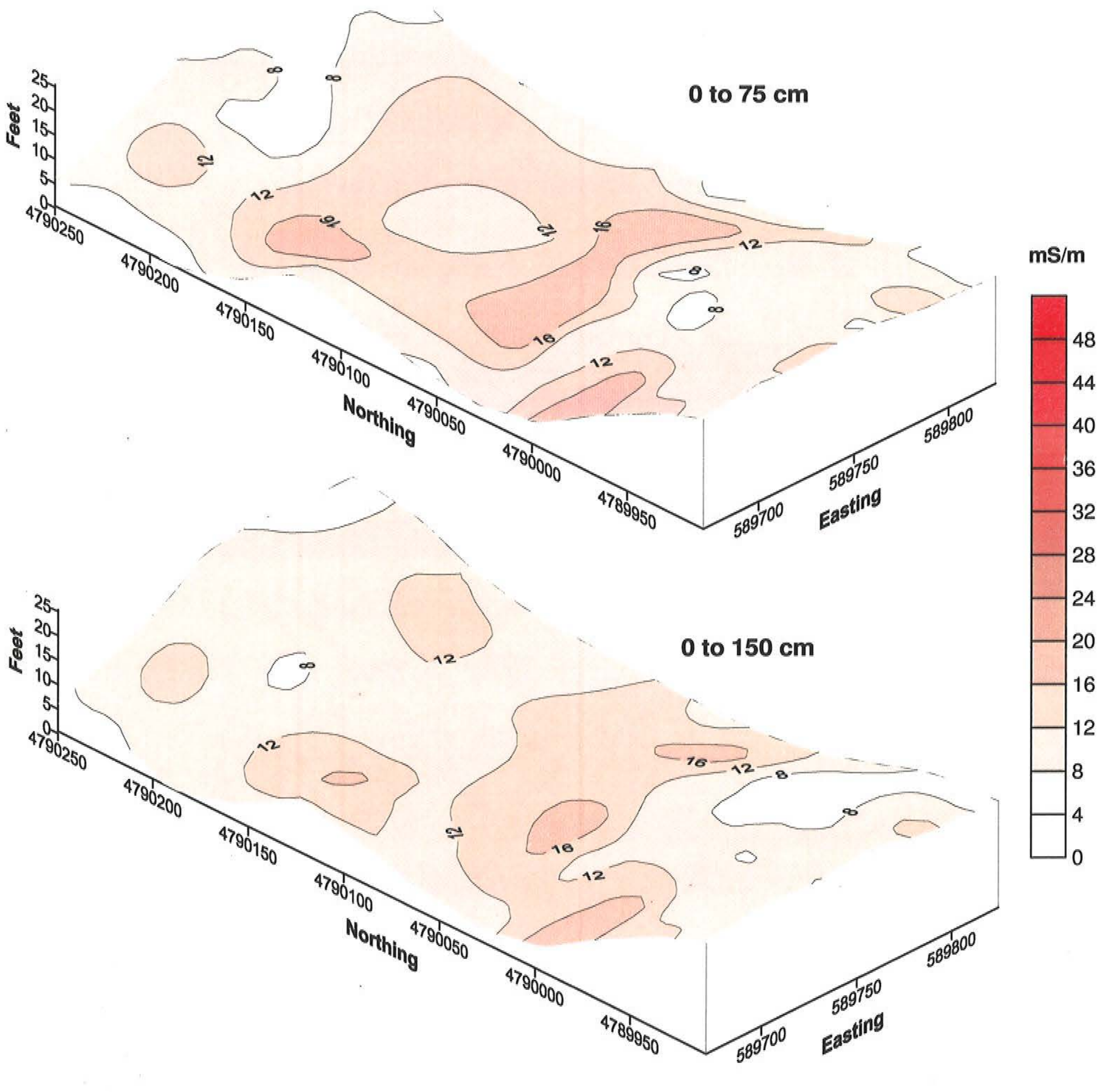


Figure 14

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #3
