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

Subject: SOI -- Electromagnetic Induction (EMI) Assistance

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To: Chris Noble
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Purpose:
The purpose of this investigation was to use of EMI to assess soil properties and hydrology of slope wetlands.

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Activities:
All field activities were completed during the period of 30 July to 10 August 2001.

Equipment:
Four different instruments were used in this study. These instruments included the EM31 meter, EM38 meter, EM38-DD meter, and GEM300 sensor.

Geonics Limited manufacturers the EM38, EM38-DD, and the EM31 meters.[1] These meters are portable and require only one person to operate. McNeill (1980b) and Geonics Limited (1998 and 2000) have described the principles of operation for the EM31, EM38, and EM38-DD meters, respectively. No ground contact is required with these meters. The depth of penetration is geometry limited. Lateral resolution is approximately equal to the intercoil spacing. The EM38 and the EM38-DD meters have a 1 m intercoil spacing and operate at a frequency of about 14,600 Hz. They have effective penetration depths of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively (Geonics Limited, 1998). The EM38-DD meter consists of two EM38 meters bolted together and electronically coupled. One meter acts as a master unit (meter that is positioned in the vertical dipole orientation and having both transmitter and receiver activated) and one meter acts as a slave unit (meter that is positioned in the horizontal dipole orientation with only the receiver switched on). The EM31 meter has a 3.66 m intercoil spacing and operates at a frequency of 9,810 Hz. It has effective penetration depths of about 3.0 and 6.0 m in the horizontal and vertical dipole orientations, respectively (McNeill, 1980b).

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[1] Trade names have been used for specific information. Their mention does not constitute endorsement.

The GEM300 sensor is manufactured by Geophysical Survey systems, Inc.[2] This sensor 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. With the GEM300 sensor, penetration depth is considered "skin depth limited" rather than "geometry limited." The skin-depth represents the maximum depth of penetration and is frequency and soil dependent: low frequency signals travel farther through conductive mediums than high frequency signals. Theoretical penetration depths of the GEM300 sensor are dependent upon the bulk conductivity of the profiled earthen material(s) and the operating frequency (ies). Multifrequency sounding with the GEM300 has been marketed as allowing multiple depths to be profiled with one pass of the sensor.

The positions of all observation points were obtained with Rockwell Precision Lightweight GPS Receivers (PLGR).[2] At the Lamar River Fen in Yellowstone National Park, Wyoming, a Trimble GeoExplorer GPS (owned by the USACE) provided enhanced PDOP beneath a thin aspen tree canopy.[2] These receivers were operated in the continuous and the mixed satellite modes. The Universal Transverse Mercator (UTM) coordinate system was used. Horizontal datum is the North American 1983. Horizontal units are expressed in meters.

To help summarize the results of this study, the SURFER for Windows (version 7.0) program, developed by Golden Software, Inc.,[2] was used to construct two- and three-dimensional simulations. Grids were created using kriging methods with an octant search.

Soils were examined and described at many observation points. In Park County, Colorado, after reviewing the computer simulations of the detailed grid site, soil samples were collected at six observation points. At each of these observation points, the soil was described to a depth of about 130 cm. Samples were collected in 30 cm intervals to a depth of 120 cm and shipped to the National Soil Survey Center for analysis.

Conclusions:

1. In an earlier study (Doolittle, 2000), apparent conductivity was used to distinguish recharge, discharge, and flowthrough depressional wetlands in a semiarid environment. This study focused on slope wetlands in semiarid uplands that are suspected to have lower concentrations of soluble salts. While results were slightly more ambiguous than those obtained in the study of depressional wetlands (Doolittle, 2000), EMI can be used to delineate and characterize soil and hydrologic properties within slope wetlands of semiarid areas.

2. Non to weak positive correlations were found to exist between apparent conductivity and the thickness of organic layers. Instruments responded to the increased moisture contents. However, in slope wetlands of the semiarid west, EMI appears to be comparatively insensitive to changes in soil water contents and thickness of surface organic layers. Factors other than changes in soil water content or organic thickness contribute more to the EMI response. The primary factors are believed to be variations in soluble salt and clay contents.

3. Results of EMI surveys partitioned slope wetlands into zones of contrasting apparent conductivity. Spatial patterns of apparent conductivity did not always conform to observable breaks in topography, drainage, or vegetation. Spatial patterns of apparent conductivity were assumed to reflect difference is soil physical and chemical properties. When conducting functional assessments of slope wetlands to determine the effects of impacts, these spatial patterns may assume additional significance to interpretations and site characterization. With EMI, a reduced number of samples can be quickly and affordably obtained from contrasting zones of apparent conductivity to improve the characterization of this wetland.

4. Results and interpretations contained in this report will be further analyzed after soil samples that were sent to the National Soil Survey Center have been processed.

[2] Trade names have been used for specific information. Their mention does not constitute endorsement.

Recommendations:

1. A major drawback of the EM38 meter is the device's inability to simultaneously record measurements of apparent conductivity in both dipole orientations. At each observation point, a measurement is made in one dipole orientation then the EM38 meter is rotated and re-nulled prior to obtaining a measurement in the other dipole orientation. This tedious operation slows survey speeds and, when recording measurements in both dipole orientations, the meter can only be operated in the station-to-station mode and not in the continuous mode. The EM38-DD meter has been recently developed by Geonics Limited in response to a growing demand to measure both dipole orientations simultaneously. The EM38-DD meter consists of two EM38 meters bolted together and electronically coupled. One meter acts as a master unit (meter that is positioned in the vertical dipole orientation and having both transmitter and receiver activated) and one meter acts as a slave unit (meter that is positioned in the horizontal dipole orientation with only the receiver switched on). The receiver coil of the slave unit must be perfectly aligned with the transmitter coil of the master unit to provide consistent and correct measurements in the horizontal dipole orientation. The lack of consistent values and spatial patterns and the large number to discrete point values suggest that this has not been achieved. The use of the EM38-DD meter cannot be recommended.

2. Plots of apparent conductivity collected with the EM31and EM38 meters and the GEM300 sensor within the slope wetlands are remarkably similar. These devices appear to be profiling similar volumes of earthen materials and have similar observation depths. The use of only one device will expedite fieldwork and provide sufficient information for the characterization of slope wetlands in semiarid areas.

3. Data collected with the GEM300 sensor in either dipole orientations, but at different frequencies, produce similar spatial patterns. High correlations were found among apparent conductivity measurements obtained at different frequencies and/or dipole orientations. The use of multiple frequencies adds time to the processing of field data, but provided no additional information on the investigated slope wetlands. In slope wetlands characterized by low to moderately high apparent conductivity, the use of a single frequency and two dipole orientations appears to provide sufficient information to select sampling points characterize spatial patterns.

4. Geophysical interpretations are considered preliminary estimates of site conditions. The results of geophysical site investigations are interpretive and do not substitute for direct ground-truth observations (soil borings). The use of geophysical methods can reduce the number of core observations, direct their placement, and supplement their interpretations. Interpretations contained in this report will be verified by analysis of soil samples.

With kind regards,

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Background:

The hydrogeomorphic (HGM) approach to wetland classification recognizes seven classes of wetlands: riverine, depressional, tidal fringe, lacustrine fringe, slope, mineral soil flats and organic soil flats (Smith et al., 1995). In this study, four slope wetlands were surveyed. Slope wetlands occur where groundwater discharges from surrounding uplands onto the soil surface. The principal sources of water in slope wetlands are groundwater discharge and precipitation (Smith et al., 1995). Slope wetlands lacks closed contours and therefore are incapable of water storage (Smith et al., 1995). Water is lost through surface and subsurface flow and evapotranspiration. Richardson and Brinson (2001) distinguished two types of slope wetlands: topographic and stratigraphic. Topographic slope wetlands develop in areas where slopes converge and groundwater is forced to the surface. Stratigraphic slope wetlands occur where a relatively impervious stratum intersects the surface and forces the groundwater to discharge on the soil surface.

Many slope wetlands are peat-covered. Fens are peat-covered wetlands that receive nutrient enriched groundwater from surrounding areas. Fens develop on flat to concave surfaces and receive their nutrient source from groundwater and precipitation (Chaddle et al., 1998). In contrast, bogs develop on convex surfaces and receive nutrients from precipitation (Chaddle et al., 1998). As a consequence, bogs are extremely nutrient deficient.

In the Northern Rocky Mountains, Chaddle and others (1998) classified fens into three groups: poor fens, rich fens, and extremely rich fens. Poor fens have calcium concentrations of 2 to 10 mg/l and pH ranging from 4.2 to 5.8 (Glasner, 1987). These fens are widespread throughout the northern Rocky Mountains. Rich fens have calcium concentrations of 10 to 30 mg/l and are less acidic (Glasner, 1987). Extremely rich fens have calcium concentrations greater than 30 mg/l and a pH greater than 7 (Glasner, 1987). Rich and extremely rich fens are generally restricted to areas underlain by limestone (Chaddle et al., 1998) or receive their groundwater from calcareous materials. Chaddle and others (1998) observed that extremely rich fens are often found near groundwater discharge areas.

Four slope wetlands located in Colorado, Wyoming, and Montana were selected for this study. These wetlands are referred to as the High Creek Fen, Teter Fen, Lamar River Fen, and the Gravelly Mountain Fen. The Lamar River Fen is a poor fen. The other fens are extremely rich or rich fens. The objective of this study was to ascertain whether EMI could be used to identify and map soil and hydrologic properties within slope wetlands in semiarid areas.

EMI:

Background:

Electromagnetic induction is a noninvasive geophysical tool that is used for high intensity surveys and detailed site assessments. Advantages of EMI are its portability, speed of operation, flexible observation depths, and moderate resolution of subsurface features. Results of EMI surveys are interpretable in the field. This geophysical method can provide in a relatively short time the large number of observations that are needed to comprehensively cover sites. Maps prepared from correctly interpreted EMI data provide the basis for characterizing site conditions, planning further investigations, and locating sampling or monitoring sites.

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). Electromagnetic induction measures vertical and lateral variations in apparent conductivity. 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. To assist interpretations, the spatial distributions of apparent conductivity are normally simulated in two- and three-dimensional plots.

Variations in apparent conductivity are caused by changes in the electrical conductivity of earthen materials. Electrical conductivity is influenced by: volumetric water content, phase of the soil water, temperature, type and concentration of ions in solution, and amount and type of clays in the soil matrix (McNeill, 1980a). Apparent conductivity is principally a measure of the combined interaction of the soil's soluble salt content, clay content and mineralogy, and water content. The apparent conductivity of soils increases with increased soluble salts, clay, and water contents (Kachanoski et al., 1988; Rhoades et al., 1976). In any soil-landscape, variations in one or more of these factors may dominate the EMI response.

The relationship between apparent conductivity and soluble salt content of soils has helped to identify recharge, discharge and flowthrough depressional wetlands. Recharge, discharge and flowthrough processes remove, translocate, and add soluble constituents to soils. In a study conducted at the Brandy Ranch Research Site in Montana (Doolittle, 2000), the sensitivity of EMI to variations in the amount of soluble salts in soil profiles were used to distinguish recharge, flowthrough, and discharge depressional wetlands. Recharge, flowthrough, and discharge wetlands had low, intermediate and high apparent conductivity, respectively. In areas of saline or salt-affected soils, 65 to 70 percent of the variance in apparent conductivity can be explained by changes in the concentration of soluble salts alone (Williams and Baker, 1982). Moderate to high correlations have been found between apparent conductivity and soil salinity (de Jong et al., 1979; Williams and Baker, 1982; and Wollenhaupt et al., 1986).

The presence of exchangeable cations on clay particle surfaces contributes to the total electrical conductivity of soils. Depending on the type and amount of clays present, the number of exchangeable cations available to conduction when an electrical field is applied will vary. If the soil water conductivity is low, the high conductivity near some clay surfaces can dominate the overall conductance (Greenhouse et al., 1998). Clays also contribute to the water-holding capacity of soils and, therefore, influences the soil water content.

Apparent conductivity is affected by changes in the electrolyte concentration of the soil water and the soil water content (Johnston et al., 1997). For soils with low concentrations of dissolved electrolytes, changes in apparent conductivity have been associated with changes in water content (Kachanoski et al., 1988, 1990; Sheets and Hendrickx, 1995). At low soil moisture contents, EMI is relatively insensitive to changes in soil-water content. However, at high soil moisture contents, and in the absences of significant changes in soluble salt or clay contents, EMI is more sensitive to changes in soil-water content (Hanson, 1997).

Depths of Penetration and Observation:

For the meters developed by Geonics Ltd., the depth of penetration is "geometry limited" and is dependent upon the intercoil spacing, coil orientation, and frequency. The EM38 and EM38-DD meters have theoretical penetration depths of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively (Geonics Limited, 1998). The EM31 meter has theoretical penetration depths of about 3.0 and 6.0 meters in the horizontal and vertical dipole orientations, respectively (McNeill, 1980b).

The theoretical penetration depth of the GEM300 sensor is dependent upon the bulk conductivity of the profiled earthen material(s) and the operating frequency of the sensor. Penetration 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 mediums than high frequency signal. Decreasing the frequency will extend the penetration depth. At a given frequency, the depth of penetration is greater in low conductivity than in high conductivity soils.

The "skin depth" is estimated using the following formula (McNeill, 1996):

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

Where s is the ground conductivity (mS/m) and f is the frequency (kHz). Three frequencies were principally used in this study: 9810, 14790, and 19950 Hz. At each study site, the GEM300 sensor held at hip height and measurements were taken in the vertical dipole orientation. At High Creek Fen, apparent conductivity averaged 8.0, 12.3, and 13.4 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 51.9 m at 9810 Hz, 37.1 m at 14790 Hz, and 30.6 m at 19950 Hz. At Teter Fen, apparent conductivity averaged 2.4, 6.1, and 5.8 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 103.1m at 9810 Hz, 52.2 m at 14790 Hz, and 46.5 m at 19950 Hz. At Lamar River Fen, apparent conductivity averaged 17.5, 12.8, and 18.4 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 38.2 m at 9810 Hz, 36.4 m at 14790 Hz, and 26.1 m at 19950 Hz.

It is impractical to assume that the GEM300 sensor is sensitive to changes in apparent conductivity at all depths within these large skin depths (12 to 103 m). Within these defined skin depth, earthen materials from all depths contribute, in varying degrees, to the measured response. With increasing depth, the relative contribution from various depth layers passes through a maximum and then decreases with increasing depth. While the induced magnetic fields may achieve these estimated skin depths, the response strengths diminish with increasing depth and, at lower soil depths, are presumed to be too weak to be sensed with the GEM300 sensor. The *depth of observation* may be defined as the depth that contributes the most to the total EMI response. Although contributions to the measured response come from all 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.

Survey area:
Park County, Colorado
High Creek Fen is located on the floor of South Park in northwest Parks County, Colorado. This fen formed on alluvium and is located about 2 miles from the eastern front of the Mosquito Range. The fen is at an elevation of about 9300 feet. The fen covers about 300 ha. Johnson (2001) described High Creek Fen as an "extremely rich fen having alkaline groundwater with high electrical conductivity and mineral content." Within this fen, pH varies from about 5 to 7.5 (Johnson, 2001). The average water table depth is about 4 inches (Johnson, 2001). The vegetation is characterized by "sedge-dominated fen expanses and mixed sedge-shrub meadows" (Johnson, 2001). High Creek Fen is included in an area that has been mapped as Cablon soils (Laura Craven, personal communication). The Cablon series consists of very deep, somewhat excessively drained soils that formed in alluvium on fan terraces. The Cablon soil is a member of the sandy-skeletal, mixed Ustic Calcicryolls family.

