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

Subject: -- Geophysical Assistance -- **Date:** 28 August 2000

To: Steve Black
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Purpose:
The purpose of this investigation was to evaluate the suitability of using electromagnetic induction (EMI) and ground-penetrating radar (GPR) methods to help assist soil survey activities within Costilla County, Colorado. In addition, training and practical exposure to different geophysical tools and survey methods were provided to soil scientists.

Participants:
Jan Cipra, GIS/Soil Scientist, Colorado State University, Ft. Collins, CO
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Jim Doolittle, Research Soil Scientist, USDA-NRCS, Radnor, PA
Eugene Kelly, Professor, Colorado State University, Ft. Collins, CO
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Andrew Neuhart, Physical Sci. Technician, USDA-ARS, Ft. Collins, CO
Alan Price, Soil DQS,USDA-NRCS, Lakewood, CO
Marisa Rice, Soil Scientist, USDA-NRCS, San Luis, CO
Alan Stuebe, MLRA Project Leader, USDA-NRCS, San Luis, CO

Activities:
All field activities were completed during the period of 24 to 28 July 2000.

Results:
1. All participants were instructed in the use and operation of the GEM300 sensor. Following instructions, participants conducted EMI surveys with the GEM300 sensor.

2. Colorado has a core of soil scientists who are trained and highly trained on the use of EMI. Their tool is the EM38 meter. An earlier study along the Platte River in northeastern Colorado (my trip report of 31 August 1999) demonstrated that multifrequency sounding with the GEM300 sensor provides little additional information over that which can be obtained with the EM38 meter. However, the GEM300 sensor is easier to operate and can provide more continuous coverage of sites in a fraction of the time that is required with the EM38 meters presently being used in Colorado. In addition, faster, more mobile systems, that continuously and simultaneously record both horizontal and vertical dipole measurements and geo-reference the results will be required in the near future to provide faster and more comprehensive coverage for precision farming, high intensity soil surveys, and salinity appraisals. Dual dipole meters with data loggers may provide these requirements. Dual dipole meters are available. The National Soil Survey Center has an EM38-DD meter. Mike Petersen (Resource Soil Scientist, Greeley, CO) has observed the use of a Dualem 2 meter. These tools should be further evaluated in Colorado and an appraisal of their suitability made.

3. 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 soils and soil properties. At each site, variations in apparent conductivity were associated with changes in soil properties. Patterns of apparent conductivity were visually correlated with soil patterns.

4. A dilemma for field soil scientists using EMI methods will be to understand what measures of apparent conductivity do and do not tell us about soils and soil properties. 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 EMI methods.

5. In the lower-lying areas of Costilla County, ground-penetrating radar was too depth restricted to be an effective tool for soil investigations. High soluble salt and 2:1 expanding lattice clay contents produced excessive rates of signal attenuation that restrict observation depths. In areas of Travelers soils, observation depths were less than 24 inches; in areas of Costilla soils, observation depths were about 40 inches. The use of GPR for soil survey investigations may be suitable on the better-leached soils that occur on higher-lying, moister, upland areas.

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.

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

With kind regards,

James A. Doolittle
Research Soil Scientist

cc:
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Electromagnetic Induction

Equipment:

Two EMI tools, the EM38 meter and the GEM300 sensor, were available for this investigation. However, the I/P fine adjustment pod on the EM38 meter was broken, and the meter could not be used. The GEM300 multifrequency sensor, developed by Geophysical Survey systems, Inc., [1] is configured to simultaneously measure up to 16 frequencies between 330 and 20,000 Hz with a fixed coil separation (1.3 m). Won and others (1996) have described the use and operation of this sensor.

The positions of observation points were obtained with Rockwell Precision Lightweight GPS Receivers (PLGR).[1] 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 1927. Horizontal units were expressed in meters. For the detailed grid of the Travelers soil sites, the coordinates of all observations collected with the GEM300 sensor along measured grid lines were processed and adjusted by the MAGMAP96 software program developed by Geometrics. [1]

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.

Interpretation of Data:

Electromagnetic induction is being used for high intensity soil surveys and precision farming initiatives. 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 primary 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 profiled materials. No ground contact is needed with EMI.

Apparent conductivity was measured and mapped across each study site. 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 data are based on the identification of spatial patterns within data sets. Though seldom diagnostic in themselves, lateral and vertical variations in apparent conductivity have been used to infer changes in soils and soil properties. Electromagnetic induction integrates the bulk physical and chemical properties 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.

Depth of Observation:

The theoretical observation depth of the GEM300 sensor is dependent upon the bulk conductivity of the profiled earthen material(s) and the operating frequency of the sensor. Observation depths are governed by the "skin-depth" effect (Won, 1980 and 1983). Skin-depth is the maximum depth of penetration for an EMI sensor operating at a particular frequency and sounding a medium with a known conductivity. Penetration depth or "skin-depth" is inversely proportional to frequency (Won et al., 1996). Low frequency signals travel farther through conductive mediums than high frequency signal. Lowering the frequency will extend the depth of penetration. At a given frequency, the depth of penetration is greater in low

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

conductivity soil than in high conductivity soils. Mutifrequency sounding with the GEM300 allows multiple depths to be profiled with one pass of the sensor.

The depth of observation may be defined as the depth that contributes the most to the total EMI response measured on the ground surface. Although contributions to the measured response come from all profiled depths, the contribution from the *depth of observation* is the largest (Roy and Apparao, 1971). As noted by Roy and Apparao (1971), for any system, the depth of observation is a good deal shallower than is generally assumed or reported.

Precision Farming

In a recent article in a popular farm magazine, a sales agronomist maintains that "Soil EC [electrical conductivity] readings are light years ahead of the soil survey manuals" (Olson, 2000). The agronomist proceeded to note that "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, this statement is untrue as soil EC maps do not provide unique solutions; they merely show spatial patterns of apparent conductivity. Without knowledge of the spatial variations in soils and soil properties, EC maps are often uninterpretable and meaningless. 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 EMI has increased rapidly. With the expansion of 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 tool that may help us to better 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 are to evaluate innovative geophysical devices, learn their strengths and weaknesses, inform others on their use and interpretations, and develop protocol for field use within NRCS.

Field Procedures:

Random traverses were made across each study area. Along each traverse line, observations were taken at intervals of about 30 paces. This procedure produced 380 and 228 observation points at sites #1 and #2, respectively. The coordinates of each observation point were obtained with a Rockwell PLGR. At Site #1, observations were located within the irrigated field, along the perimeter road and outside the perimeter road in rangeland. The locations of these observation points are shown in the upper plot of Figure 1. At Site #2, observations were located within the irrigated field and along a perimeter road. The locations of these observation points are shown in the upper plot of Figure 4. In each plot of Site #2, the dark circle represents the approximate boundary of the irrigated field.

The GEM300 sensor was operated in the station mode. At each observation point, apparent conductivity measurements were taken with the GEM300 sensor held at hip-height in both the horizontal and vertical dipole orientations. Measurements were obtained at frequencies of 9810, 14790, and 19950 Hz.

In most EMI studies, negative conductivity values are removed by electronic nulling of the data set. The negative offset was not taken out of the EMI data. As a consequence, some negative apparent conductivity values appear in the data set and simulated plots. At Site #1, high negative values were obtained over the buried utility lines to the center pivot. Negative values are often indicative of buried metallic objects. These measurements formed linear patterns of conspicuously high apparent conductivity values across the field. As these high values masked spatial patterns attribute to changes in soil properties and types, they (N=14) were removed from the data set.

Discussion:

<u>Site #1</u>

The irrigated field was in barley. The site is in an area of Costilla and Mosca soils. The deep, well-drained Costilla soil formed in reworked alluvium from mixed rocks. Costilla soil is a member of the mixed, frigid Typic Torripsamments family.

The deep, well drained Mosca soils formed in mixed alluvium from basalt and similar iron-magnesium rich rocks. The Mosca soil is a member of the coarse-loamy, mixed, frigid Typic Natrargids family.