VERIS 3100 SYSTEM

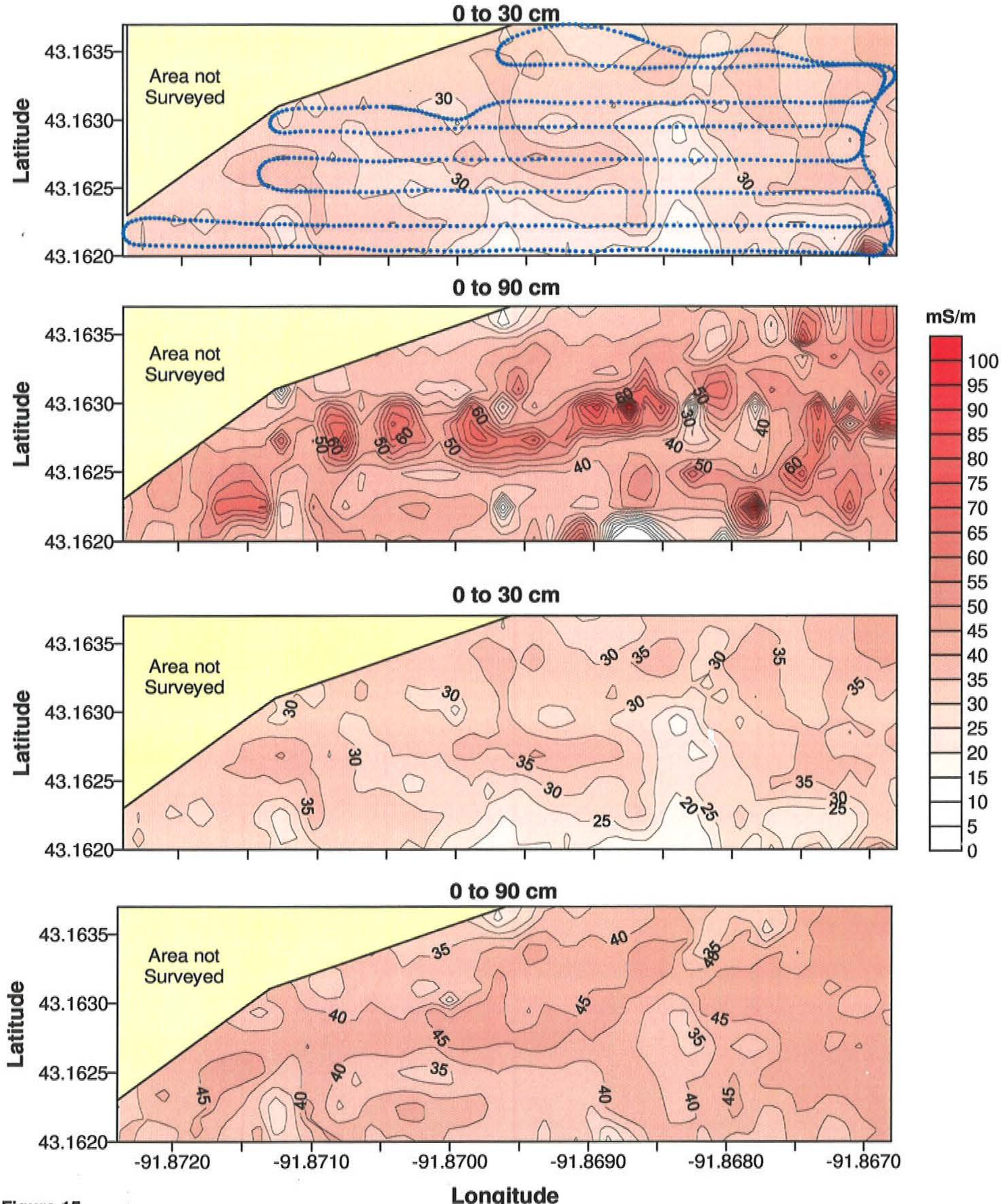


Figure 15

EMI SURVEY