The topography of the survey area within High Creek Fen is shown in Figure 1. In Figure 1, the contour interval is 1-ft.

Teter Fen is also located on the floor of South Park near the eastern base of the Mosquito Range in northwest Parks County. It is part of the larger Teter-Michigan Creek wetland that covers about 526 ha. The fen is at an elevation of about 9700 feet. Teter Fen formed over Pleistocene outwash deposits. Johnson (2001) has described this fen as being "extremely rich." Within the fen, pH varies from about 5.7 to 7.4 (Johnson, 2001). The fen has no surface inlets or outlets and has an average water table depth of about 9 inches (Johnson, 2001). The soils in this area have not been mapped.

The topography of the survey area within Teter Fen is shown in Figure 2. In Figure 2, the contour interval is 1-ft.

Table 1 lists the average dissolved cations found in the groundwater that flows into High Creek and Teter fens (Johnson, 2001). Based on calcium contents, High Creek Fen would be classified as and extremely rich fen and Teter Fen would be classified as a rich fen (after Glasner, 1987).

Table 1
Average Dissolved Cations within the Groundwater
(From Johnson, 2001)

	Ca (mg/l)	Mg (mg/l)	Na (mg/l)	K (mg/l)	P(mg/l)
High Creek Fen	117.8	43.7	9.2	1.3	0.1
Teter Fen	16.0	3.5	6.6	0.8	0.1

Lamar River Fen, Yellowstone National Park, Wyoming
The site is located in northeastern Yellowstone National Park, in the foothills of the Absoraka Range, and at an elevation of 6700 feet. The site overlooks the Lamar River Valley. The site is on a southwest-facing slope and includes a small aspen parkland. It is located in an area that had been mapped as Hobacker Family-Bedrock Outcrop-Arrowpeak Family Complex (Rodman et al., 1996). Hobacker soil is a member of the loamy-skeletal, mixed, superactive Pachic Cryoborolls family. The Arrowpeak soil is a member of the loamy-skeletal, mixed, superactive Lithic Cryoborolls family. Less than 5 percent of the unit is considered wet soils.

The topography of the Lamar River Fen survey area is shown in Figure 3. In Figure 3, the contour interval is 5-ft.

Gravelly Mountain Fen, Montana

This site is located (45° 8.226 N, 111° 45.202W) in the eastern foothills of the Gravelly Range in southwestern, Montana. The site is at an elevation of about 5775 feet and is on an east-facing slope in rangeland. It is located in an area that had been mapped as Nuley sandy loam, 2 to 12 percent slopes (Boast and Shelito, 1989). The deep, well drained Nuley soil formed in material derived from metamorphic and igneous rock. Nuley is a member of the fine-loamy, mixed, superactive, frigid Calcidic Argiustolls family.

The topography of the Gravelly Mountain Fen survey area is shown in Figure 4. In Figure 4, the contour interval is 5-ft.

Field Procedures:

Park County, Colorado

Rectangular grids were established at both the High Creek and Teter fens. Both survey areas covered only a portion of these selected slope wetlands. Grid dimensions were 400 by 200 feet (1.8 acres). Flags were inserted in the ground at 50 ft intervals and served as observation points (N=45). The coordinates of each of these observation points were obtained with a Rockwell PLGR. An engineer level and stadia rod was used to determine the relative elevation at each observation point. The lowest measured point in each grid served as the 0.0 ft datum.

Measurements were taken at each observation point with the GEM300 sensor and the EM31 meter held at hip-height in both the horizontal and vertical dipole orientations. In-phase, quadrature phase, and conductivity data were recorded with the GEM300 sensor at three different frequencies (9810, 14790, and 19950 Hz) at each observation point. While in-phase and quadrature data were recorded and stored on disc, these values are neither shown nor discussed in this report. Measurements were also obtained with an EM38-DD meter placed on the ground surface in both the horizontal and vertical dipole orientations.

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 from High Creek and Teter fens. As a consequence, negative apparent conductivity values appear in the data set and simulated plots of these sites.

Lamar River Fen, Yellowstone Park, Wyoming

A rectangular grid was established across the site. The survey area covered the entire area of the slope wetland. Grid dimensions were 300 by 200 feet (1.4 acres). Flags were inserted in the ground at 50 and 25 ft intervals along the X and Y-axis, respectively. The survey flags served as observation points (N=62). The coordinates of each of these observation points were obtained with a Trimble GeoExplorer II receiver. The presence of an aspen stand seriously reduced the accuracy of coordinates obtained with the Rockwell PLGR for observation points located near or beneath the canopy. An engineer level and stadia rod was used to determine the relative elevation at each observation point. The lowest measured point in each grid served as the 0.0 ft datum.

Measurements were taken at each observation point with the GEM300 sensor and the EM31 meter held at hip-height in both the horizontal and vertical dipole orientations. In-phase, quadrature phase, and conductivity data were recorded with the GEM300 sensor at three different frequencies (9810, 14790, and 19950 Hz) at each observation point. While in-phase and quadrature data were recorded and stored on disc, these values are neither shown nor discussed in this report.

Gravelly Mountain Fen, Montana

A rectangular grid was established across the site. The survey area covered the entire slope wetland. Grid dimensions were 300 by 400 feet (2.8 acres). Flags were inserted in the ground at 50-ft intervals. The survey flags served as observation points (N=63). The coordinates of each observation point were obtained with a Rockwell PLGR. An engineer level and stadia rod was used to determine the relative elevation at each observation point. The lowest measured point in each grid served as the 0.0 ft datum.

Measurements were taken at each observation point with the GEM300 sensor and the EM31 meter held at hip-height in both the horizontal and vertical dipole orientations. In-phase, quadrature phase, and conductivity data were recorded with the GEM300 sensor at four different frequencies (5010, 9810, 14790, and 19950 Hz) at each observation point. While in-phase and quadrature data were recorded and stored on disc, these values are neither shown nor discussed in this report. Measurements were also obtained with an EM38 meter placed on the ground surface in both the horizontal and vertical dipole orientations. Negative conductivity values are removed by electronic nulling of the data set.

Results:
At the four fens, apparent conductivity was generally higher in the deeper-sensing vertical dipole orientation than in the shallower-sensing horizontal dipole orientation. This trend was attributed to the presence of more moist and conductive soil materials at greater soil depths. With the GEM300 sensor, apparent conductivity decreased with decreasing frequency. This trend was attributed to lower signal amplitudes at lower frequencies.

High Creek Fen:
Table 2 summarizes the results of this EMI survey. Measurements obtained with the EM38-DD meter were higher and more variable than the measurements obtained with the other instruments. Within High Creek Fen, apparent conductivity was characterized as increasing with increased penetration depth. With all instruments, the averaged apparent conductivity was higher in the deeper-sensing, vertical dipole orientation than in the shallower-sensing, horizontal dipole orientation. This trend was assumed to reflect the presence of more moist and conductive soil materials at greater soil depths.

With the GEM300 sensor, apparent conductivity decreased with increasing penetration depth (lower frequency).

Table 2
High Creek Fen
Basic Statistics
Apparent Conductivity
(All values are in mS/m)

					Quartiles		
	Average	**Minimum**	**Maximum**	**SD**	**First**	**Second**	**Third**
EM38-DD-H	16.7	9.8	29.0	4.3	13.5	15.4	18.9
EM38-DD-V	24.0	13.2	32.0	4.0	21.7	23.7	26.8
EM31-H	11.9	10.2	14.6	1.0	11.2	11.8	12.6
EM31-V	14.2	13.0	16.0	0.7	13.6	14.0	14.4
9810-H	3.5	-1.2	7.9	1.9	2.9	3.9	4.6
9810-V	8.0	5.2	12.4	1.8	6.3	8.0	9.4
14790-H	7.4	2.6	11.1	2.0	6.1	7.6	8.7
14790-V	12.3	9.5	17.3	1.8	10.6	12.0	13.5
19950-H	8.4	4.8	12.7	1.8	7.4	8.3	9.3
19950-V	13.4	10.3	18.5	2.0	11.9	13.2	14.7

Teter Fen:
Table 3 summarizes the results of this EMI survey. Compared with High Creek Fen, values of apparent conductivity were slightly lower within Teter Fen. Negative values were not removed from the data collected with the EM38-DD and the GEM300 sensor. As a consequence negative values occur in these data sets.

Within Teter Fen, apparent conductivity was characterized as increasing with increased penetration depth. With all instruments, the averaged apparent conductivity was higher in the deeper-sensing vertical dipole orientation than in the shallower-sensing horizontal dipole orientation. This trend reflects the presence of more moist and conductive soil materials at greater soil depths. These materials are presumably layers of medium and moderately fine textured soil materials.

With the GEM300 sensor, the averaged apparent conductivity decreased with increasing penetration depth (lower frequency).

Lamar River Fen:
Table 4 summarizes the results of this EMI survey. Measurements were obtained only with the EM31 meter and the GEM300 sensor at this site. For these instruments, apparent conductivity was highest at this site. The higher apparent conductivity measured within this site reflects the presence of more conductive earthen materials and/or groundwater.

Five observation points had exceedingly high negative values. Buried metallic objects probably produced these negative values. Metallic objects interfere with the electromagnetic fields and can produce distinctly high negative values. The five observation points were removed from the data sets and were not further analyzed.

Table 3
Teter Fen
Basic Statistics
Apparent Conductivity
(All values are in mS/m)

	Average	Minimum	Maximum	SD	Quartiles First	Quartiles Second	Quartiles Third
EM38-DD-H	0.6	-14.1	11.2	5.5	-3.0	1.9	3.8
EM38-DD-V	16.7	11.1	24.2	2.9	14.3	16.8	18.4
EM31-H	11.3	8.4	13.8	1.3	10.4	11.2	12.4
EM31-V	15.5	11.6	20.8	2.4	13.4	15.2	16.8
9810-H	-3.2	-11.0	0.8	2.7	-4.2	-2.5	-1.4
9810-V	2.4	-0.7	6.5	2.1	0.7	2.5	4.3
14790-H	0.6	-5.0	4.1	2.3	-0.9	1.0	2.3
14790-V	6.1	2.9	10.6	2.0	4.4	6.0	7.7
19950-H	0.6	-3.5	4.7	2.0	-0.3	0.9	1.9
19950-V	5.8	2.5	9.9	2.0	4.3	5.6	7.6

Table 4
Lamar River Fen
Basic Statistics
Apparent Conductivity
(All values are in mS/m)

	Average	Minimum	Maximum	SD	First	Second	Third
EM31-V	31.3	20.0	49.4	6.3	26.5	30.6	35.9
EM31-H	20.8	13.8	32.2	4.0	18.4	20.2	23.3
9810-V	21.4	0.8	37.0	7.7	17.1	21.7	27.0
9810-H	12.8	3.7	40.6	6.0	8.6	12.3	15.1
14790-V	25.1	-2.9	41.4	8.3	20.8	26.2	30.8
14790-H	16.2	-0.8	45.5	6.5	12.7	15.8	18.5
19950-V	25.9	-7.2	43.2	8.9	21.4	27.3	31.8
19950-H	16.9	-5.9	50.6	7.6	13.1	16.5	18.9

Within this site, apparent conductivity was characterized as increasing with increased penetration depth. With the EM31 meter and the GEM300 sensor, averaged apparent conductivity was higher in the deeper-sensing, vertical dipole orientation than in the shallower-sensing, horizontal dipole orientation. This trend was assumed to reflect the presence of more conductive soil materials or bedrock at greater depths.

With the GEM300 sensor, the averaged apparent conductivity once again decreased with increasing penetration depth (lower frequency).

Gravely Mountain Fen:
Table 5 summarizes the results of this EMI survey. The EM38 meter was also used at this site. An additional, lower frequency (5010 Hz) was also recorded with the GEM300 sensor. All measurements made with the GEM300 sensor were *zero adjusted* (all measurements were adjusted upwards based on the lowest recorded value). With the exception of measurements obtained with the GEM300 sensor operating at the lowest selected frequency (5010 Hz), the averaged apparent

conductivity was higher in the deeper-sensing vertical dipole orientation than in the shallower-sensing horizontal dipole orientation. Again, this trend was assumed to reflect the presence of more conductive soil materials at greater soil depths. These materials are believed to be layers of saturated, medium and moderately fine textured soil materials.

With the GEM300 sensor, the averaged apparent conductivity remained constant with increasing penetration depth (lower frequency).

Table 5
Gravely Mountain Fen
Basic Statistics
Apparent Conductivity
(All values are in mS/m)

	Average	Minimum	Maximum	SD	First	Second	Third
EM38-V	9.5	1.8	29.3	6.2	4.9	7.3	13.6
EM38-H	8.0	1.1	30.8	6.4	3.3	5.9	10.6
EM31-V	10.5	5.2	19.0	3.8	6.9	10.6	13.4
EM31-H	8.3	4.2	15.8	3.1	5.6	7.6	10.6
5010-V	8.0	0.0	21.3	5.8	3.4	6.5	12.0
5010-H	10.4	1.7	20.3	4.1	7.0	9.3	13.4
9810-V	7.7	0.0	21.1	5.8	2.9	5.9	11.8
9810-H	5.6	0.0	15.7	4.0	2.2	4.3	8.5
14790-V	7.6	0.0	21.1	5.9	2.6	6.0	11.4
14790-H	4.9	0.0	15.6	4.0	1.8	3.7	8.1
19950-V	7.8	0.0	22.4	6.1	2.9	6.3	11.9
19950-H	5.1	0.0	16.2	4.1	1.7	3.8	8.0

Interpretations:

High Creek Fen

The survey area was located within the northern portion of the High Creek fen. Figure 1 is a contour plot of the survey area. Relief is about 4.5 feet. Within the survey area, although there exist many micro-features, the surface slopes gently towards the southeast. A channel crosses the survey area in a west to east direction. Surrounding the channel is a wetter portion of the fen that is distinguished by sedge vegetation (see vegetation lines in Figure 1) and the presence of surface water. Eleven springs were identified within the survey area. The locations of these springs are shown in Figure 1. These springs often had accumulations of stones and cobbles at the surface.

Figure 5 shows the distribution and thickness of surface organic layers. Based on measurements made at 45 observation points, the thickness of surface organic layers averaged 7.0 inches and ranged from 0 to 25 inches. Forty-four percent of the observation points lacked organic layers at the surface. These observation points were located principally outside the sedge-vegetation lines shown in Figure 5. Soils at these observation points were classified as being members of the fine-loamy, mixed, calcareous Typic Cryaquepts family. Profiles were similar to those of the Girardot series. Sixteen percent of the observation points had surface organic layers greater than 16 inches thick. These soils are Histosols. Two (sample numbers CO638-2 and CO638-4) of the four pedons sampled were classified as fine-loamy Terric Cryosaprists. In Figure 5, the locations of these pedons have been incorrectly plotted outside of the 16-inch contour by the software.

Table 6 shows the correlations between thickness of the surface organic layers and apparent conductivity as measured with different instruments, dipole orientations and frequencies. When all 45-observation points were included in the analysis, non to weak positive correlations exist between apparent conductivity and the thickness of organic layers. The strongest correlation was obtained with the GEM300 sensor operated in the vertical dipole orientation and at a frequency of 14790 Hz. When the data set was reduced to include only those soils with histic epipedons or Histosols, correlations weakened for all instruments, dipole orientations, and frequencies. These relationships appear to reflect the comparative insensitivity of the instruments to changes in soil water contents and thickness of surface organic layers in slope wetlands of the semiarid west.

Factors other than changes in soil water content or organic thickness apparently contribute more to the EMI response. The primary factor is believed to be variations in the soluble salt content of the soils.