Figures 1, 2, and 3 show data recorded at frequencies of 19950, 14790, and 9810 Hz, respectively. In each figure the upper and lower plots represent data collected in the horizontal (shallower-sensing) and vertical (deeper sensing) dipole orientations, respectively. In each plot, the isoline interval is 6 mS/m. In Figure 1, the locations of 366 observation points are shown in the upper plot.

The theoretical depth of penetration 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 29.0, 33.5, and 38.8 mS/m at frequencies of 9810, 14790, and 19950 Hz, respectively. Based on equation [1], the selected frequencies, and these averaged conductivities, the estimated skin depths were 29.6, 22.5, and 18.0 m at 9810, 14790, and 19950 Hz, respectively. While the induced magnetic fields may achieve these depths, the strengths of the response from these depths are too weak to be sensed by the GEM300 sensor. The actual depth of observation is much shallower and is defined by the depth-weighting function of the sensor and the conductivity of shallower soil horizons. 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 sensor, 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 taken in the deeper-sensing, vertical dipole orientation were higher than those obtained in the shallower-sensing, horizontal dipole orientation. This relationship suggests the presence of more conductive layers in the subsurface than at 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. Though inconclusive, these relationships suggest a comparatively resistive (indicative of low soluble salt, clay, and/or moisture contents) superficial layer(s) underlain by a more conductive layer(s) that is itself underlain by a less conductive layer(s).

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

	Frequency (Hz)					
	9810v	**9810h**	**14790v**	**14790h**	**19950v**	**19950h**
AVERAGE	29.0	22.3	33.5	27.0	38.8	32.5
MINIMUM	2.5	-6.3	1.0	7.6	-3.1	7.8
MAXIMUM	124.8	83.4	129.0	88.4	137.6	95.7
FIRST	16.9	13.1	22.9	19.0	26.6	23.0
SECOND	27.7	22.5	32.7	26.9	39.1	32.9
THIRD	35.8	27.5	39.5	31.6	46.3	38.5

Table 2 summarizes the data collected at Site #1. With a frequency of 9810 Hz, apparent conductivity ranged from about – 6.3 to 83.4 mS/m in the horizontal dipole orientation and from about 2.5 to 124.8 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observations had values of apparent conductivity between 13.1 and 27.5 mS/m. In the vertical dipole orientation, half of the observations had values of apparent conductivity between 16.9 and 35.8 mS/m. With a frequency of 14790 Hz, apparent conductivity ranged from 7.6 to 88.4 mS/m in the horizontal dipole orientation and from 1.0 to 129.0 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observations had values of apparent conductivity between 19.0 and 31.6 mS/m. In the vertical dipole orientation, half of the observations had values of apparent conductivity between 22.9 and 39.5 mS/m. With a frequency of 19950 Hz, apparent conductivity ranged from 7.8 to 95.7 mS/m in the horizontal dipole orientation and from –3.1 to 137.6 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observations had values of apparent conductivity between 23.0 and 38.5 mS/m. In the vertical dipole orientation, half of the observations had values of apparent conductivity between 26.6 and 46.3 mS/m.

While measured values and spatial patterns of apparent conductivity did vary slightly with different frequencies and dipole orientations, the plots in figures 1, 2, and 3 are remarkable similar. This similarity cast doubts on the value of multifrequency soundings in this soil landscape. The use of one frequency with measurements taken in both the horizontal and vertical dipole orientation provides as much useful information as multi-frequency measurements taken in both dipole orientations.

A noticeable increase in apparent conductivity occurs immediately outside the irrigated field and in the adjoining rangeland. Increases in moisture content will increase the apparent conductivity of soils. The irrigated field had appreciably higher moisture contents than the surrounding rangeland. Consequently, these spatial patterns of apparent conductivity (low in irrigated field; high in non-irrigated rangeland) do not reflect changes in soil moisture contents. However, the increased moisture from sprinkler irrigation has leached soluble salts to greater soil depths within the irrigated field. In the non-irrigated rangeland, these salts are closer to the soil surface and are believed to be responsible for the higher apparent conductivity. These spatial patterns are therefore an artifact of management.

Within the irrigated field, spatial patterns are believed to principally reflect differences in clay rather than water or salt contents. Values of apparent conductivity are higher in the southwest quarter and lowest in the northeast quarter. These patterns are believed to represent the occurrence and relative thickness of finer- and coarser-textured alluvial sediments. Following this interpretation, soils should have lower clay contents in the northeast quarter than in the southwest quarter. It is presumed that Costilla soils dominate the northeast quarter and Mosca soils the southwest quarter of the study site. Within the irrigated field, spatial patterns and, presumably, the orientation of soil delineations have a northwest to southeast trend or orientation.

The conspicuous high apparent conductivity, circular anomaly in the southwest portion of the study area (414500 N, 444000 E) represents a small depression. Soils within this depression are noticeably wetter and are believed to be sodium-affected.

Site #2

The irrigated field was in potatoes. The site is in an area of Platoro and a coarse-loamy, mixed, frigid, superactive Typic Haplocamids soil. The deep, well-drained Platoro soil formed in calcareous alluvial materials derived from basalt and beds of sands and gravel. Platoro soil is a member of the fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Ustic Haplargids family.

Because of an active sprinkler system, only three-quarters of the field could be surveyed. Figures 4, 5, and 6 show the results of the EMI survey conducted with the GEM300 sensor. In each figure, the isoline interval is 8 mS/m. In Figure 4, the locations of the 228 observation points recorded with the GEM300 sensor are shown in each plot.

With the GEM300 sensor held at hip height in the vertical dipole orientation, apparent conductivity averaged 37.2, 43.2, and 47.5 mS/m at frequencies of 9810, 14790, and 19950 Hz, respectively. Based on equation [1], the selected frequencies and these averaged conductivities, the estimated skin depths (penetration depths) were about 26.2 m at 9810 Hz, 19.8 m at 14790 Hz and 16.2 m at 19950 Hz. These depths are theoretical and represent maximums. As discussed earlier, the actual depth of observation is much shallower than the skin-depth and is defined by the depth-weighting function of the sensor and the conductivity of shallower soil horizons. However, in a comparative sense, skin depths are useful as they show the relationships between operating frequency, conductivity, and penetration depth.

Table 2 summarizes the GEM300 data collected at Site #2. Measurements taken in the horizontal dipole orientation were typical lower and less variable than measurements taken in the vertical dipole orientation. In both dipole orientation, with decreasing frequency and increasing penetration depth, values of apparent conductivity became lower and less variable. With a frequency of 9810 Hz, apparent conductivity ranged from 7.6 to 50.8 mS/m in the horizontal dipole orientation and from 16.9 to 66.3 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observations had values of apparent conductivity between 21.6 and 28.1 mS/m. In the vertical dipole orientation, half of the observations had values of apparent conductivity between 32.0 and 41.4 mS/m. With a frequency of 14790 Hz, apparent conductivity ranged from 5.3 to 57.4 mS/m in the horizontal dipole orientation and from 9.7 to 70.7 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observations had values of apparent conductivity between 27.5 and 33.8 mS/m. In the vertical dipole orientation, half of the observations had values of apparent conductivity between 38.0 and 47.7 mS/m. With a frequency of 19950 Hz, apparent conductivity ranged from –4.7 to 62.6 mS/m in the horizontal dipole orientation and from –2.9 to 76.9 mS/m in the vertical dipole orientation. In the horizontal dipole orientation, half of the observations had values of apparent conductivity between 31.4 and 38.6 mS/m. In the vertical dipole orientation, half of the observations had values of apparent conductivity between 42.3 and 52.1 mS/m.

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

	Frequency (Hz)					
	9810v	9810h	14790v	14790h	19950v	19950h
AVERAGE	37.2	25.9	43.2	31.3	47.5	35.7
MINIMUM	16.9	7.6	9.7	5.3	-2.9	-4.7
MAXIMUM	66.3	50.8	70.7	57.4	76.9	62.6
FIRST	32.0	21.6	38.0	27.5	42.3	31.4
SECOND	36.0	24.5	42.5	30.3	46.3	34.9
THIRD	41.4	28.1	47.7	33.8	52.1	38.6

Spatial patterns of apparent conductivity measured with the GEM300 sensor within the study site are shown in figures 4, 5, and 6. These figures represent apparent conductivity data collected at 19950 (Figure 4), 14790 (Figure 5), and 9810 (Figure 6) Hz. In each figure the upper and lower plots represent data collected in the horizontal (shallower-sensing) and vertical (deeper sensing) dipole orientations, respectively.