WINNESHIEK COUNTY, IOWA
SITE #2
ISU's TOWED EM38 METER

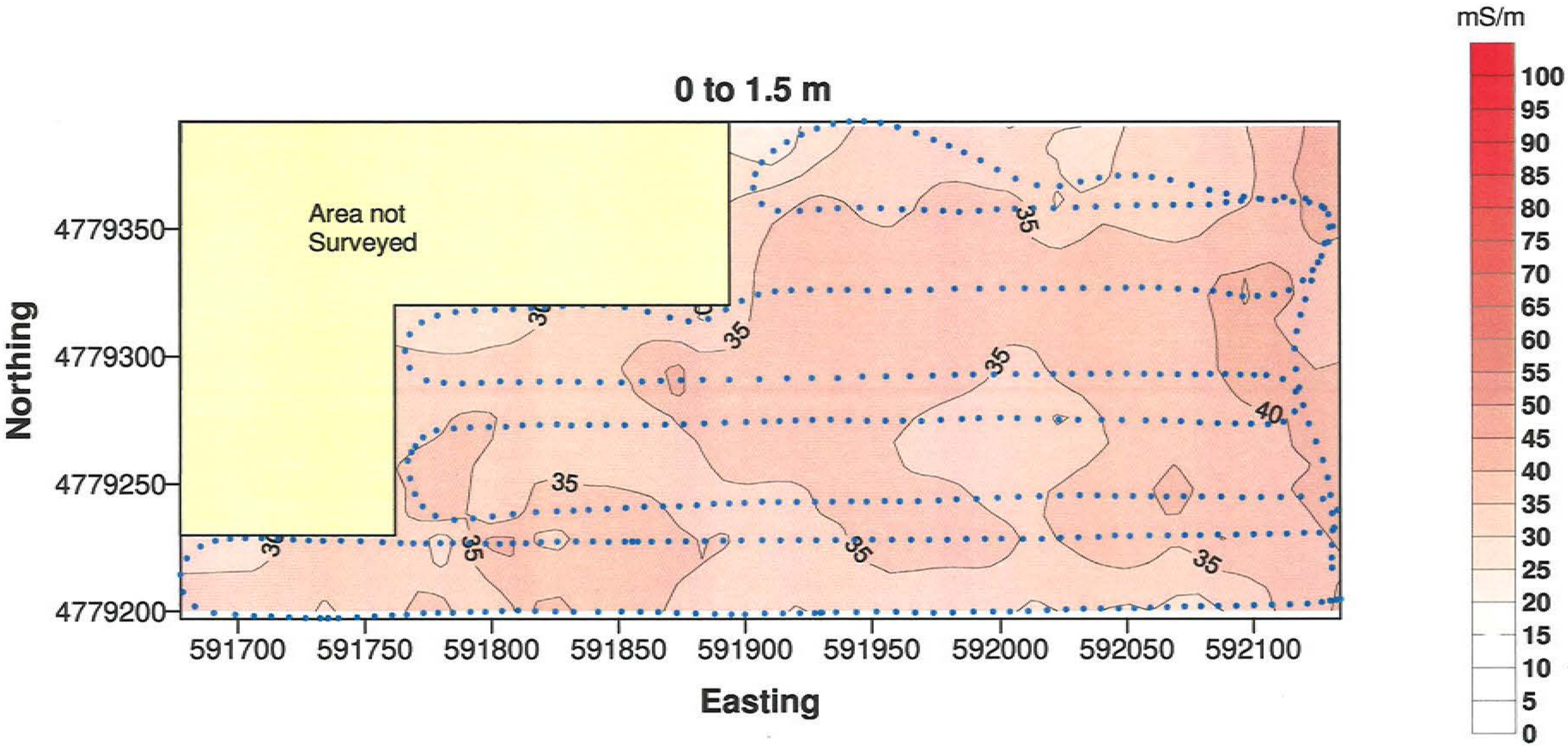


Figure 16