Table 6
Correlation between Thickness of Organic Layers and Apparent Conductivity

	All	Histic/Histosols
EM38-DD-V	-0.08	-0.28
EM38-DD-H	-0.16	0.06
EM31-H	0.17	0.07
EM31-V	0.10	-0.13
9810-V	0.42	0.19
9810-H	0.37	0.27
14790-V	0.43	0.20
14790-H	0.39	0.32
19950-V	0.40	0.18
19950-H	0.38	0.30

Figure 6 shows the spatial distribution of apparent conductivity as measured with the EM38-DD meter. The spatial distributions of apparent conductivity collected in the horizontal and vertical dipole orientations are shown in the left-hand and right-hand plots, respectively. In each plot, the isoline interval is 4 mS/m. The locations of the channel, springs, vegetation lines, and sample points are also shown in these plots.

Values of apparent conductivity measured with the EM38-DD meter were low to moderate (9.8 to 32 mS/m) and spatially variable within the survey area (see Table 2). Patterns shown in Figure 6 do not correspond with observed differences in topography, drainage, organic thickness, or vegetation. Spatial patterns are believed to reflect difference in clay and soluble salt contents of the mineral soil.

A major drawback of the EM38 meter has been the device's inability to simultaneously record measurements of apparent conductivity in both dipole orientations. Measurements are made in one dipole orientation then the EM38 meter is rotated and re-nulled prior to obtaining measurements in the other dipole orientation. This tedious operation slows survey speeds and, when recording measurements in both dipole orientations, the meter can only be operated in the station-to-station mode and not in the continuous mode. The EM38-DD meter has been recently developed by Geonics Limited in response to a growing demand to measure both dipole orientations simultaneously. Simultaneous measurements of both dipole orientations and the lack of the requirement to repeatedly re-nulling the EM38-DD meter will reduce survey time and effort. The EM38-DD meter consists of two EM38 meters bolted together and electronically coupled. One meter acts as a master meter (meter that is positioned in the vertical dipole orientation and having both transmitter and receiver activated) and one meter acts as a slave unit (meter that is positioned in the horizontal dipole orientation with only the receiver switched on). The receiver coil of the slave unit must be perfectly aligned with the transmitter coil of the master unit to provide consistent and correct measurements in the horizontal dipole orientation. In Figure 6, the lack of consistent values and patterns, and the large number to discrete point values suggest that this has not been achieved. In addition, while surveying, noticeable changes in values were observed with slight changes in the position or orientation of the EM38-DD meter.

Figure 7 shows the spatial distribution of apparent conductivity as measured with the EM31 meter. The spatial distributions of apparent conductivity collected in the horizontal and vertical dipole orientations are shown in the left-hand and right-hand plots, respectively. In each plot, the isoline interval is 2 mS/m. The locations of the channel, springs, vegetation lines, and sample points are also shown in these plots.

Compared with the data collected with the EM38-DD meter, broader and more consistent patterns are evident in the data collected with the EM31 meter. However, these patterns do not correspond with topography, vegetative zones, drainage, or other visible wetland characteristics. It is probably that the penetration depth of this meter is too great and/or the meter is insensitive to these visible wetland characteristics. When applying functional assessments to determine the effects of impacts, the spatial patterns shown if Figure 7 may become significant. Results of the EMI survey partitioned the survey area into zones of contrasting apparent conductivity. With EMI, a reduced number of samples can be quickly and affordably obtained from contrasting zones of apparent conductivity to improve the characterization of this wetland.

Figure 8 shows the spatial distribution of apparent conductivity as measured with the GEM300 sensor. Data collected at 19950 Hz, 14790 Hz, and 9810 Hz are shown in the upper, middle, and lower sets of plots, respectively. Frequencies of 14790 and 9810 Hz were selected as they approximate the frequencies of the EM38-DD and the EM31 meters, respectively. For each frequency, data collected in the horizontal and vertical dipole orientations are shown in the left-hand and right-hand plots, respectively. In each plot, the isoline interval is 2 mS/m. The locations of the channel, springs, vegetation lines, and sample points are also shown in these plots.

Spatial patterns shown in these plots are more variable than those obtained with the EM31 meter and less random than those obtained with the EM38-DD meter. Differences in spatial patterns reflect differences in the depth and volume of soil material profiled with each instrument, and, in the case of the EM38-DD meter, slight misalignment in the orientations of the coils.

The plots of apparent conductivity in Figure 8 are remarkably similar. In particular, data collected in the same dipole orientation, but at different frequencies, are remarkably alike. In each set of plots, patterns are similar, but signal amplitudes decrease with decreased frequency. Table 7 shows the correlation coefficients for measurements obtained with the GEM300 sensor at different frequencies and/or dipole orientations. Correlations are extraordinarily high, suggesting that the GEM300 sensor is measuring similar volumes of soil materials at different frequencies. The GEM300 sensor appears to be most sensitive to soil properties that occur at shallow depths and that the depth of observation is restricted. Correlations, though strong and positive, were lowest for measurements obtained at similar frequencies but in different dipole orientations (see section A, Table 7). Correlations were highest for measurements obtained in the vertical dipole orientation, but at different frequencies (see section B, Table 7). In this wetland, the use of one frequency and two dipole orientations appears to provide as much information as the use of three frequencies (9810, 14790, and 19950 Hz).

Table 7
Correlation Between Apparent Conductivity Measurements obtained with the GEM300 Sensor Operating at Different Frequencies and in Different Dipole Orientations.
High Creek Fen

A

	9810-V	14790-V	19950-V
9810-H	0.8218	0.7896	0.7925
14790-H	0.8806	0.8643	0.8683
19950-H	0.9189	0.9070	0.8934

B

	9810-V	14790-V	19950-V
9810-V	1.0000	0.9819	0.9793
14790-V		1.0000	0.9835
19950-V			1.0000

C

	9810-H	14790-H	19950-H
9810-H	1.0000	0.8887	0.9069
14790-H		1.0000	0.9385
19950-H			1.0000

Teter Fen

The survey area was located within the eastern portion of the Teter Fen. Figure 2 is a contour plot of the survey area. Relief is about 9.5 feet. Within the survey area, the surface slopes gently away from a slight ridge. The ridge trends in a southeasterly direction from the north-central portion of the survey area. The surveyed portion of Teter Fen had more surface water and was generally wetter than the surveyed portion of High Creek Fen. One spring was identified within the survey area. The locations of the spring and the two soil sampling sites are shown in Figure 2.

Figure 9 shows the distribution and thickness of organic soil layers. Based on measurements made at 45 observation points, the thickness of surface organic layers averaged 26.4 inches and ranged from 5 to 46 inches. Soils at 44 of the 45 observation points were Histosols. Organic materials are thickest along the prominent southeasterly trending ridge.

Table 8 shows the relationships between the thickness of the surface organic layers and apparent conductivity as measured with different instruments, dipole orientations and frequencies. Non to weak positive correlations exist between apparent conductivity as measured with the EM31 meter and the GEM300 sensor, and the thickness of organic layers. These instruments are probably responding to the increased moisture contents at observation points with thicker organic layers. Once again, the strongest correlation was obtained with the GEM300 sensor in the vertical dipole orientation and operating at a frequency of 14790 Hz. The relationships shown in Table 8 appear to reflect the comparative insensitivity of EMI to changes in soil water contents and the thickness of surface organic layers in slope wetlands of the semiarid west. Factors other than changes in soil water content or organic thickness may contribute more to the EMI response. The primary factor is believed to be variations in the clay and soluble salt content of the mineral soil.

The lack of a relationship between apparent conductivity as measured with the EM38-DD meter and thickness of organic layers is believed to reflect coil misalignment and calibration errors. Considering the depth of interest, stronger relationships are probably attainable with an EM38 meter.

Table 8
Correlation Between Thickness of Organic Layers and Apparent Conductivity as Measured with Different Instruments, Dipole Orientations, and Frequencies.

Instrument	Thickness
EM38-DD-V	-0.0761
EM38-DD-H	-0.1641
EM31-V	0.0961
EM31-H	0.1730
9810-V	0.4167
9810-H	0.3662
14790-V	0.4326
14790-H	0.3911
19950-V	0.4027
19950-H	0.3823

Figure 10 shows the spatial distribution of apparent conductivity as measured with the EM38-DD meter. The spatial patterns of apparent conductivity as measured in the horizontal and vertical dipole orientations are shown in the left-hand and right-hand plots, respectively. In each plot, the isoline interval is 4 mS/m. The locations of the two sample points are shown in both plots. Negative conductivity values were not removed from the data sets by electronic nulling. As a consequence, negative apparent conductivity values appear in the data set and simulated plots of Teter Fen.

Values of apparent conductivity measured with the EM38-DD meter were lower (-14.1 to 24.2 mS/m) and more variable (standard deviation of 5.5 and 2.9 in the horizontal and vertical dipole orientations, respectively) than apparent conductivity values measured with the EM31 meter or the GEM300 sensor (see Table 3). In Figure 10, many observation points (see left-hand plot for location of observation points) have apparent conductivity 4 to 8 mS/m higher or lower than adjacent observation points. This produces a spotty appearance. The pockmarked appearance is, in part, an aberration caused by slight misalignment of transmitter and receiver coils in the EM38-DD meter. The spotty appearance is more pronounced in the data collected in the horizontal dipole orientation

Figure 11 shows the spatial distribution of apparent conductivity as measured with the EM31 meter. The spatial distributions of apparent conductivity collected in the horizontal and vertical dipole orientations are shown in the left-hand and right-hand plots, respectively. In each plot, the isoline interval is 2 mS/m. The locations of the two sample points are also shown in these plots.

Values of apparent conductivity measured with the EM31 meter were relatively low (8.4 to 20.8 mS/m) and invariable (standard deviation of 1.3 and 2.4 in the horizontal and vertical dipole orientations, respectively) across the survey area (see Table 3). Compared with the data collected with the EM38-DD meter, broader and more consistent linear patterns are evident in plots of apparent conductivity prepared from data collected with the EM31 meter. These patterns trend in a consistent north - south direction and more closely approximate the topography and organic thickness with the survey area than data collected with the EM38-DD meter.

Figure 12 shows the spatial distribution of apparent conductivity as measured with the GEM300 sensor. Data collected at 19950 Hz, 14790 Hz, and 9810 Hz are shown in the upper, middle, and lower sets of plots, respectively. For each frequency, data collected in the horizontal and vertical dipole orientations are shown in the left-hand and right-hand plots, respectively. Negative conductivity values were not removed from the data sets by electronic nulling. Negative apparent conductivity values appear along the eastern portion of the survey area. Negative values are more prevalent in the data collected in the horizontal dipole orientation. In each plot, the isoline interval is 2 mS/m. The locations of the two sample points are also shown in each plot.

Values of apparent conductivity measured with the GEM300 sensor were low (-11.0 to 10.6 mS/m) and relatively invariable (standard deviation ranging from 2.0 to 2.7) within the survey area (see Table 3). In Figure 12, linear patterns trend across the survey area in a north – south orientation. Spatial patterns shown in these plots are similar to those obtained with the EM31 meter and less random or spotty than those obtained with the EM38-DD meter.

Table 9
Correlation Between Apparent Conductivity Measurements obtained with the GEM300 Sensor Operating at Different Frequencies and in Different Dipole Orientations.
Teter Fen

A

	9810-V	14790-V	19950-V
9810-H	0.5554	0.6024	0.6620
14790-H	0.6403	0.7004	0.7451
19950-H	0.6236	0.6860	0.7486

B

	9810-V	14790-V	19950-V
9810-V	1.0000	0.9844	0.9679
14790-V		1.0000	0.9896
19950-V			1.0000

C

	9810-H	14790-H	19950-H
9810-H	1.0000	0.9018	0.9185
14790-H		1.0000	0.9176
19950-H			1.0000

The plots of apparent conductivity shown in Figure 12 are similar. In particular, data collected in the vertical dipole orientation, but at different frequencies, are nearly identical. In each set of plots, patterns are similar, but signal amplitudes decrease with decreased frequency and increased penetration depths. Table 9 shows the correlation coefficients for measurements obtained at different frequencies and/or dipole orientations. Compared with High Creek Fen, correlations are slightly weaker but still strong in Teter Fen. Once again, correlations were lowest for measurements obtained at similar frequencies but in different dipole orientations (see section A, Table 9). Correlations were highest for measurements obtained in the vertical dipole orientation, but at different frequencies (see section B, Table 9). In this wetland, characterized by low apparent conductivity, data collected with a single frequency but two dipole orientations provide similar information and spatial patterns as data collected with multiple frequencies and two dipole orientations.

Lamar River Fen

Figure 3 is a contour plot of the survey area. Relief is about 45 feet within the survey area. Within the survey area, the surface slopes steeply from a prominent ridge that trends in a southeasterly direction along northern border of the survey area. The ridge is composed of a thin layer of colluvium over basalt. The ridge exerts stratigraphic and topographic control over the slope wetland. Seeps occur along the back slope of this ridge. A channel flows across this slope and disappears in the lower part of the slope wetland. The channel beings at a spring that is located just off the northern border of the survey area. The wetland boundary shown in Figure 3 includes the channel. The boundaries of this slope wetland were difficult to define by both botanist and soil scientist. Vegetative patterns were indistinct and transitional.

Figure 13 shows the spatial distribution of apparent conductivity measured with the EM31 meter. The spatial distributions of apparent conductivity collected in the horizontal and vertical dipole orientations are shown in the upper and lower plots, respectively. In each plot, the isoline interval is 2 mS/m. The locations of the 63 observation points are shown in the upper plots.

Values of apparent conductivity measured with the EM31 meter were low to moderately high (13.8 to 49.4 mS/m) and variable (standard deviation of 4.0 and 6.3 in the horizontal and vertical dipole orientations, respectively) within the survey area (see Table 4).

In Figure 13, an arch of higher high apparent conductivity can be observed extending from the southwest corner of the survey area, through the slope wetland, to near the southeast corner of the survey area. Although this arch contains a major portion of the slope wetland, it also contains substantial areas outside the delineated wetland. This enlarged area of higher apparent conductivity may have resulted from subsurface groundwater flow, or perhaps dissimilar or deeper soil materials. A zone of moderately high conductivity also extends towards the northwest corner of the survey area from the wetland. This zone may represent soils that are deeper to bedrock than surrounding areas. This zone may facilitate groundwater flow. Conspicuously higher values of apparent conductivity near the northeast corner of the survey area, helped to identify a seep area (see Figure 13). The high apparent conductivity values in this portion of the survey area attracted immediate attention and were associated with a discharge area. The accumulation of soluble salts in soil profiles is often associated with values of apparent conductivity greater than 40 mS/m.

Figures 14, 15, and 16 show the spatial distribution of apparent conductivity as measured with the GEM300 sensor at frequencies of 9810, 14790, and 19950 Hz, respectively. In each figure, data collected in the horizontal and vertical dipole orientations are shown in the upper and lower plots, respectively. In each plot, the isoline interval is 2 mS/m. In the original data set, five observation points had exceptionally high negative values. Buried metallic objects that interfered with the electromagnetic fields probably produced these values. These observation points were removed from the data sets and were not further analyzed.

The plots of apparent conductivity collected with the GEM300 sensor at the Lamar River Fen are remarkably similar. In addition, these plots are similar to those obtained with the EM31 meter. Data collected with the GEM300 sensor in either dipole orientations, but at different frequencies, are alike. In each set of plots, patterns are similar, but signal amplitudes decrease with decreased frequency and increased penetration depths. Table 10 shows the correlation coefficients for measurements obtained at different frequencies and/or dipole orientations. Correlations among the data collected in different dipole orientations are slightly weaker than those obtained at High Creek and Teter fens. Once again, correlations were lowest for measurements obtained at similar frequencies but in different dipole orientations (see section A, Table 10). Correlations were highest for measurements obtained in similar dipole orientations, but at different frequencies (see sections B and C, Table 10). In this wetland, characterized by low to moderately high apparent conductivity, the use of a single frequency and two dipole orientations appears to provide satisfactory information.