Unlike the survey conducted at Site #1, at Site #2 no measurements were made in the adjoining non-irrigated rangeland areas. Within the irrigated field, spatial patterns are believed to principally reflect differences in clay rather than water or salt contents. The high apparent conductivity values that are noticeable along the eastern half of the east-west diameter line are attributed to buried utility lines and the center pivot.

Spatial patterns and conductivity levels do vary in each plot. In general, for each dipole orientation, apparent conductivity decreases with increasing observation depth. This relationship is believed to reflect lower clay and moisture contents at lower soil depths. However, without ground-truth observations or a greater knowledge of soils and soil properties, interpretations cannot be made at this time with any degree of confidence.

Bedrock Mapping:

Background:

Traditionally, soil scientists have used shovels and augers to acquire information on the depth to bedrock. These tools are rather slow and tedious to operate, and the data collected are relatively expensive and therefore limited. In many areas, the depth to bedrock is highly variable over short distances and extrapolations made from a limited number of widely spaced auger observations can be flawed. A large number of borings is required to adequately characterize the distribution of bedrock depths within soil map units. Soils containing rock fragments limit the effectiveness of shovels and augers for measuring the depths to bedrock. In these soils, the probably of encountering a rock fragment increases with increasing soil depth. Studies have shown that the depths to bedrock are underestimated with traditional soil survey tools (Doolittle et al., 1988; Collins et al., 1989). Limited by the tools normally used, soil scientists must infer the depth to bedrock from vegetative cover and landscape position. These inferences are often based on anticipated rather than confirmed depths to bedrock. For these reasons, alternative techniques are needed to complement traditional soil survey tools and to improve the characterization of bedrock depths within soil map units.

Alternative field methods are available. Electromagnetic induction and ground-penetrating radar have been used extensively to characterize and map bedrock depths. Ground-penetrating radar has proven to be highly effective in coarse- and moderately coarse-textured, more thoroughly leached soils of eastern United States. In semi-arid and arid regions of the United States, soluble salts of potassium and sodium and less soluble carbonates of calcium and magnesium are more likely to accumulate in the upper parts of the soil. These salts produce high attenuation rates that restricts the radar's penetration depths (Doolittle and Collins, 1995).

Electromagnetic induction methods 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.

Study Site:

The site was located in an area of Travelers soil. The Travelers series consists of shallow, excessively drained soils that formed in material weathered from basalt. Travelers is a member of the loamy-skeletal, mixed, active, frigid Lithic Ustic Haplocambids family. The study site was in rangeland. Basalt bedrock was exposed on higher-lying, convex areas of the study site.

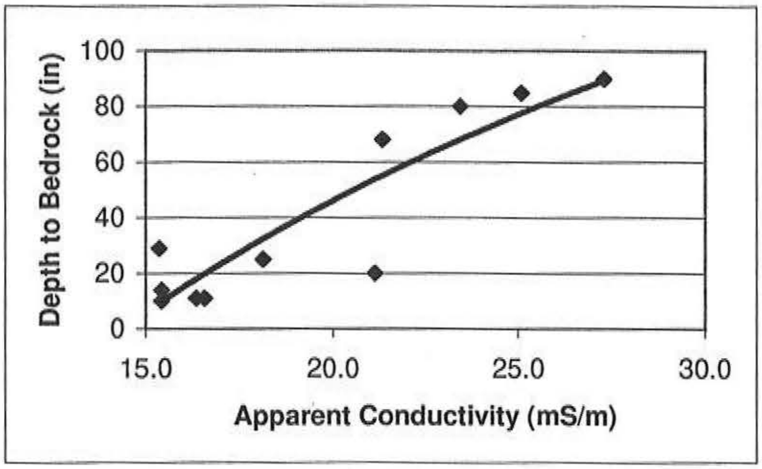
Field Procedures:

A 100 by 100 m grid was established with a Rockwell PLGR. Eleven survey lines were established across the study site at intervals of 10 m. The length of each survey line was 100 m. The GEM300 sensor was operated in the continuous mode. Measurements were taken with the GEM300 sensor held at hip-height in the vertical dipole orientation and at a frequency of 19950 Hz. The GEM300 sensor was configured to record an observation every 2 seconds. Walking at a uniform pace along each of the eleven parallel survey lines resulted in 757 observations. The locations of these observation points were processed and adjusted by the MAGMAP96 software program. The locations of these observation points are shown in Figure 7.

Eleven additional sampling points were selected to compare the observed depth to bedrock with EMI measurements. At each of these sampling point the depth to bedrock was determined with a power auger or shovels and screw augers. Measurements were obtained with the GEM300 sensor, operated in the station mode over each of these sampling points.

Estimation of Depths to Basalt

The thickness of alluvium and the depth to basalt varied across the site because of differences in erosion, deposition, and landscape position. Because of differences in clay, soluble salt, and water contents between the alluvium and the underlying basalt, vertical contrasts in electrical conductivity were assumed to exist. It was assumed that variations in the magnitude of the EMI response could be used to provide estimates of the thickness of the alluvium and/or the depth to basalt bedrock. Areas with higher apparent conductivity were assumed to have thicker sola and greater depths to bedrock than areas with lower apparent conductivity.



Relationship Between Apparent Conductivity and the Depth to Bedrock

At eleven sampling points, the depth to basalt was estimated from power auger or shovel observations. Observed depths to bedrock averaged 40.3 inches and ranged from about 10 to 90 inches. A comparison of soil probe and EMI data collected at the eleven sampling points is shown in the chart above. A strong positive correlation (r = 0.86) was obtained between depth to basalt and EMI response. This relationship conforms to the basic conceptual model of the site: the medium-textured soil has higher clay, moisture, and soluble salt contents and is therefore more conductive than the underlying basalt. Areas having greater depths to basalt generally have higher EMI responses.

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

$$D = -39.68 + (3.21 * 19950Hz)) \quad [2]$$

where "D" is depth to basalt (in) and "19950Hz" is the apparent conductivity (mS/m) measured by the GEM300 sensor at an operating frequency of 19950 Hz and in the vertical dipole orientation. The coefficients used in Equation [2] are relatively large. These large coefficients will magnify small measurement errors.

Based on 757 EMI measurements and predictive Equation [2], the average depth to basalt within the study site was estimated to be 29.3 inches with a range of 9.3 to 66.7 inches. One-half of the observations had depths to basalt between 18.5 and 35.3 inches. The basalt was shallow (< 20 inches) at 38 percent, moderately deep (20 to 40 inches) at 37 percent, deep (40 to 60 inches) at 22 percent, and very deep (>60 inches) at 3 percent of the observation points. The preponderance of moderately deep and shallow soils is in accord with the soils and map units delineated within the study site.

The distribution of apparent conductivity measured with the GEM300 sensor in the vertical dipole orientation and at a frequency of 19950 Hz is shown in Figure 7. Within the study site, apparent conductivity averaged 21.6 mS/m with a range of 15.3 to 33.2 mS/m. One-half of the observations had apparent conductivity between 18.2 and 24.8 mS/m. In general, values of apparent conductivity were lower on higher-lying convex surfaces and higher on lower-lying concave surfaces.

Figure 8 is a two-dimensional simulation showing the distribution of depths to basalt across the study site. Depths are based on EMI measurements and predictive Equation [2]. The spatial patterns indicate that the depths to basalt are dominantly shallow and moderately deep across the site. Within the study site, areas of shallow soils occur principally on higher-lying convex surfaces. Areas of deep and very deep soils occur mainly as elongated linear features located on lower-lying concave surfaces.