Table 10
Correlation Between Apparent Conductivity Measurements obtained with the GEM300 Sensor Operating at Different Frequencies and in Different Dipole Orientations.
Lamar River Fen

A

	9810-V	14790-V	19950-V
9810-H	0.6766	0.6828	0.6277
14790-H	0.7187	0.7081	0.6721
19950-H	0.6766	0.6791	0.6528

B

	9810-V	14790-V	19950-V
9810-V	1.0000	0.9814	0.9483
14790-V		1.0000	0.9901
19950-V			1.0000

C

	9810-H	14790-H	19950-H
9810-H	1.0000	0.9648	0.9262
14790-H		1.0000	0.9891
19950-H			1.0000

Gravelly Mountain Site
Figure 4 is a contour plot of the survey area. Relief is about 40 feet within the survey area. A prominent ridge extends in a southwest to northeast direction across the northern portion of the survey area. Folded bedrock outcrops and occurs at shallow depths across this ridge. Along the side of this ridge, a spring occurs that feeds water to the wetland (see Figure 4). Both botanist and soil scientist easily defined the boundaries of this slope wetland. The wetland and sedge boundaries are shown in Figure 4.

Figure 17 shows the spatial distribution of apparent conductivity as measured with the EM38 meter. The spatial distributions of apparent conductivity collected in the horizontal and vertical dipole orientations are shown in the upper and lower plots, respectively. In each plot, the isoline interval is 2 mS/m.

Values of apparent conductivity measured with the EM38 meter were low to moderate (1.1 to 30.8 mS/m) and variable (standard deviation of 6.4 and 6.2 in the horizontal and vertical dipole orientations, respectively) within the survey area (see Table 5). Areas of low apparent conductivity were shallow to bedrock. Areas of high apparent conductivity represent *edge effect* accumulations of calcium carbonate. The spatial patterns of apparent conductivity shown in Figure 17 approximate the boundaries of the slope wetland. These plots of apparent conductivity can help soil scientists and hydrologist locate zones of higher conductivity that reflect deeper, more weathered earthen materials, which directs subsurface groundwater flow.

Figure 18 shows the spatial distribution of apparent conductivity as measured with the EM31 meter. The spatial distributions of apparent conductivity collected in the horizontal and vertical dipole orientations are shown in the upper and lower plots, respectively. In each plot, the isoline interval is 2 mS/m.

Values of apparent conductivity measured with the EM31 meter were low (4.2 to 19.0 mS/m) and slightly variable (standard deviation of 3.1 and 3.8 in the horizontal and vertical dipole orientations, respectively) within the survey area (see Table 5). Although apparent conductivity values were lower, spatial patterns for measurements collected with the EM31 meter were similar to those of the EM38 meter (see Figure 17). Areas of low apparent conductivity were shallow to bedrock. Areas of high apparent conductivity represent *edge effect* accumulations of calcium carbonate. The spatial patterns of apparent conductivity shown in Figure 18 approximate the boundaries of the slope wetland.

Figures 19 and 20 show the spatial distribution of apparent conductivity as measured with the GEM300 sensor. In each figure, data collected in the horizontal and vertical dipole orientations are shown in the upper and lower plots, respectively. Figure 19 shows the spatial distribution of apparent conductivity as measured with the GEM300 sensor at frequencies of

5010 Hz (upper plots) and 9810 Hz (lower plots). Figure 20 shows the spatial distribution of apparent conductivity as measured with the GEM300 sensor at frequencies of 14790Hz (upper plots) and 19950 Hz (lower plots). In each plot, the isoline interval is 2 mS/m

With the exception of absolute values, the plots of apparent conductivity collected with the GEM300 sensor at the Gravelly Mountain Fen are remarkably similar. In addition, these plots are similar to those obtained with the EM38 and the EM31 meters. With the GEM300 sensor, data collected in either dipole orientations, but at different frequencies, are similar. For operating frequencies of 19950, 14790, and 9810 Hz, patterns are similar and signal amplitudes decrease with decreased frequency and increased penetration depths. However, while spatial patterns of apparent conductivity remain similar, signal amplitudes collected at 5010 Hz increase. This reversal of the trend (signal amplitudes decrease with decreased frequency and increased penetration depths) may reflect the presence of more conductive materials at greater depths or system noise. As similar spatial patterns are obtain with the GEM300 sensor at each of the four frequencies, system noise contributing to higher apparent conductivity values at 5010 Hz is suspected.

Table 11
Correlation Between Apparent Conductivity Measurements obtained with the GEM300 Sensor Operating at Different Frequencies and in Different Dipole Orientations.
Gravelly Mountain Fen

A

	5010-V	9810-V	14790-V	19950-V
5010-H	0.9545	0.9517	0.9554	0.9522
9810-H	0.9617	0.9620	0.9664	0.9653
14790-H	0.9525	0.9535	0.9577	0.9568
19950-H	0.9586	0.9597	0.9636	0.9637

B

	5010-V	9810-V	14790-V	19950-V
5010-V	1.0000	0.9980	0.9978	0.9966
9810-V		1.0000	0.9984	0.9979
14790-V			1.0000	0.9983
19950-V				1.0000

C

	5010-H	9810-H	14790-H	19950-H
5010-H	1.0000	0.9835	0.9751	0.9755
9810-H		1.0000	0.9922	0.9919
14790-H			1.0000	0.9940
19950-H				1.0000

Table 11 shows the correlation coefficients for measurements obtained at different frequencies and/or dipole orientations. Correlations among the data collected in different dipole orientations are very high. As at the other sites, correlations were lowest for measurements obtained at similar frequencies but in different dipole orientations (see section A, Table 11). Correlations were highest for measurements obtained in similar dipole orientations, but at different frequencies (see section B and C, Table 11). In this wetland, characterized by low to moderate apparent conductivity, the use of a single frequency with different dipole orientations appears to provide sufficient information.

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EMI SURVEY OF HIGH CREEK FEN
PARK COUNTY, COLORADO
RELATIVE ELEVATION

Contour Interval = 1 Foot

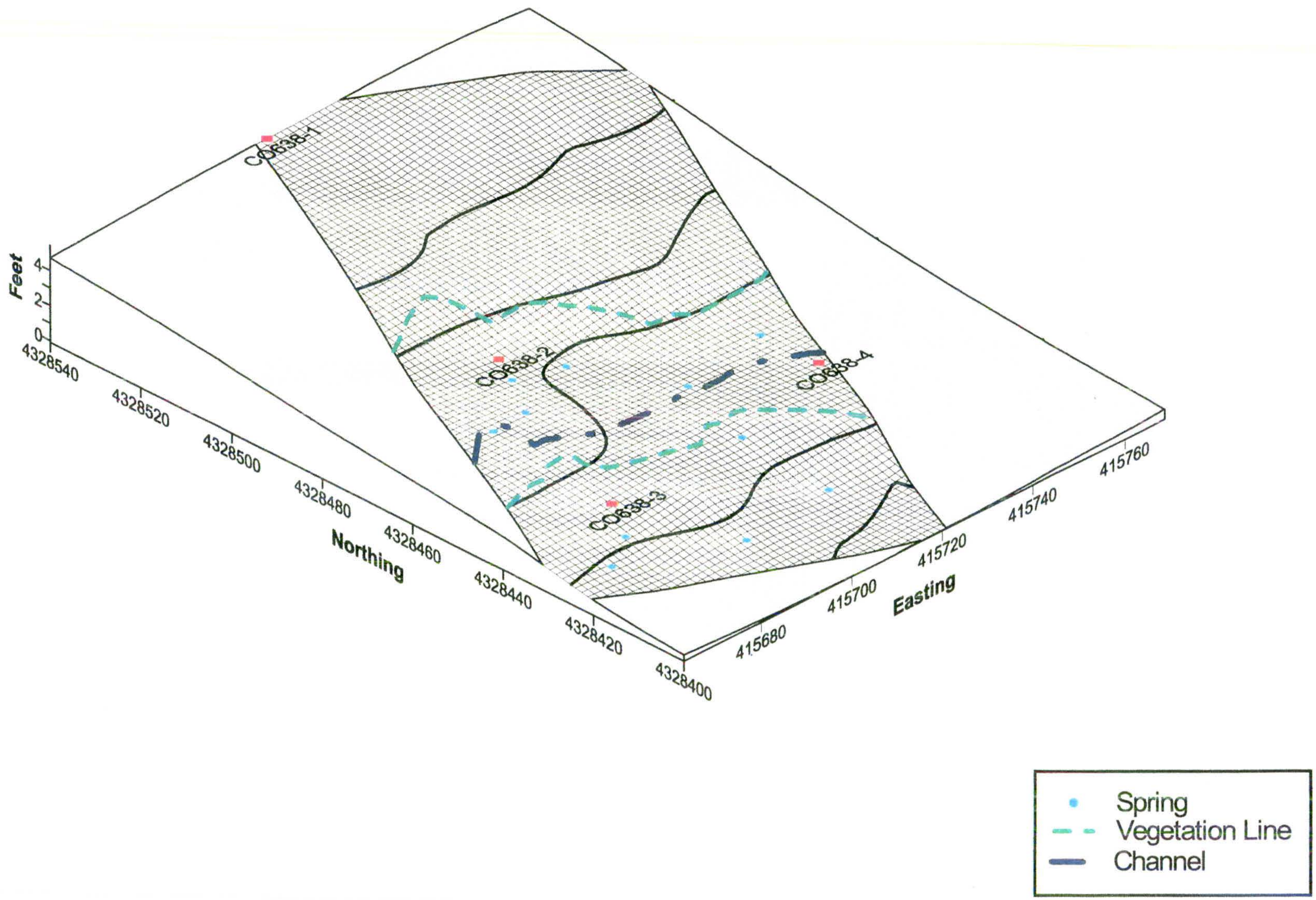


Figure 1

EMI SURVEY OF TETER FEN
PARK COUNTY, COLORADO
RELATIVE ELEVATION

Contour Interval = 1 Foot

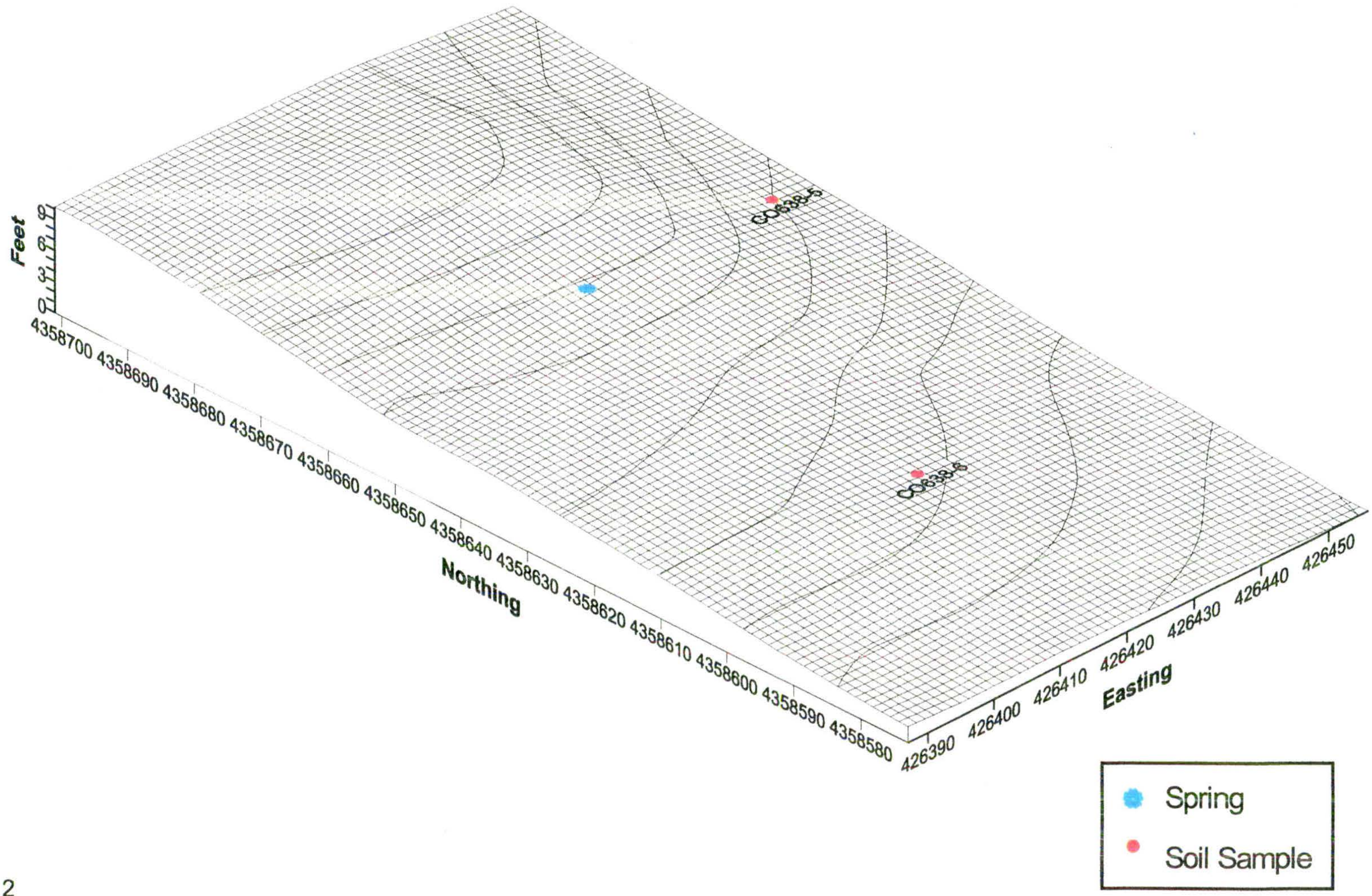


Figure 2

EMI SURVEY OF LAMAR RIVER SITE
YELLOWSTONE NATIONAL PARK
RELATIVE ELEVATION

Contour Interval = 5 Feet

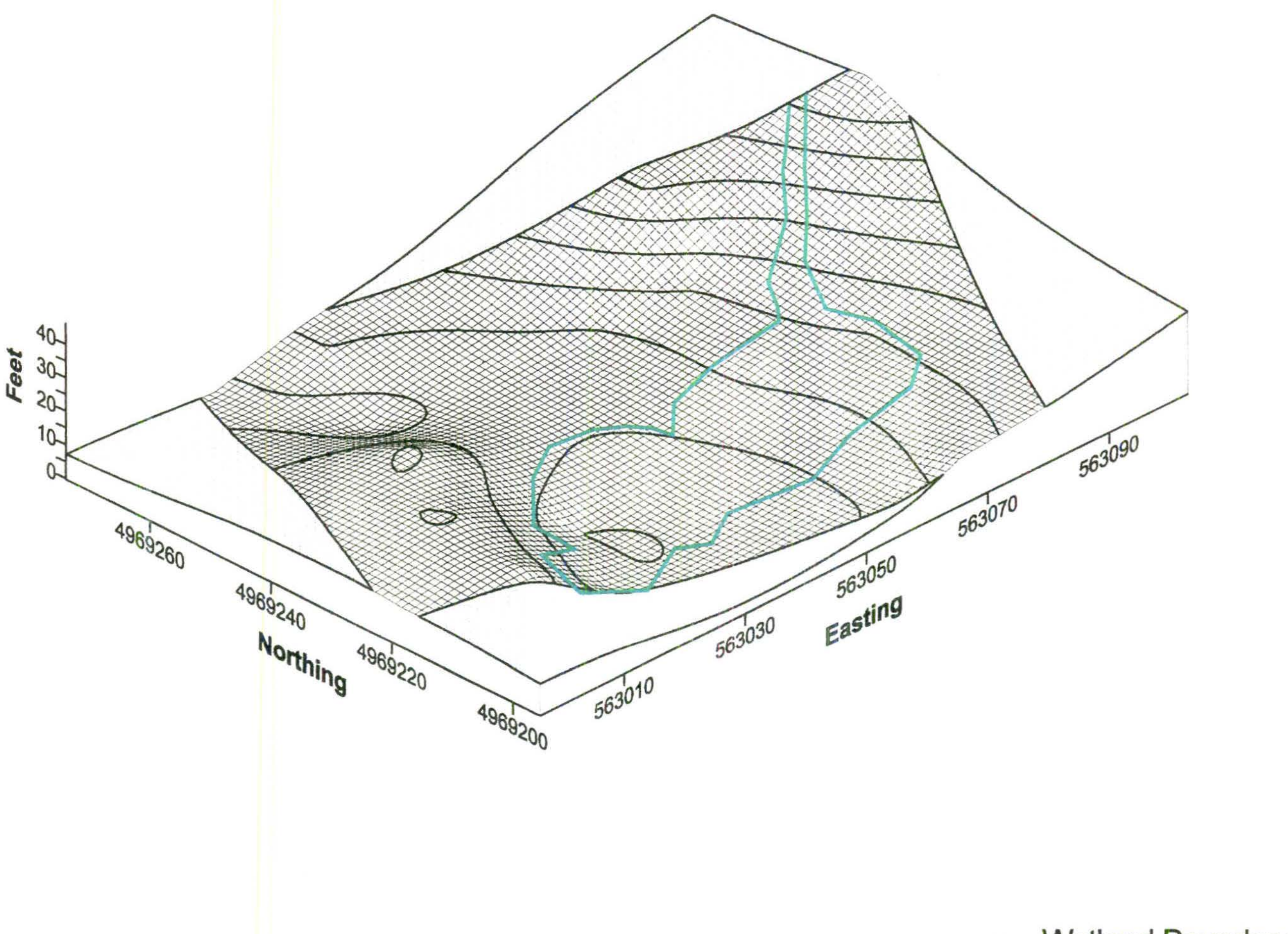


Figure 3

EMI SURVEY OF GRAVELY MOUNTAIN FEN
MADISON COUNTY, MONTANA
RELATIVE ELEVATION

Contour Interval = 5 Feet

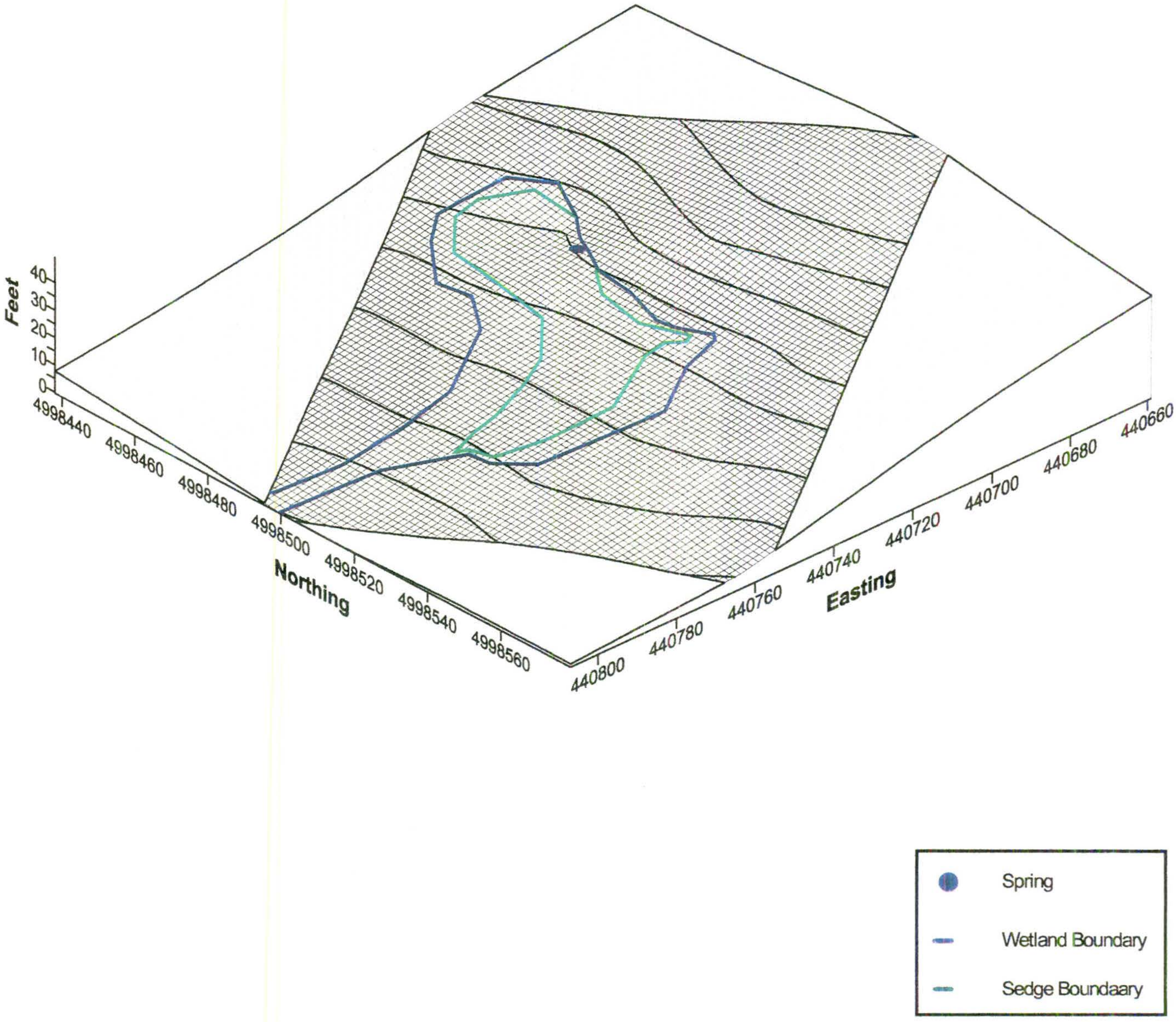


Figure 4

EMI SURVEY OF HIGH CREEK FEN
PARK COUNTY, COLORADO
THICKNESS OF ORGANIC DEPOSITS

Contour Interval = 8 Inches

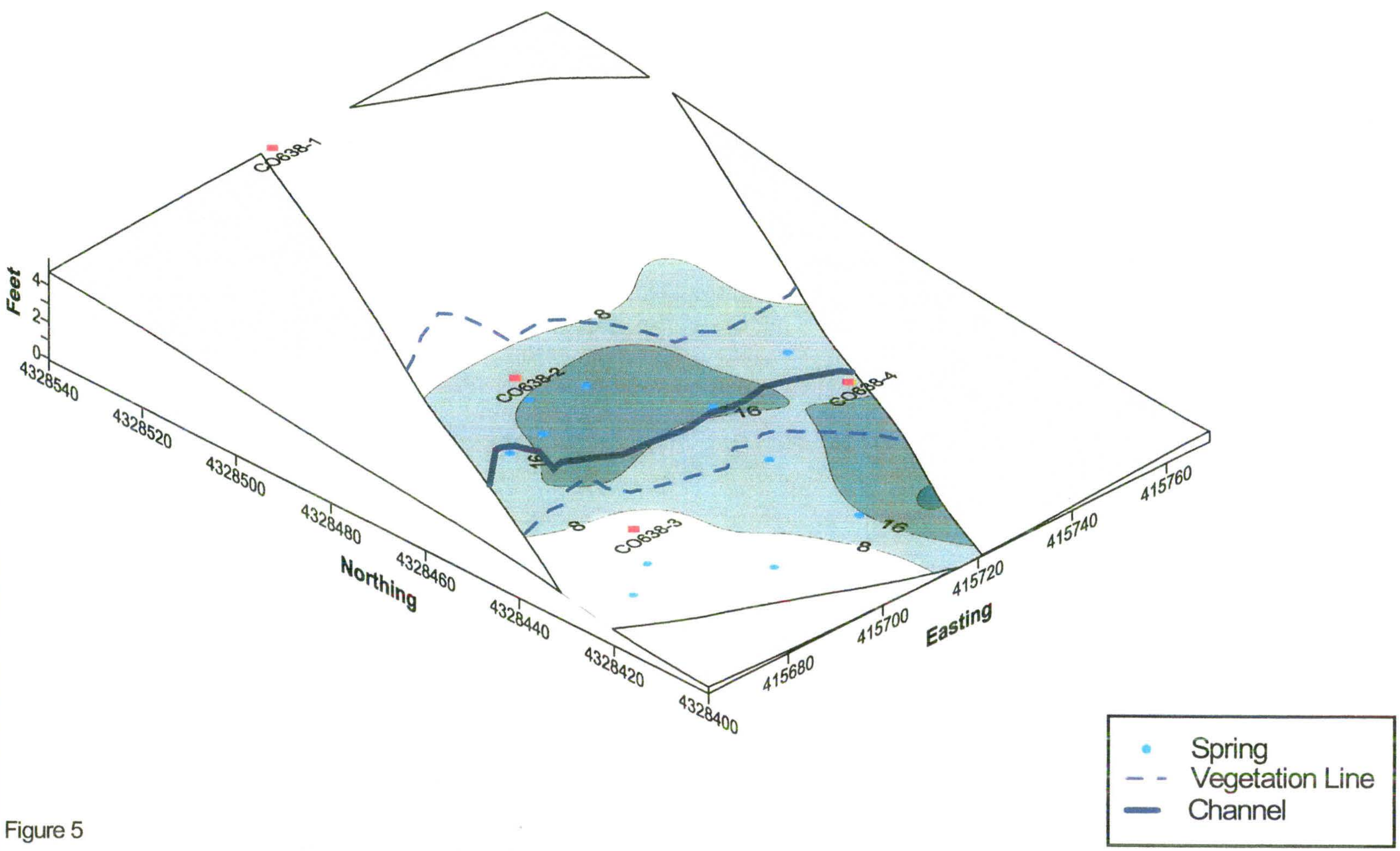


Figure 5

EMI SURVEY OF HIGH CREEK FEN
PARK COUNTY, COLORADO
EM38-DD METER

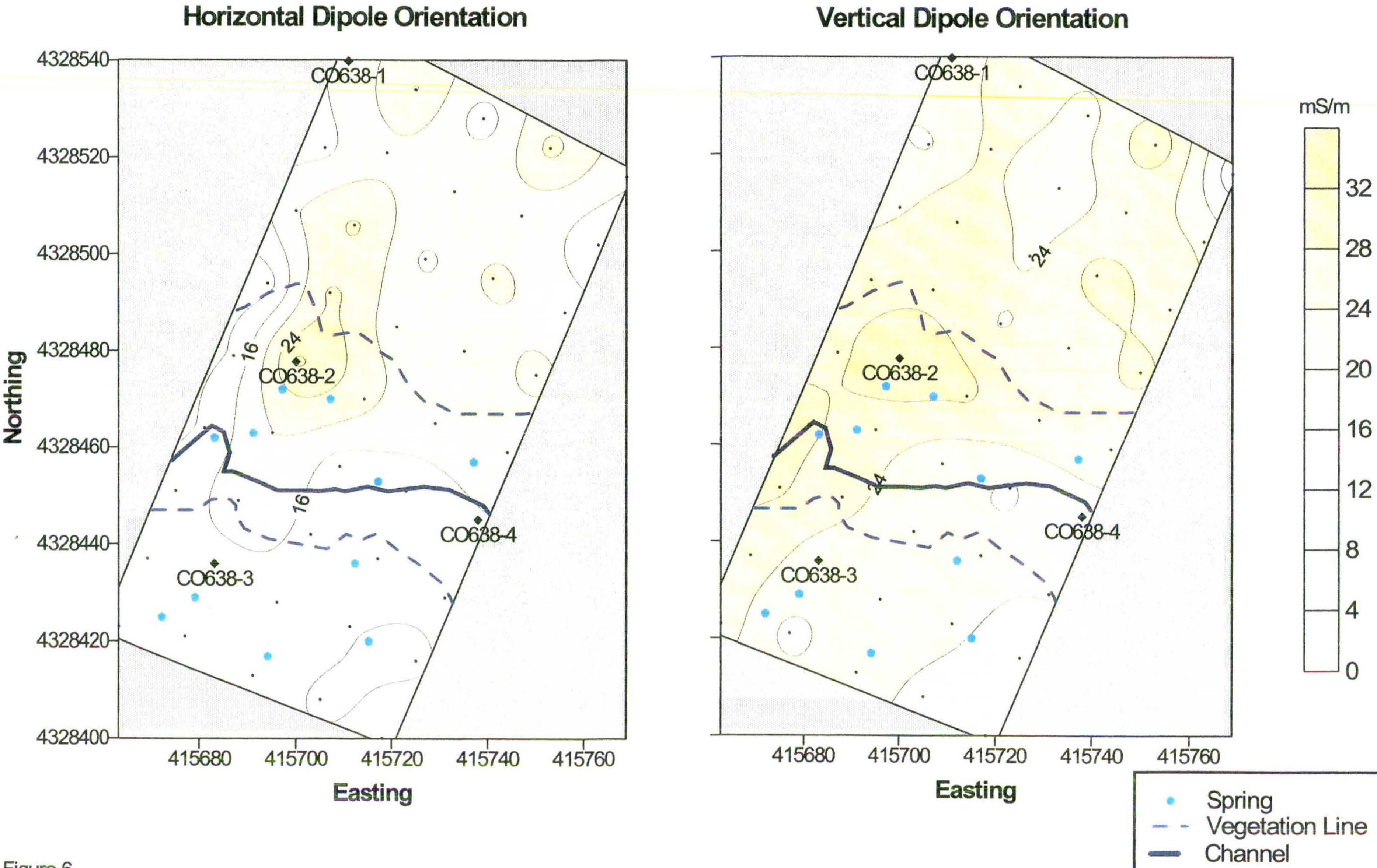
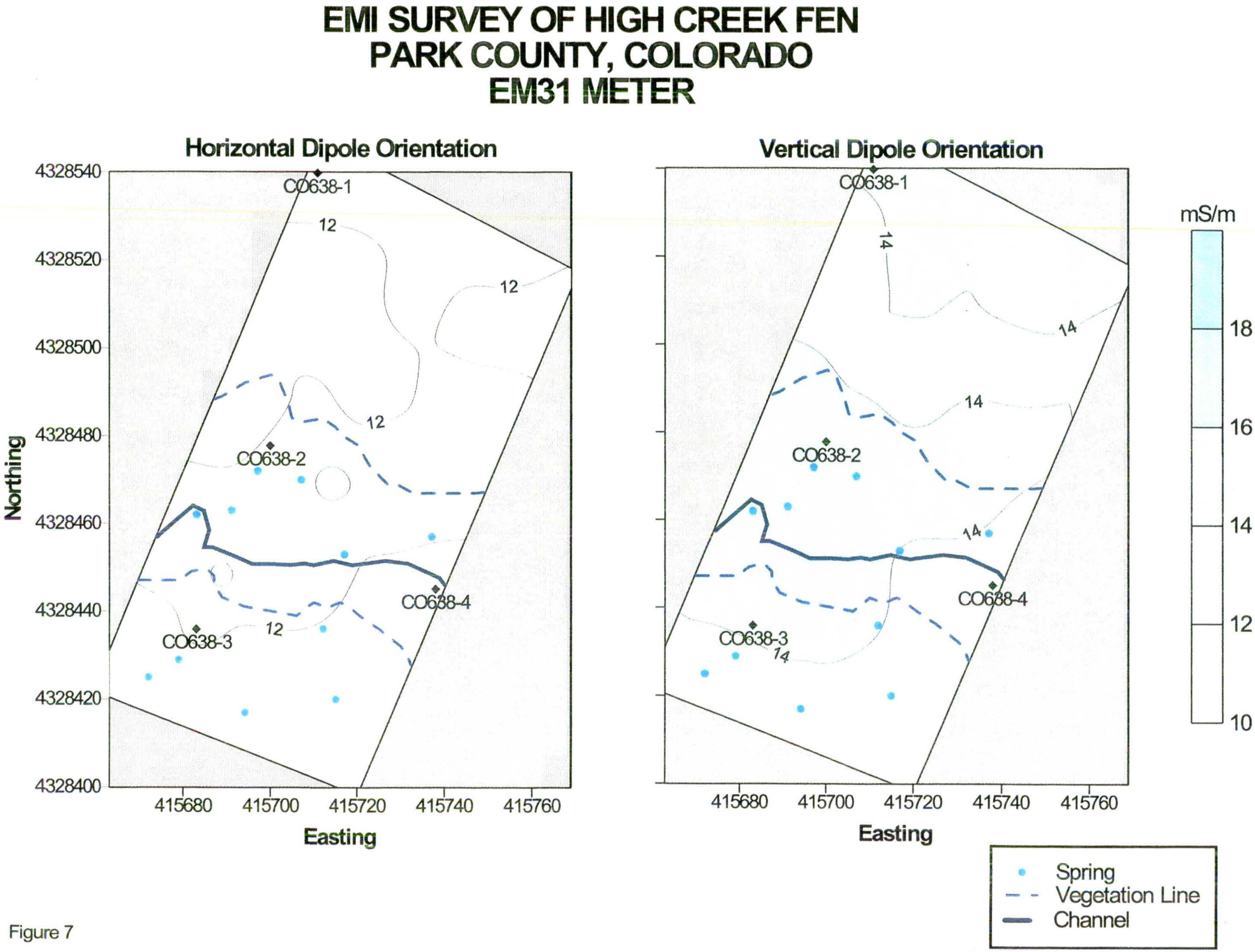