The empirical relationship shown in Equation [2] is site specific. Additional observations are needed to transfer the results of this study to other sites. At a second site, the relationship between depth to bedrock and EMI response was reversed as values of apparent conductivity increased as the depth to bedrock decreased. At the second site the basalt was of a different age, and may contain different minerals and a greater amounts of magnetite than at the reported site. Results may reflect differences in magnetic susceptibility between the sites or a malfunctioning of the sensor (GEM300 sensor latter failed to operate at the second site).

Ground-Penetrating Radar

Equipment:

The radar unit is the Subsurface Interface Radar (SIR) System-2, manufactured by Geophysical Survey Systems, Inc.[2] The SIR System-2 consists of a digital control unit (DC-2) with keypad, VGA video screen, and connector panel. A 12-volt battery powered the system. Morey (1974), Doolittle (1987), and Daniels (1996) have discussed the use and operation of GPR. The SIR System-2 is backpack portable and requires two people to operate. The models 5103 (400 MHz), 5106 (200 MHz) and 3110 (120 MHz) antennas were used in this study. The scanning time was either 50 or 60 nanoseconds (ns); the scanning rate was 32 scan/second were used in this survey.

Field Procedures:

Pulling the antenna across selected areas of soil map units completed radar surveys. Although, GPR provides a continuous profile of subsurface conditions, interpretations were restricted to observation points. These observation points were spaced at intervals that ranged from about 15 to 50 feet. At each observation point, the radar operator impressed a dashed, vertical line on the radar profile. This line identified an observation point on the radar record.

Each radar traverse was stored as a separate file on a hard disc. Radar files were reviewed and subsurface or bedrock interfaces identified.

Discussion:

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

$$v = 2d/t \quad [3]$$

Velocity is expressed in meter per nanosecond. The amount and physical state of water (temperature dependent) have the greatest effect on the dielectric permittivity of a material.

The radar was calibration during fieldwork. The velocity of propagation was determined at several calibration sites. These values were used to establish depth scales for the radar imagery. At the Costilla soil site, a metallic reflector was buried at a depth of 18 inches. Based on the round-trip travel time to the buried reflector, the averaged velocity of propagation was estimated to be 0.1003 m/ns. Based on an average velocity of propagation of 0.1003 m/ns, a scanning time of 60 ns provided a maximum observation depth of about 3.0 m.

Results:

Results were disappointing, but not unexpected. Observations depths were severely restricted by high rates of signal attenuation that were attributed to the presence of sufficient amounts of soluble salts and 2:1 expanding lattice clays in soil profiles. At the Travelers soil (loamy-skeletal, mixed, active, frigid Lithic Ustic Haplocambids) site, the 200 MHz antenna provide the best balance of resolution and observation depth. However, because of the high calcium carbonate content of this loamy-skeletal soil, the bedrock interface was discernible only at relatively shallow depths (< 24 inches).

Costilla (mixed, frigid Typic Torripsamments) represents the coarsest textured soil mapped within Costilla County. In the lower-lying areas of Costilla County, this soil represents one of the most favorable mediums for the use GPR. However, because of rapid rates of signal attenuation, observation depths were restricted to depths of less than 1.3 m.

Figure 9 is a representative radar profile from an area of Costilla loamy sands, 0 to 3 percent slopes. This profile was obtained with the 200 MHz antenna and a scanning time of 60 ns. Along the left-hand border of the radar profile is a depth scale. The depth scale (left-hand margin) is based on the estimated velocity of propagation, a scanning time of 60 ns, and

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[2] Manufacturer's names are provided for specific information; use does not constitute endorsement.

equation [3]. The depth scale is expressed in meters. The white vertical lines at the top of the radar profile represent observation points that are spaced at intervals of about 5 meters.

In general, the quality of the radar image shown in Figure 9 is fair. In the right-hand portion of this profile, the conspicuous hyperbolic reflection ("A") is from a metallic reflector that had been buried at a depth of 46 cm. A conspicuous planar reflector is evident in this profile at depths ranging from about 80 to 100 cm. In Figure 9, the upper surface of this reflector has been highlighted with a dark line. This reflector is believed to represent a coarser-textured subsurface horizon of calcium carbonate enrichment.

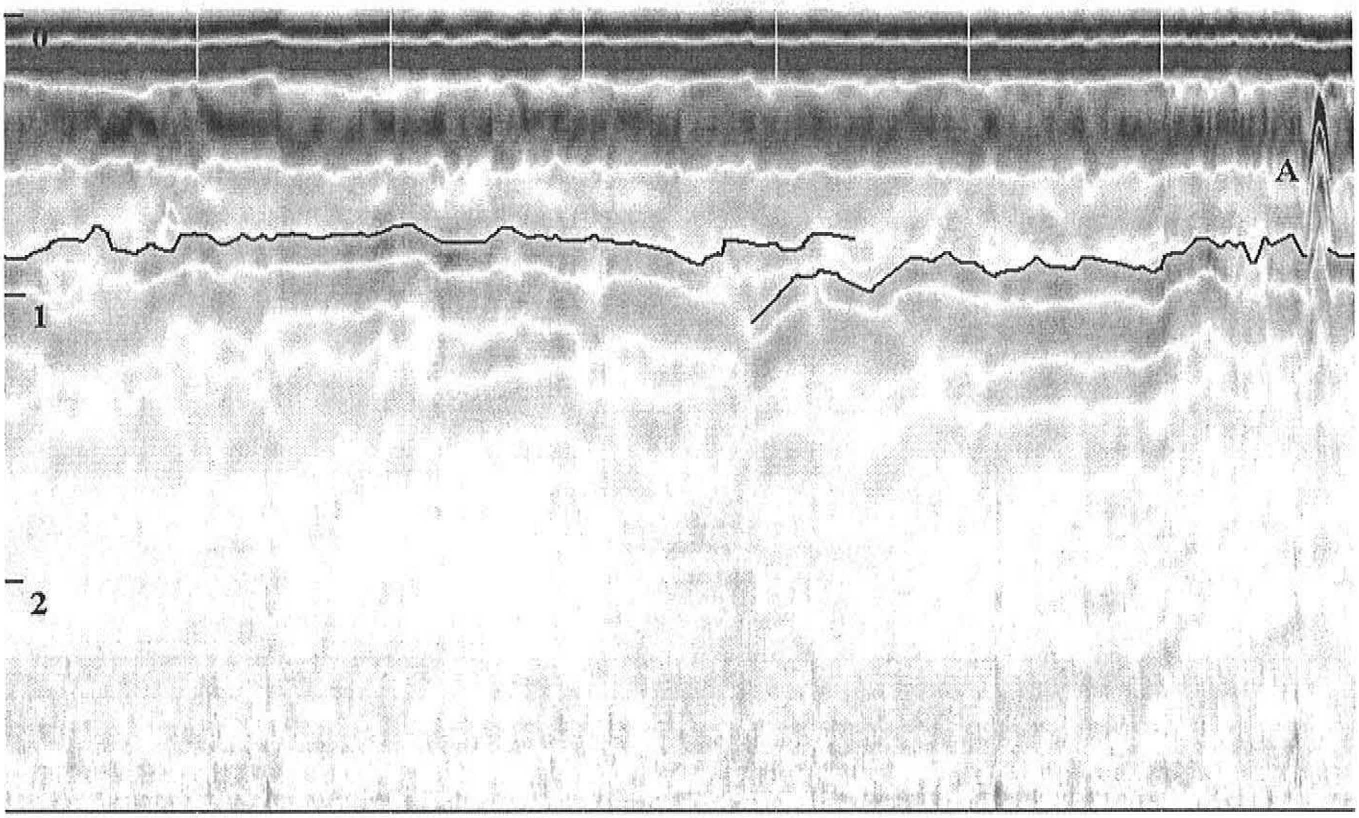

Figure 9
Representation GPR Profile of Costilla Soil

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GEM300 SENSOR
19950 Hz
IRRIGATED BARLEY FIELD