Figure 6



EMI SURVEY OF HIGH CREEK FEN
PARK COUNTY, COLORADO
EM31 METER
Horizontal Dipole Orientation
Vertical Dipole Orientation
Northing
Easting
4328540
4328520
4328500
4328480
4328460
4328440
4328420
4328400
415680
415700
415720
415740
415760
CO638-1
CO638-2
CO638-3
CO638-4
12
14
mS/m
18
16
14
12
10
Spring
Vegetation Line
Channel

Figure 7

EMI SURVEY OF HIGH CREEK FEN
PARK COUNTY, COLORADO
GEM300 SENSOR

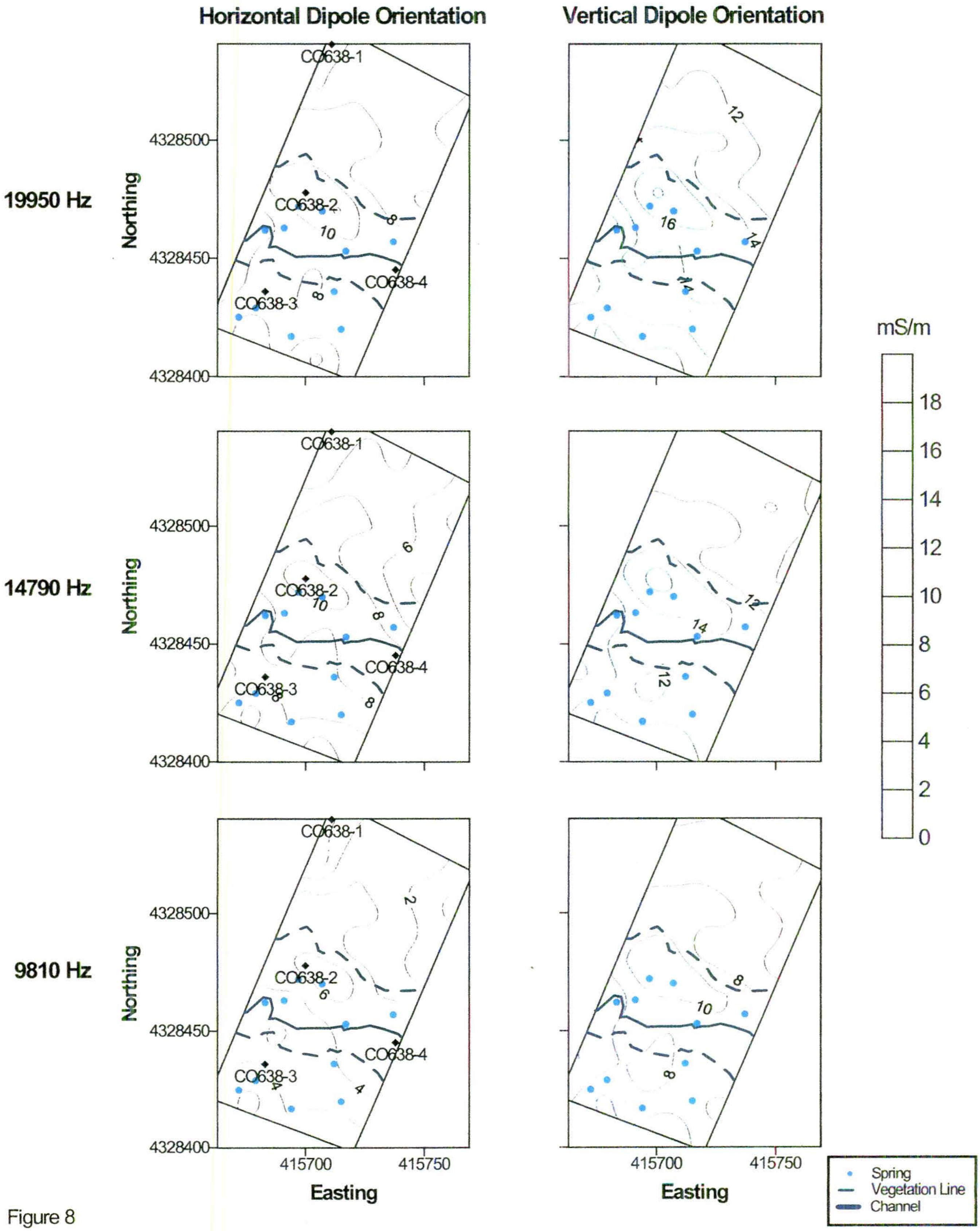


Figure 8

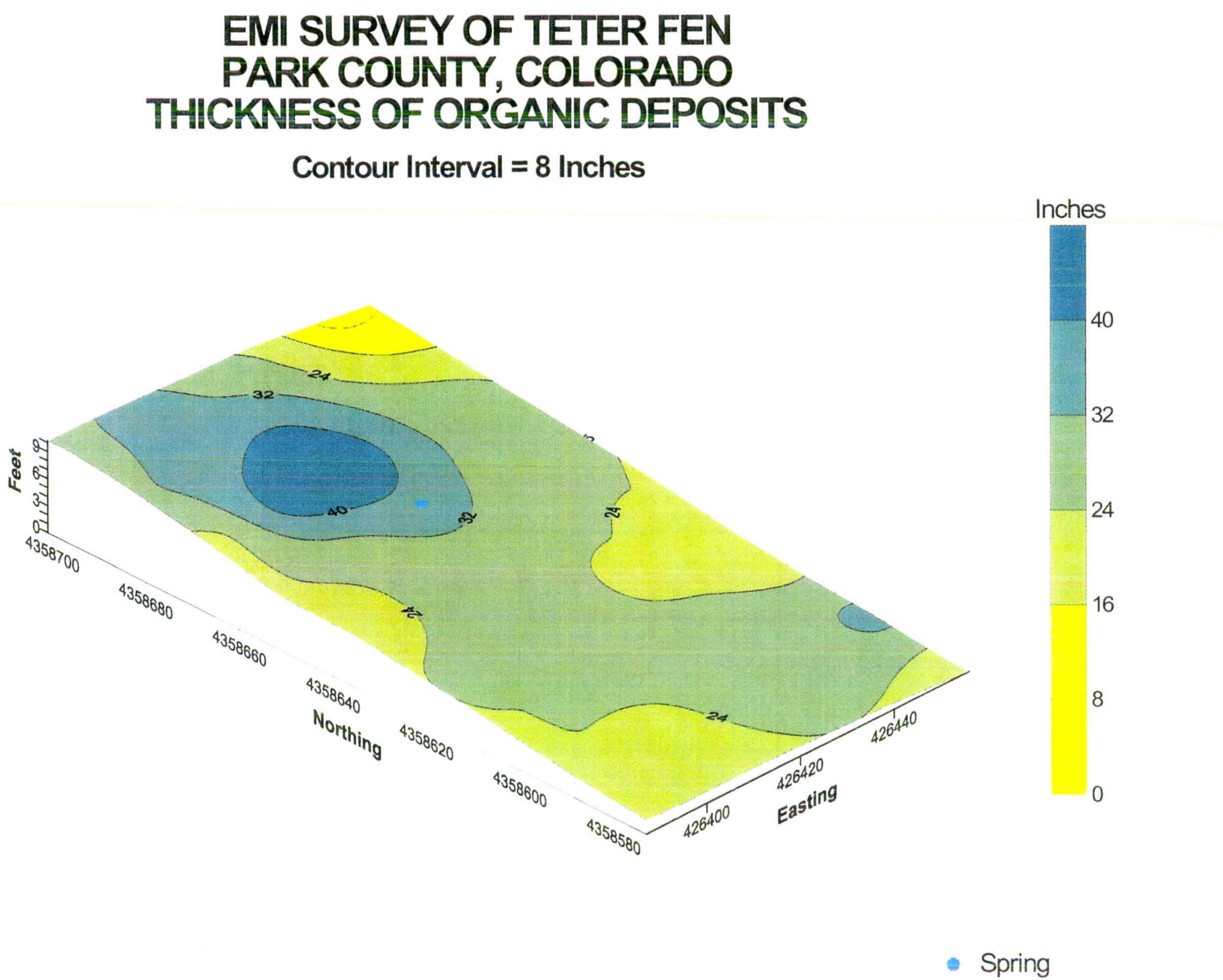

EMI SURVEY OF TETER FEN
PARK COUNTY, COLORADO
THICKNESS OF ORGANIC DEPOSITS
Contour Interval = 8 Inches
Inches
40
32
24
16
8
0
Feet
4358700
4358680
4358660
4358640
Northing
4358620
4358600
4358580
426400
426420
Easting
426440
Spring

Figure 9

EMI SURVEY OF TETER FEN
PARK COUNTY, COLORADO
EM38-DD METER

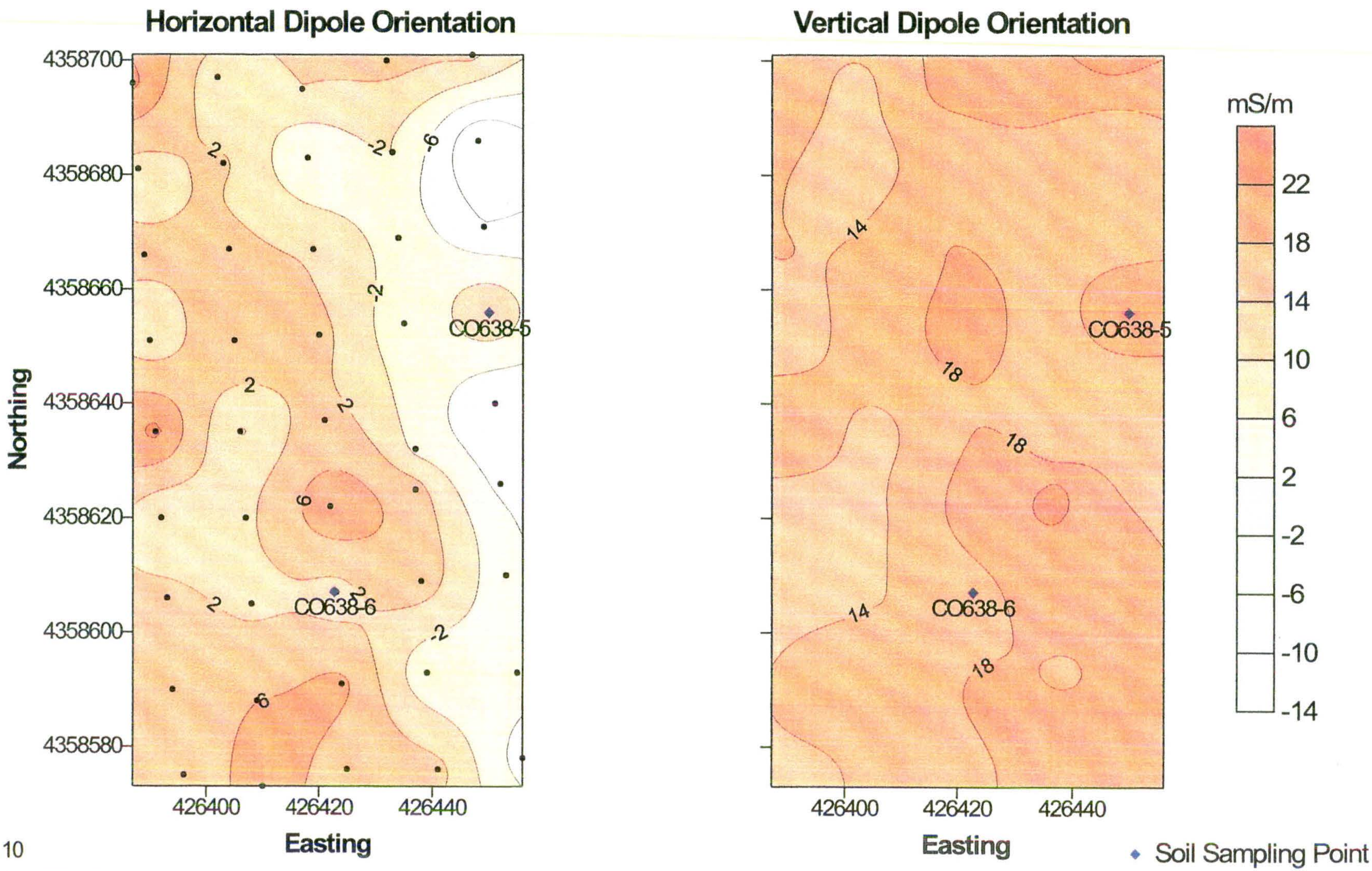


Figure 10

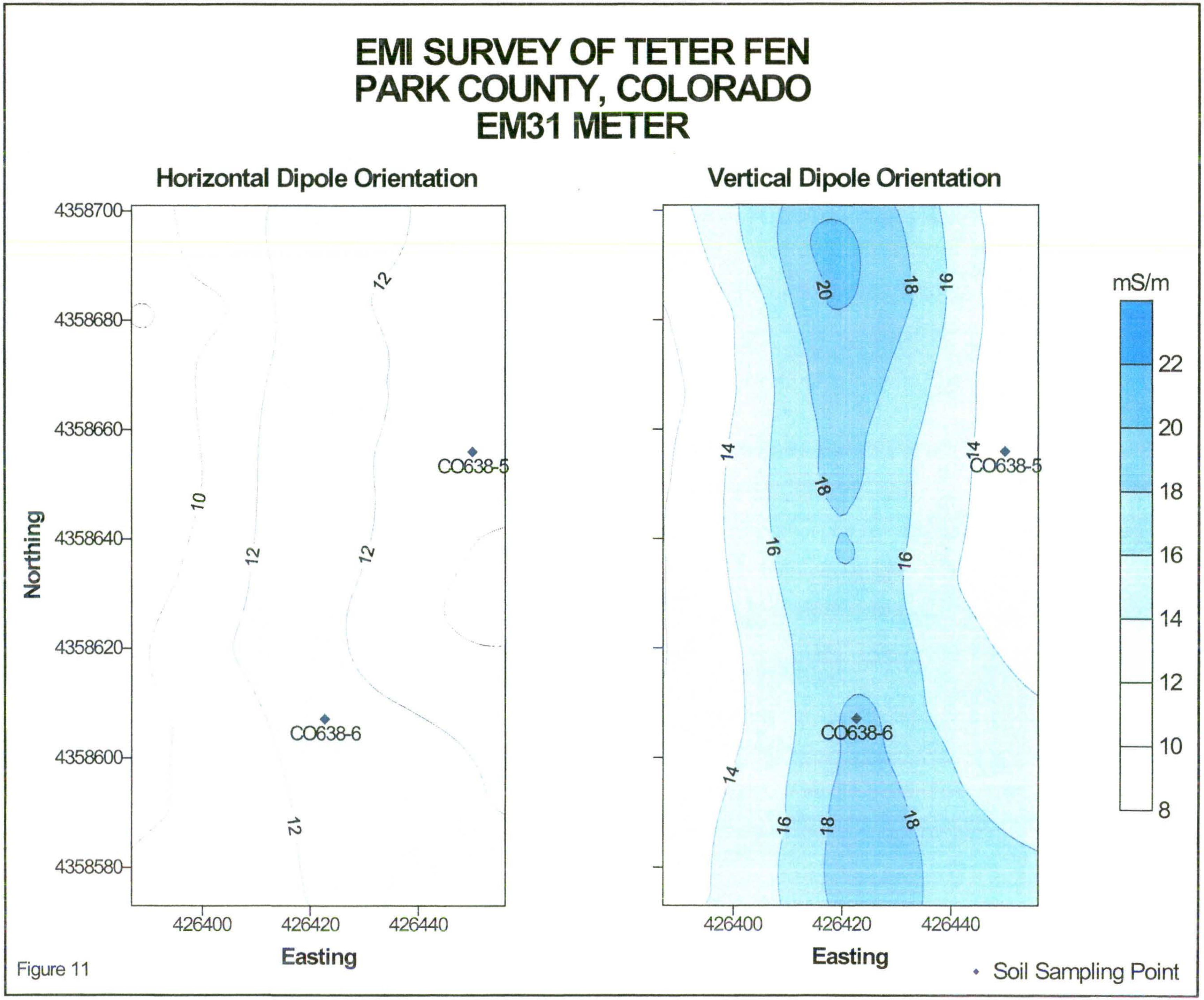

EMI SURVEY OF TETER FEN
PARK COUNTY, COLORADO
EM31 METER
Horizontal Dipole Orientation
Vertical Dipole Orientation
Northing
4358700
4358680
4358660
4358640
4358620
4358600
4358580
426400
426420
426440
Easting
Easting
CO638-5
CO638-6
10
12
14
16
18
20
mS/m
22
20
18
16
14
12
10
8
Soil Sampling Point

Figure 11

EMI SURVEY OF TETER FEN
PARK COUNTY, COLORADO
GEM300 SENSOR

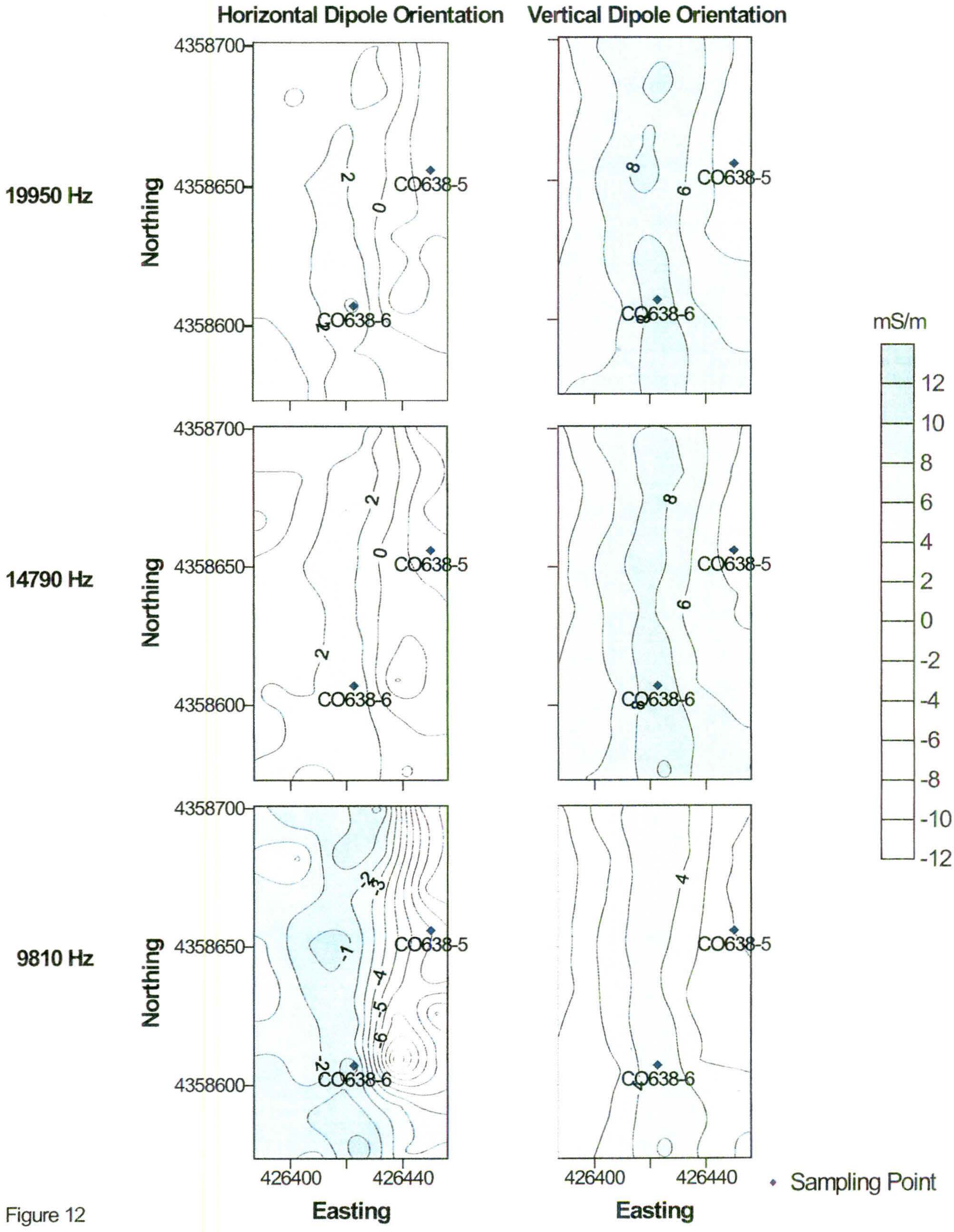


Figure 12

EMI SURVEY OF LAMAR RIVER SITE
YELLOWSTONE NATIONAL PARK
EM31 METER

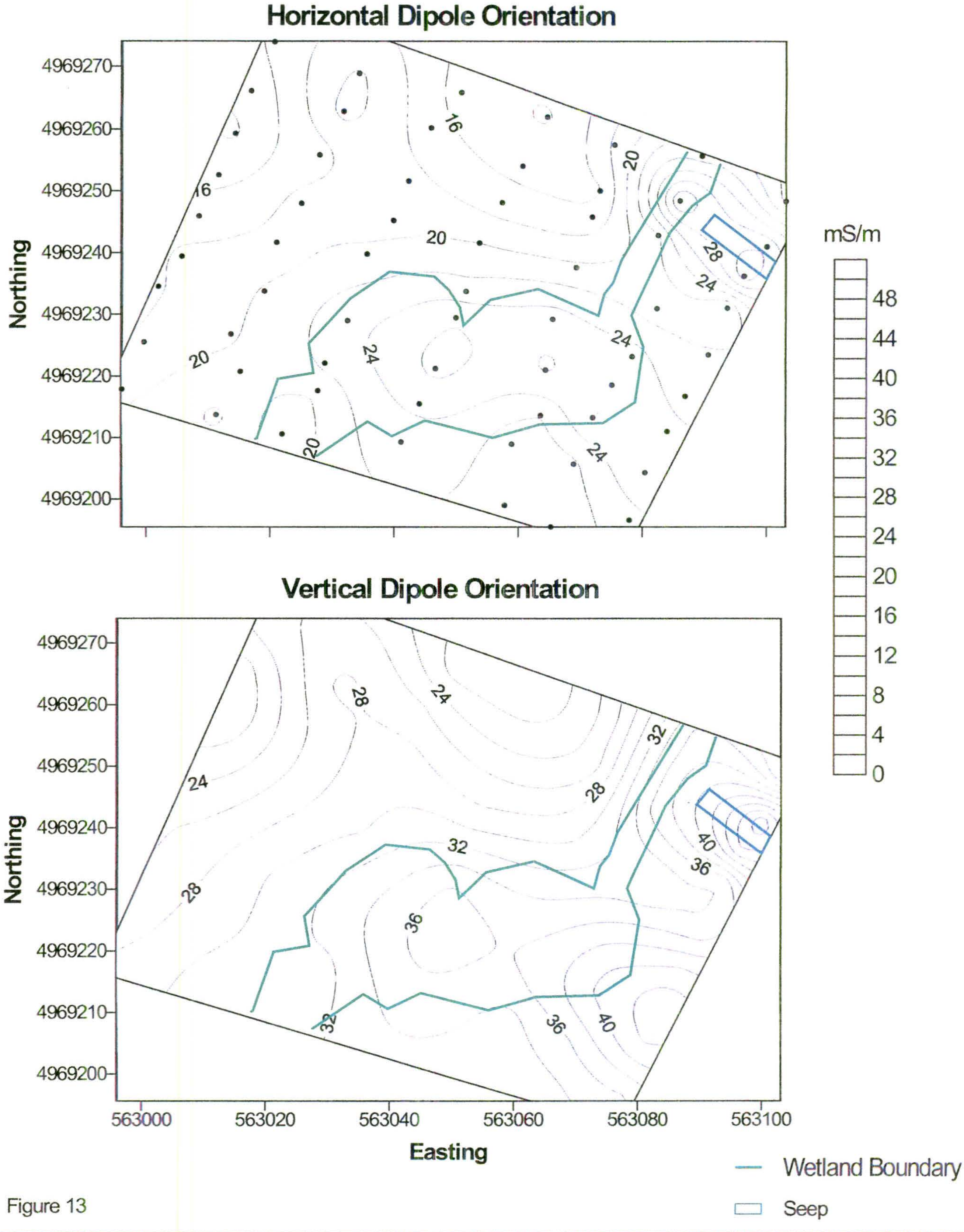


Figure 13

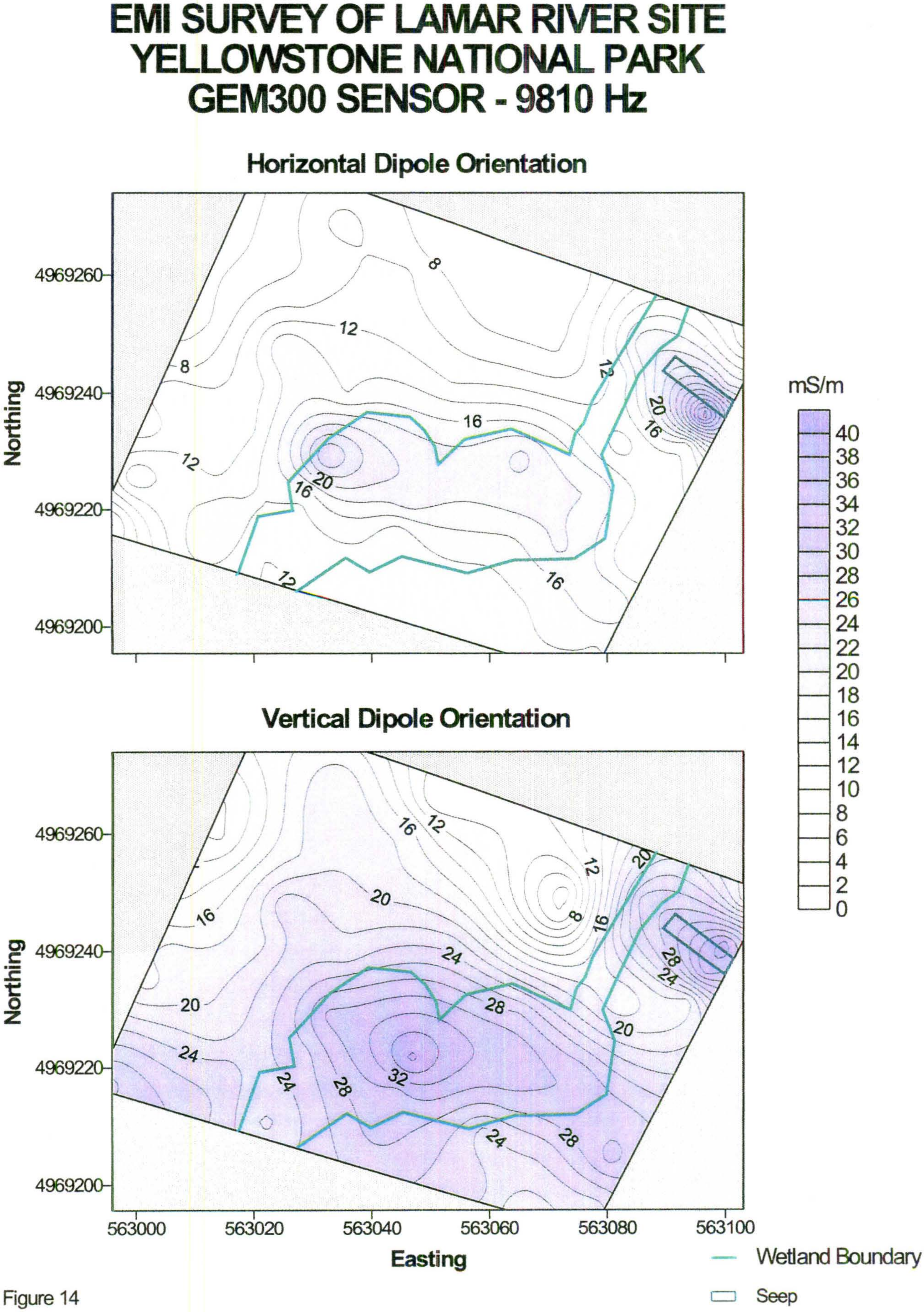

EMI SURVEY OF LAMAR RIVER SITE
YELLOWSTONE NATIONAL PARK
GEM300 SENSOR - 9810 Hz
Horizontal Dipole Orientation
Vertical Dipole Orientation
Northing
Easting
mS/m
Wetland Boundary
Seep