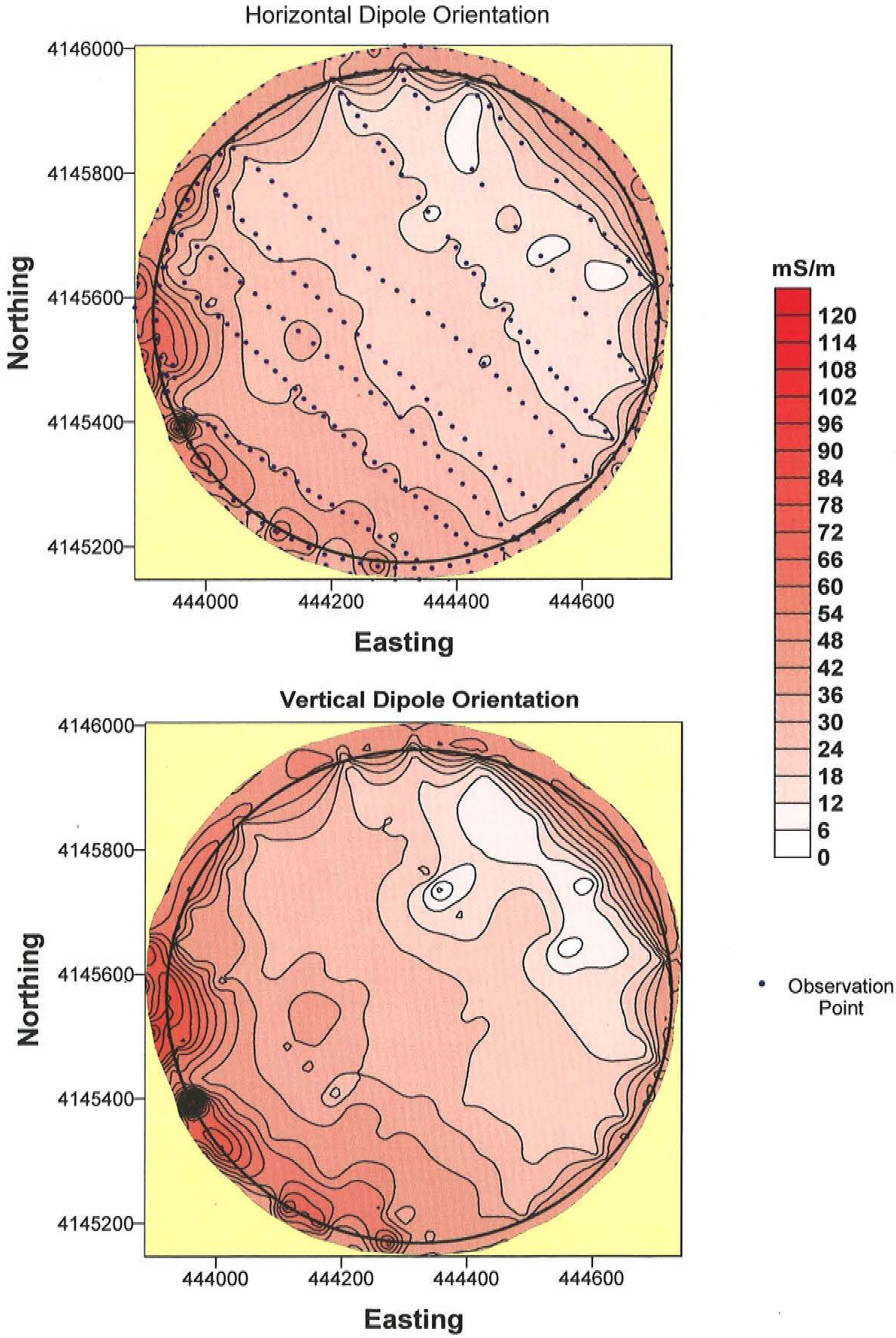


Figure 1

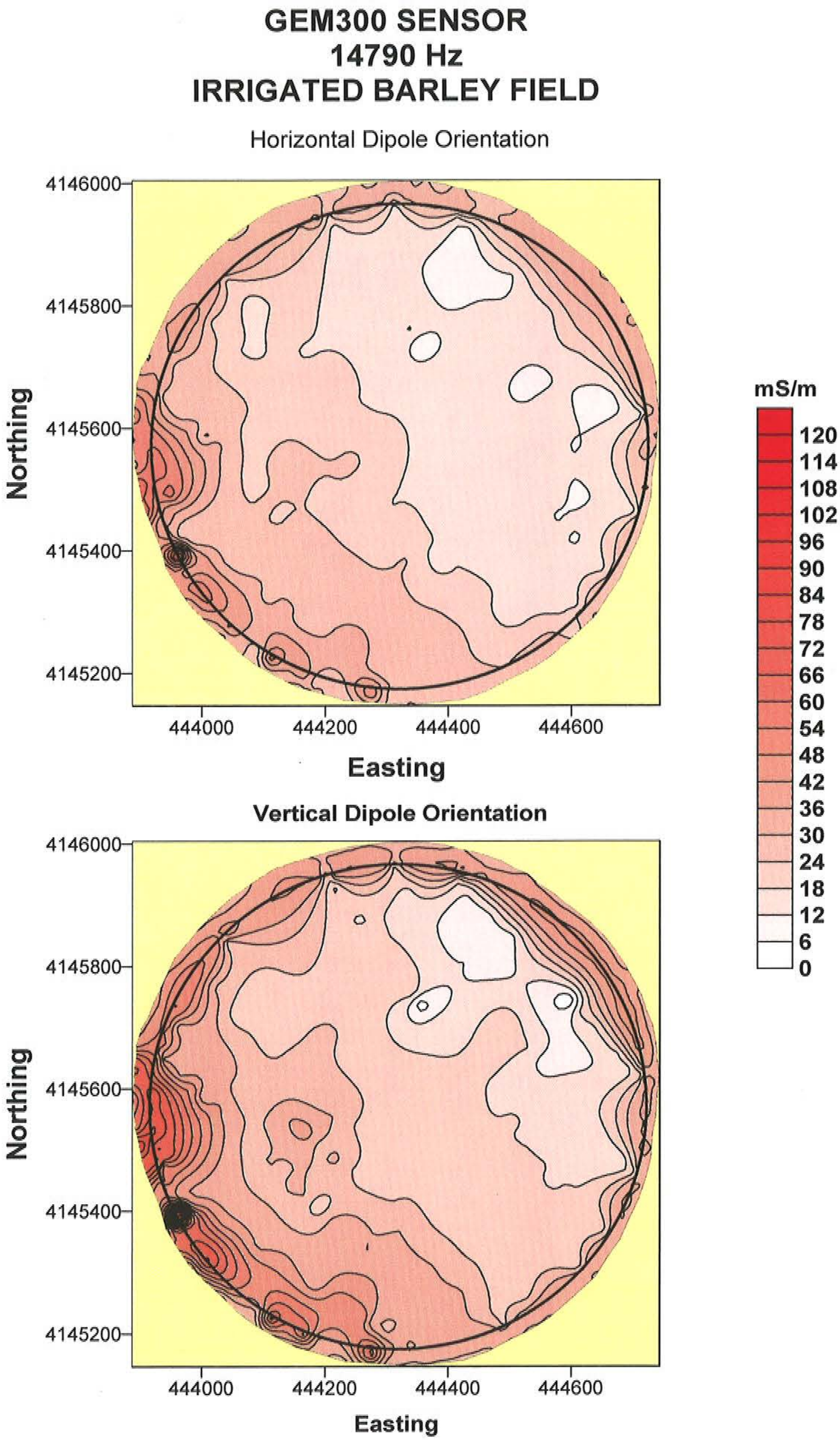

GEM300 SENSOR
14790 Hz
IRRIGATED BARLEY FIELD
Horizontal Dipole Orientation
Vertical Dipole Orientation
Northing
Easting
4146000
4145800
4145600
4145400
4145200
444000
444200
444400
444600
mS/m
120
114
108
102
96
90
84
78
72
66
60
54
48
42
36
30
24
18
12
6
0

Figure 2

GEM300 SENSOR
9810 Hz
IRRIGATED BARLEY FIELD

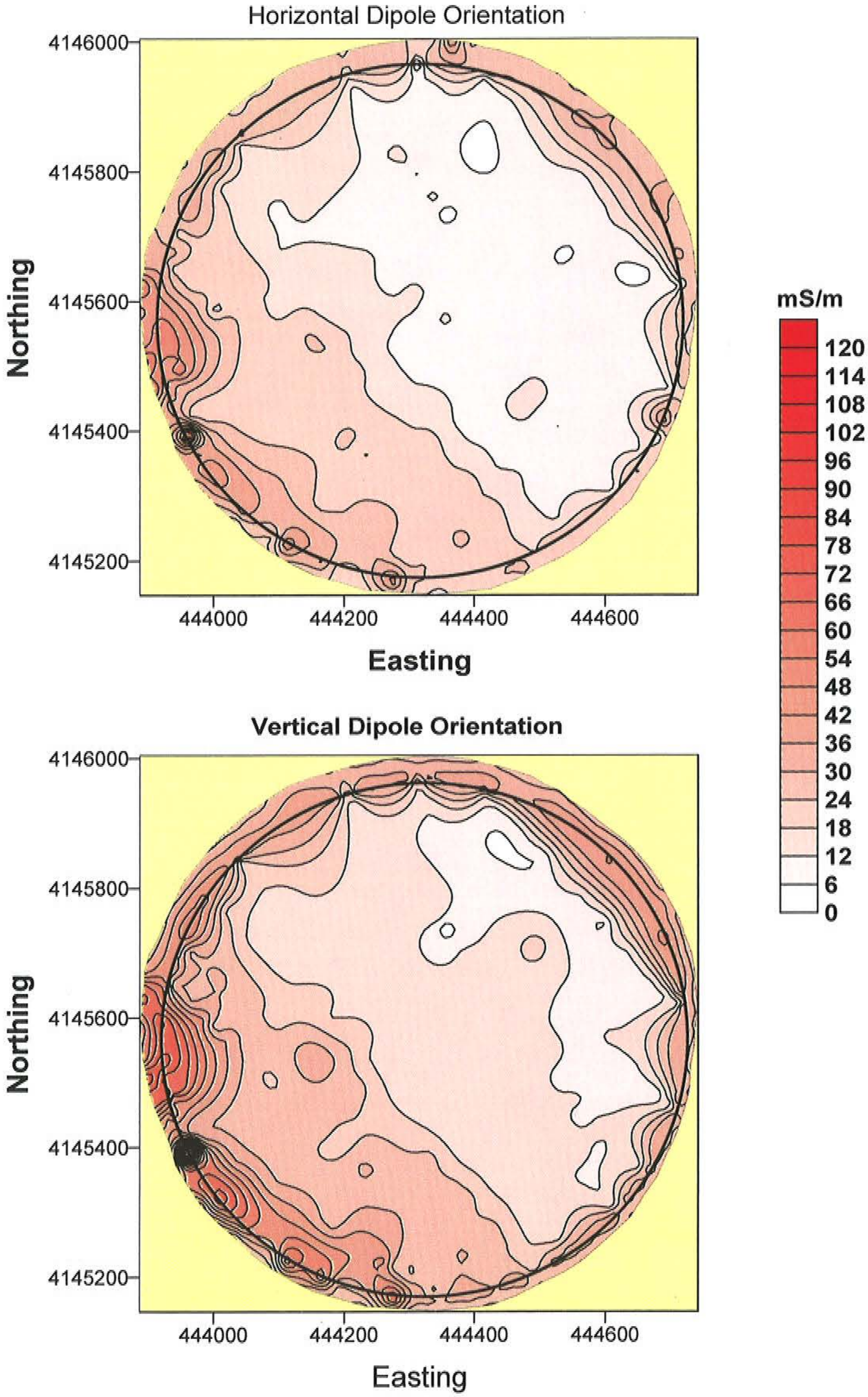


Figure 3

GEM300 SENSOR
14790 Hz
IRRIGATED POTATO FIELD

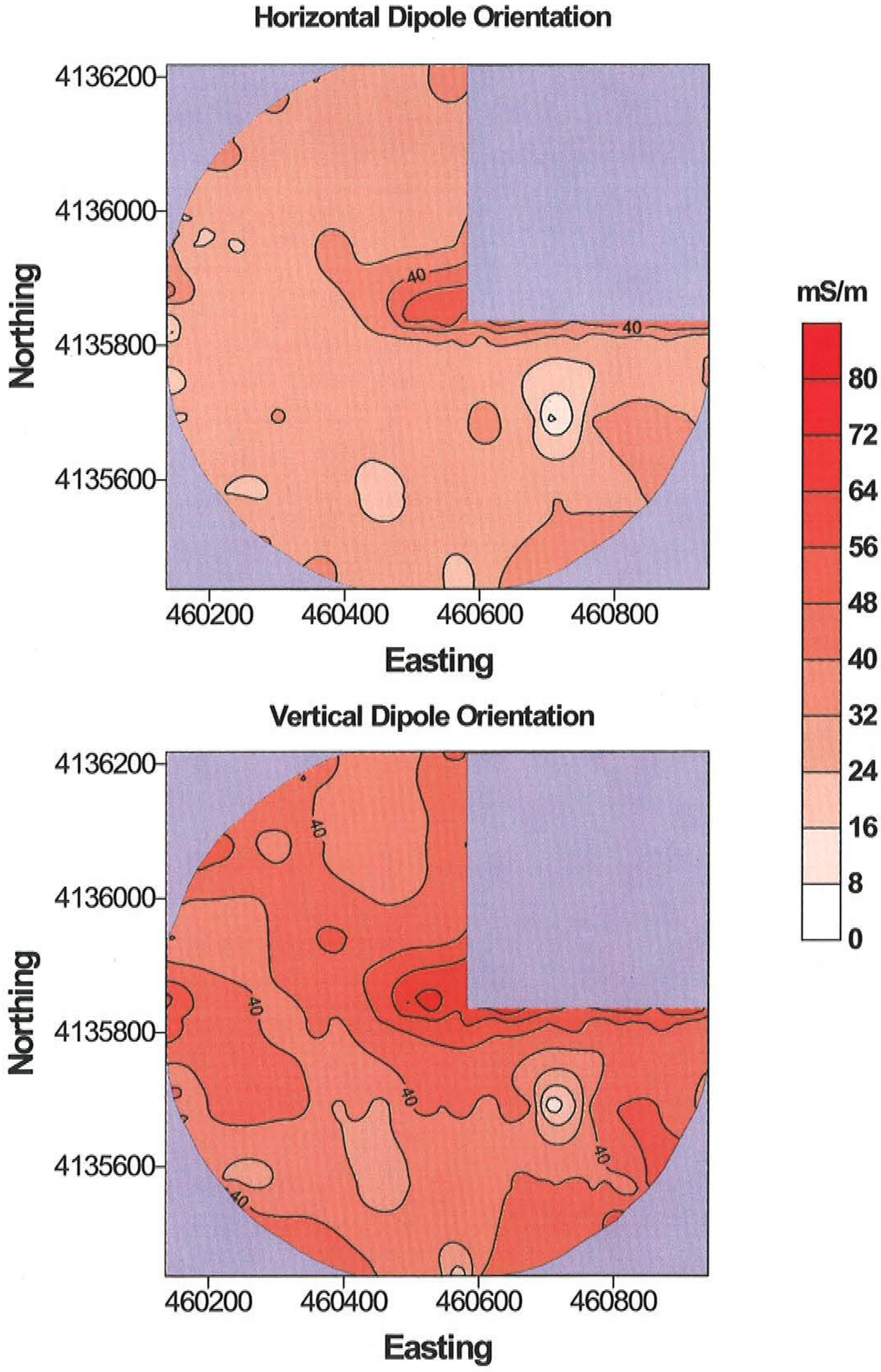


Figure 5

GEM300 SENSOR
19950 Hz
IRRIGATED POTATO FIELD

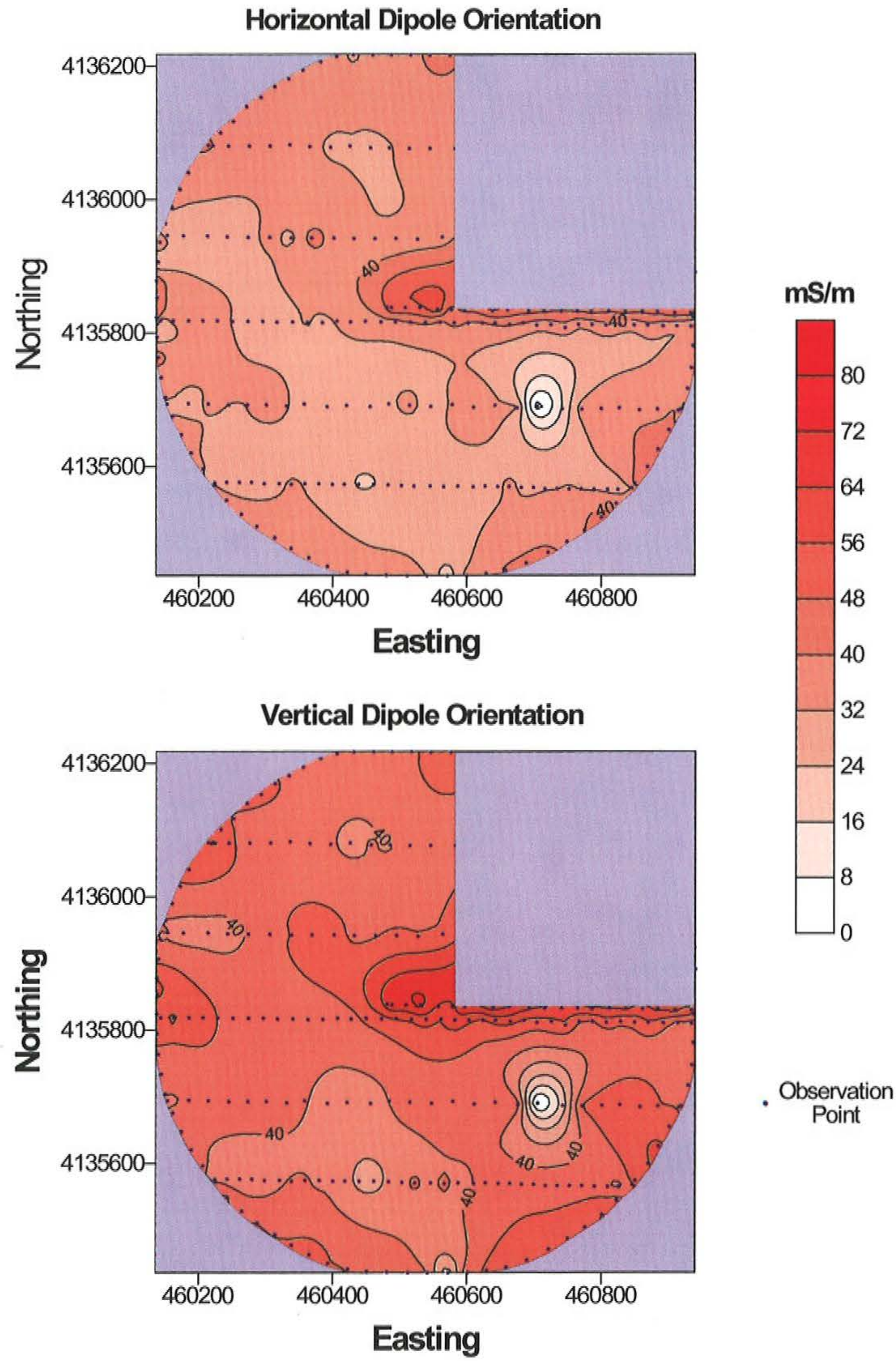


Figure 4

GEM300 SENSOR
9810 Hz
IRRIGATED POTATO FIELD

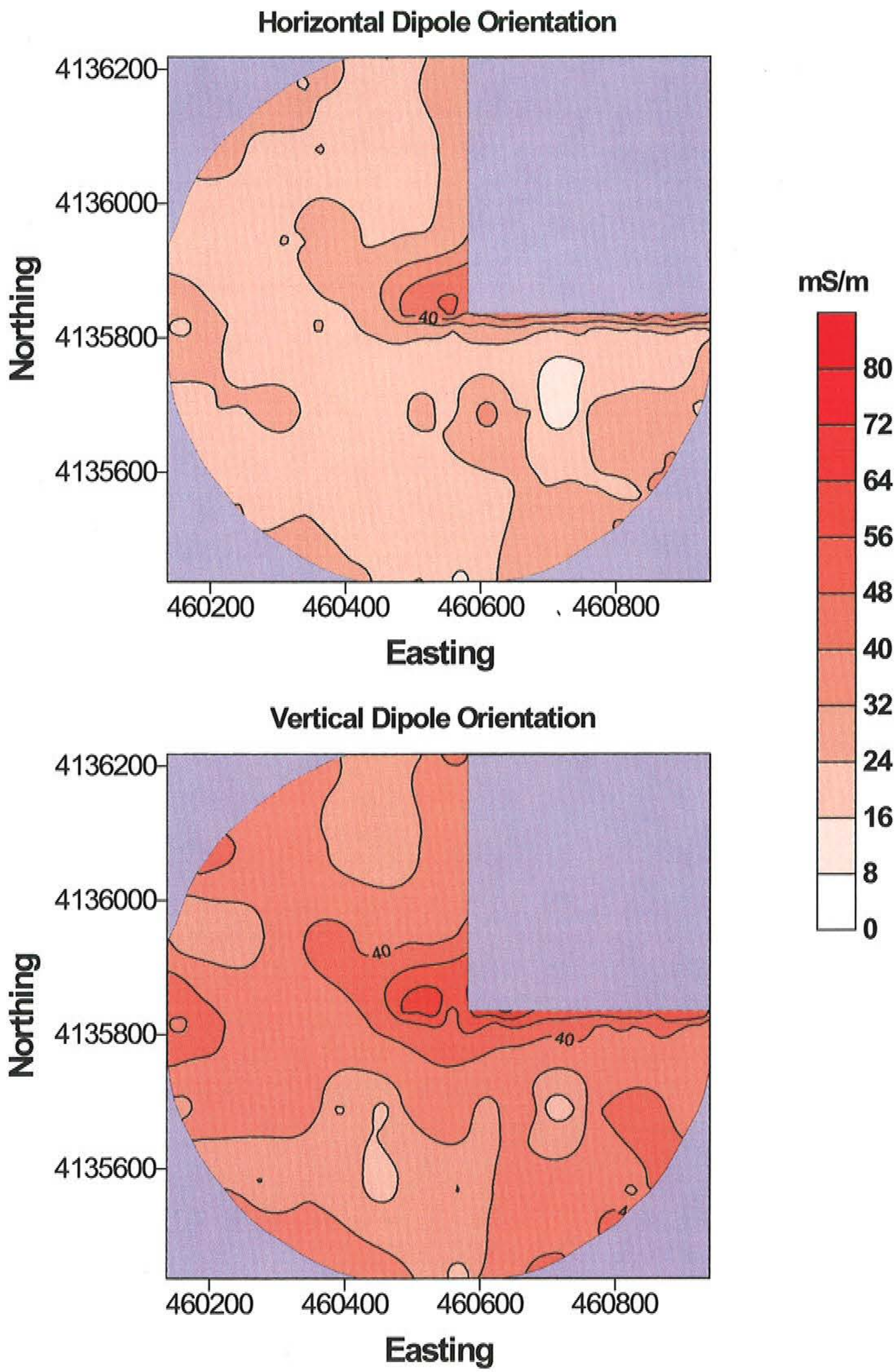


Figure 6

EMI SURVEY
AREA OF TRAVELER SOIL
GEM300 SENSOR
19950Hz
VERTICAL DIPOLE ORIENTATION

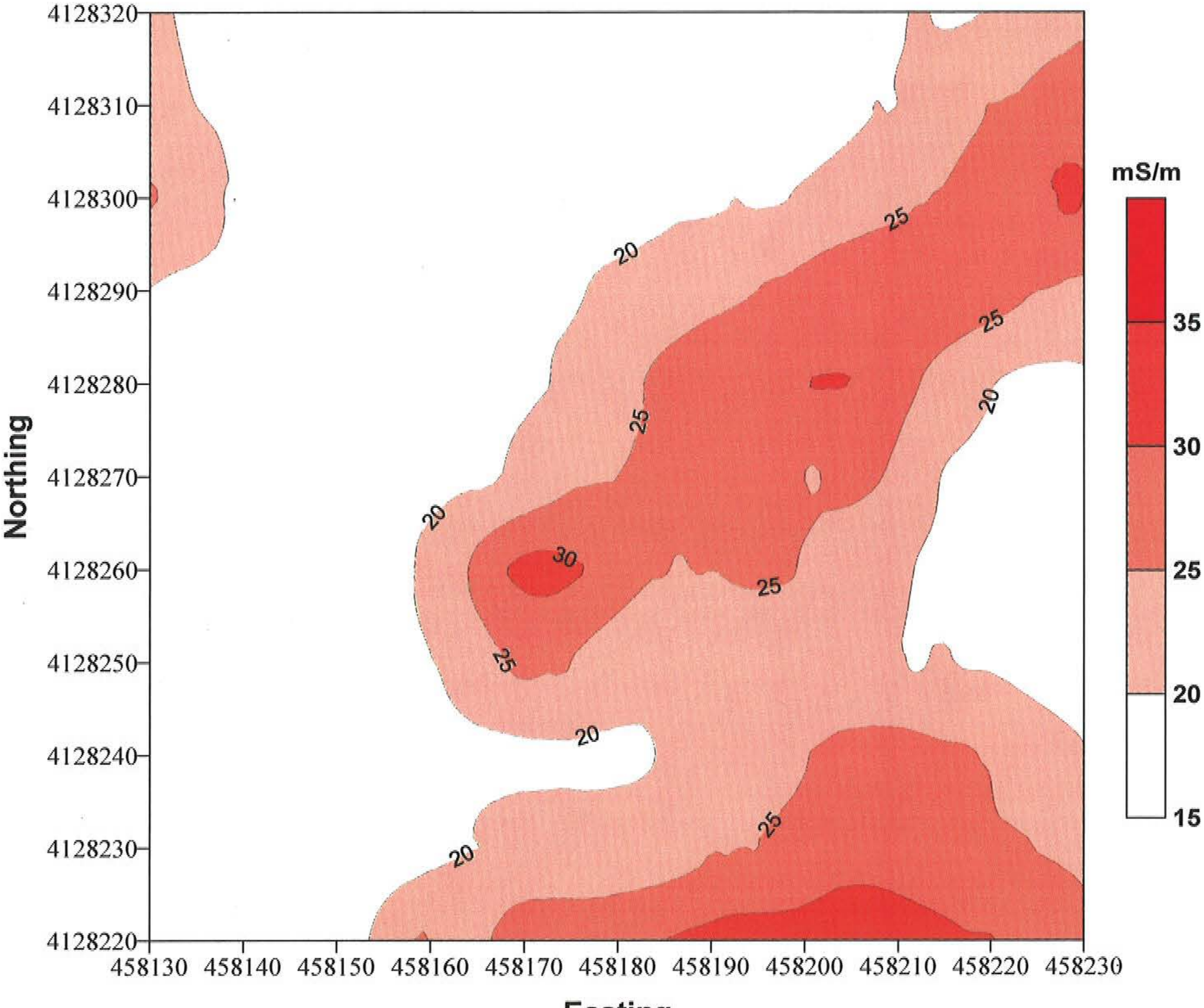
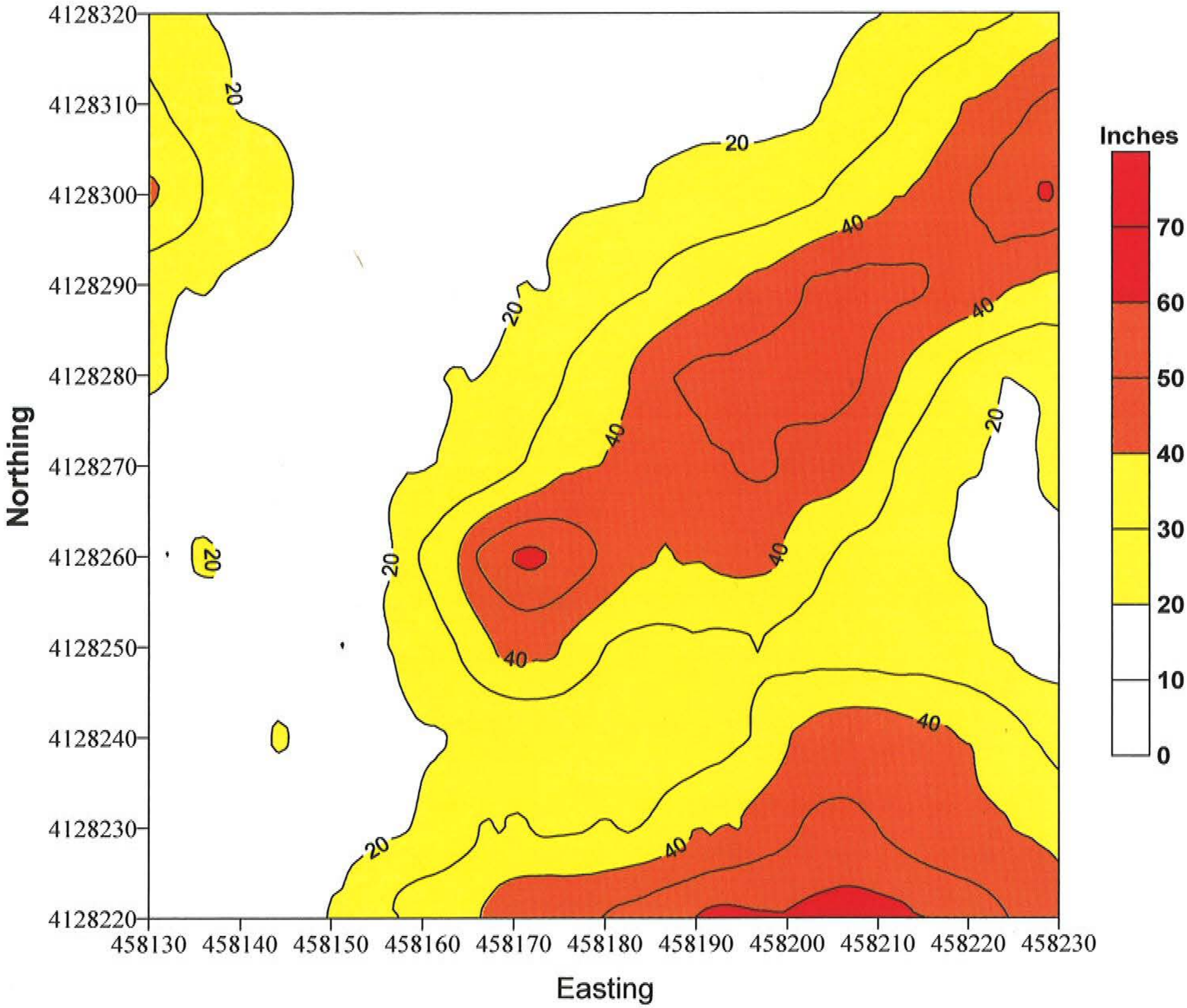


Figure 7

INTERPRETATIVE RESULTS OF AN EMI SURVEY
AREA OF TRAVELER SOIL
DEPTH TO BASALT BEDROCK



Depth Class	Observations	Percent
Shallow	290	38%
Moderately Deep	280	37%
Deep	166	22%
Very Deep	21	3%

Figure 8