Figure 14

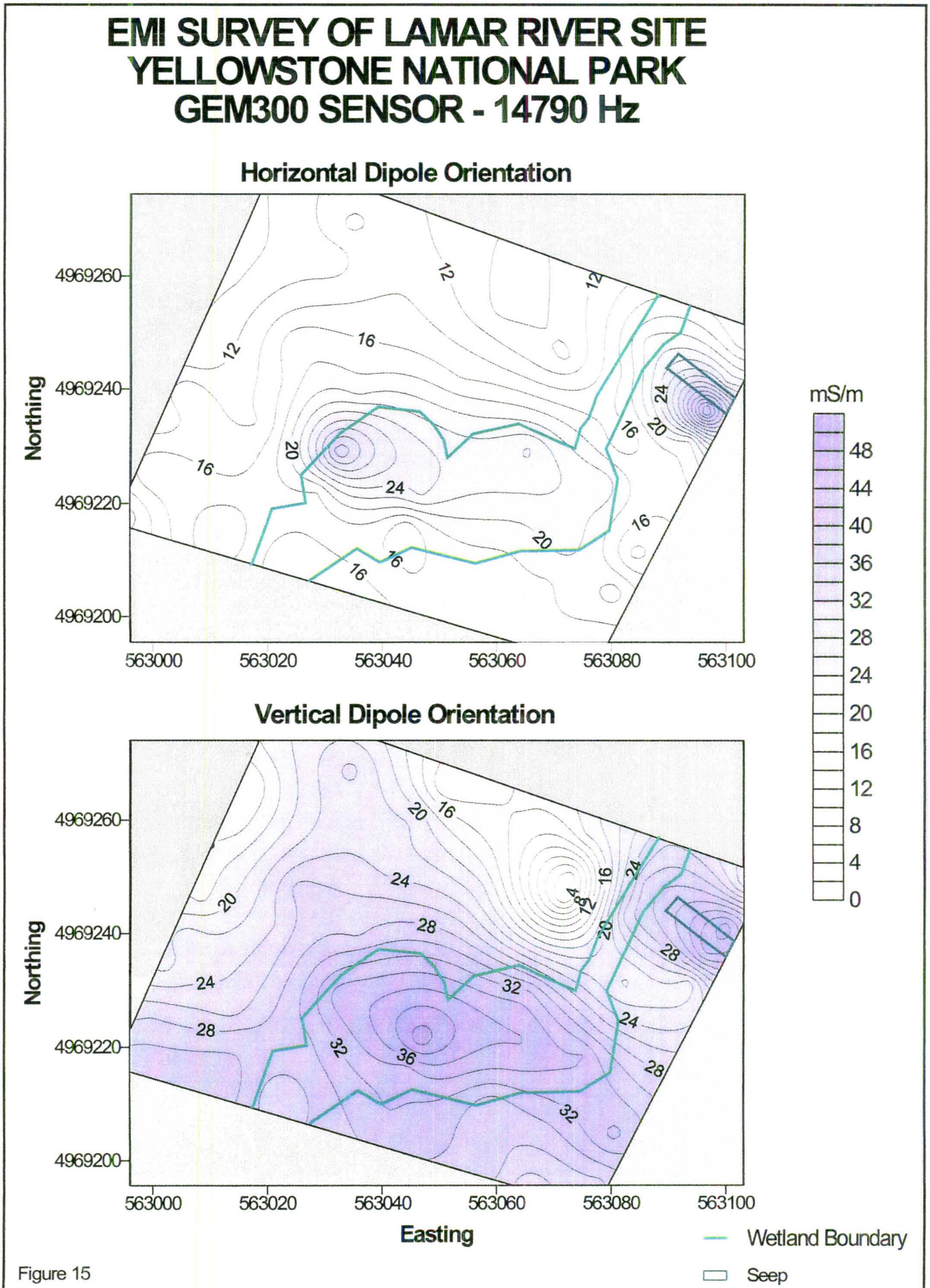

EMI SURVEY OF LAMAR RIVER SITE
YELLOWSTONE NATIONAL PARK
GEM300 SENSOR - 14790 Hz
Horizontal Dipole Orientation
Vertical Dipole Orientation
Northing
Easting
4969260
4969240
4969220
4969200
563000
563020
563040
563060
563080
563100
mS/m
48
44
40
36
32
28
24
20
16
12
8
4
0
Wetland Boundary
Seep

Figure 15

EMI SURVEY OF LAMAR RIVER SITE
YELLOWSTONE NATIONAL PARK
GEM300 SENSOR - 19950 Hz

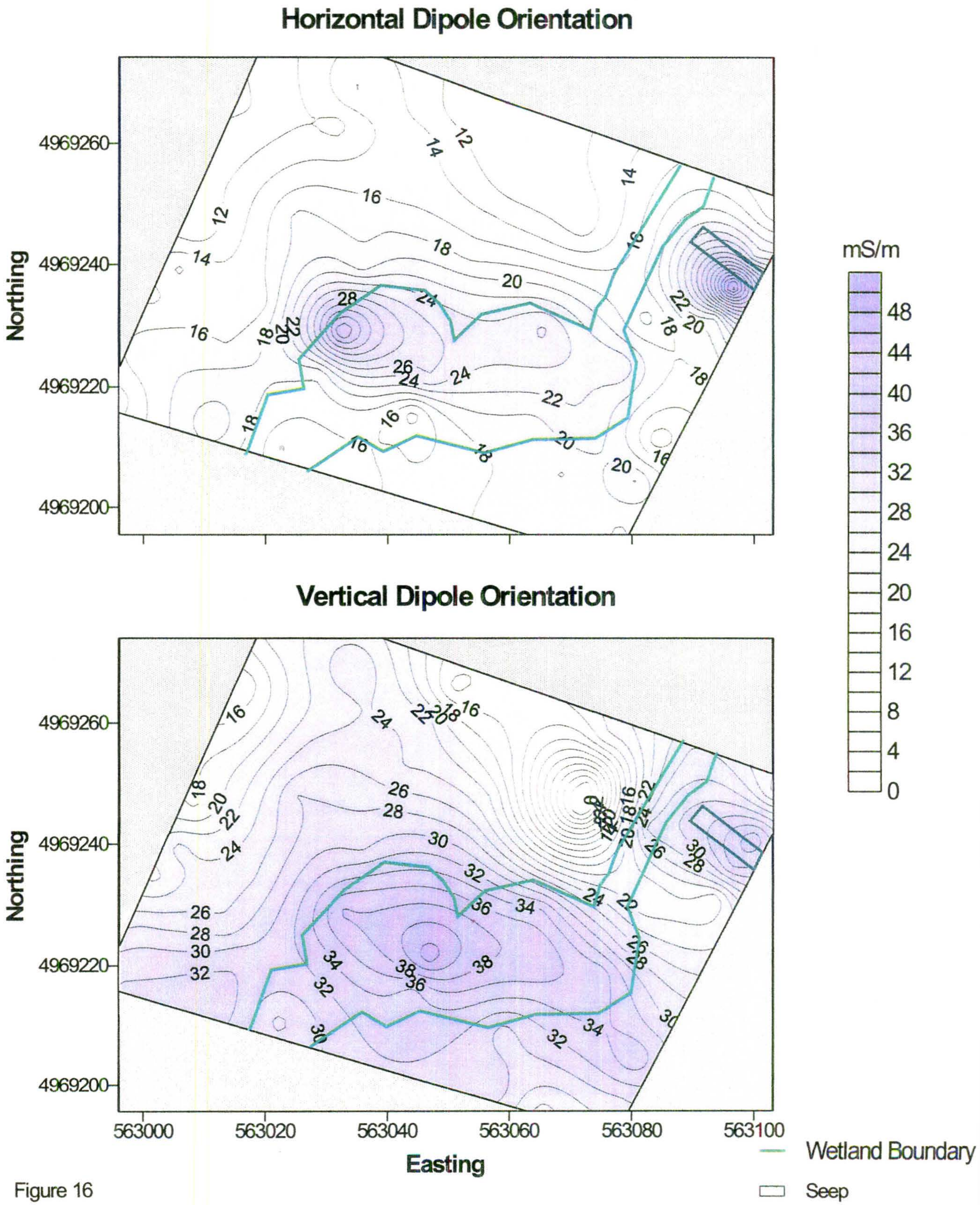


Figure 16

EMI SURVEY OF GRAVELY MOUNTAIN FEN
MADISON COUNTY, MONTANA
EM38 METER

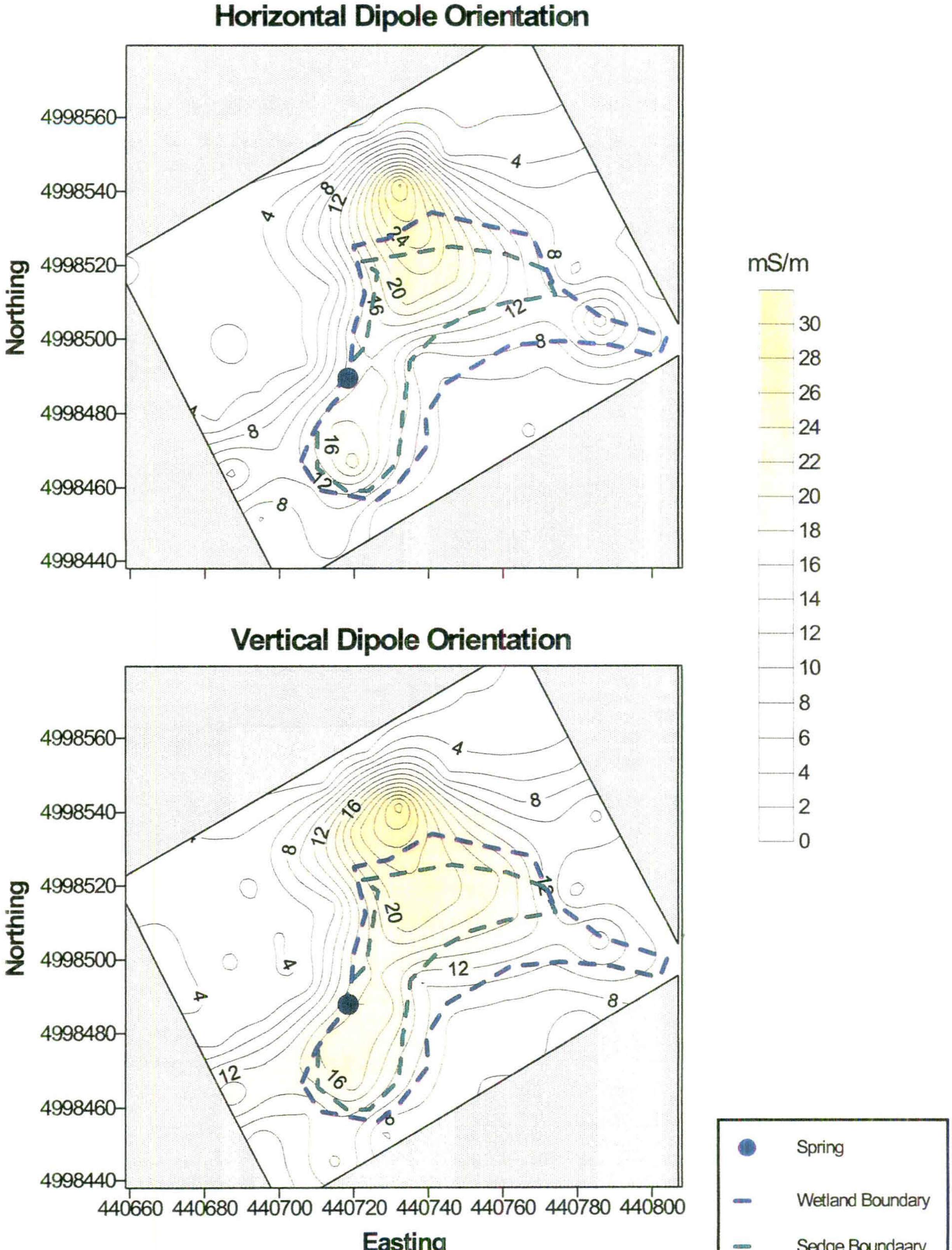


Figure 17

EMI SURVEY OF GRAVELY MOUNTAIN FEN
MADISON COUNTY, MONTANA
EM31 METER

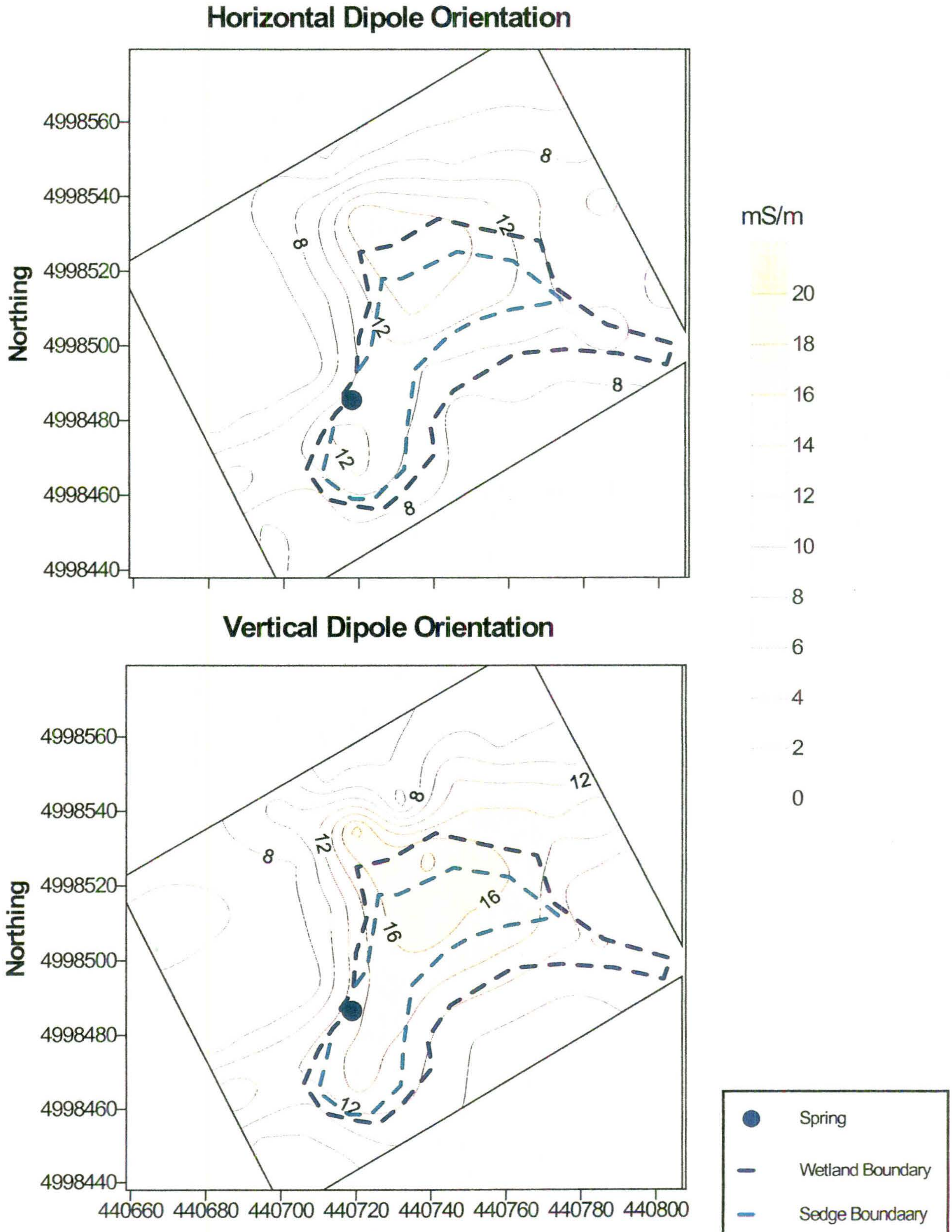
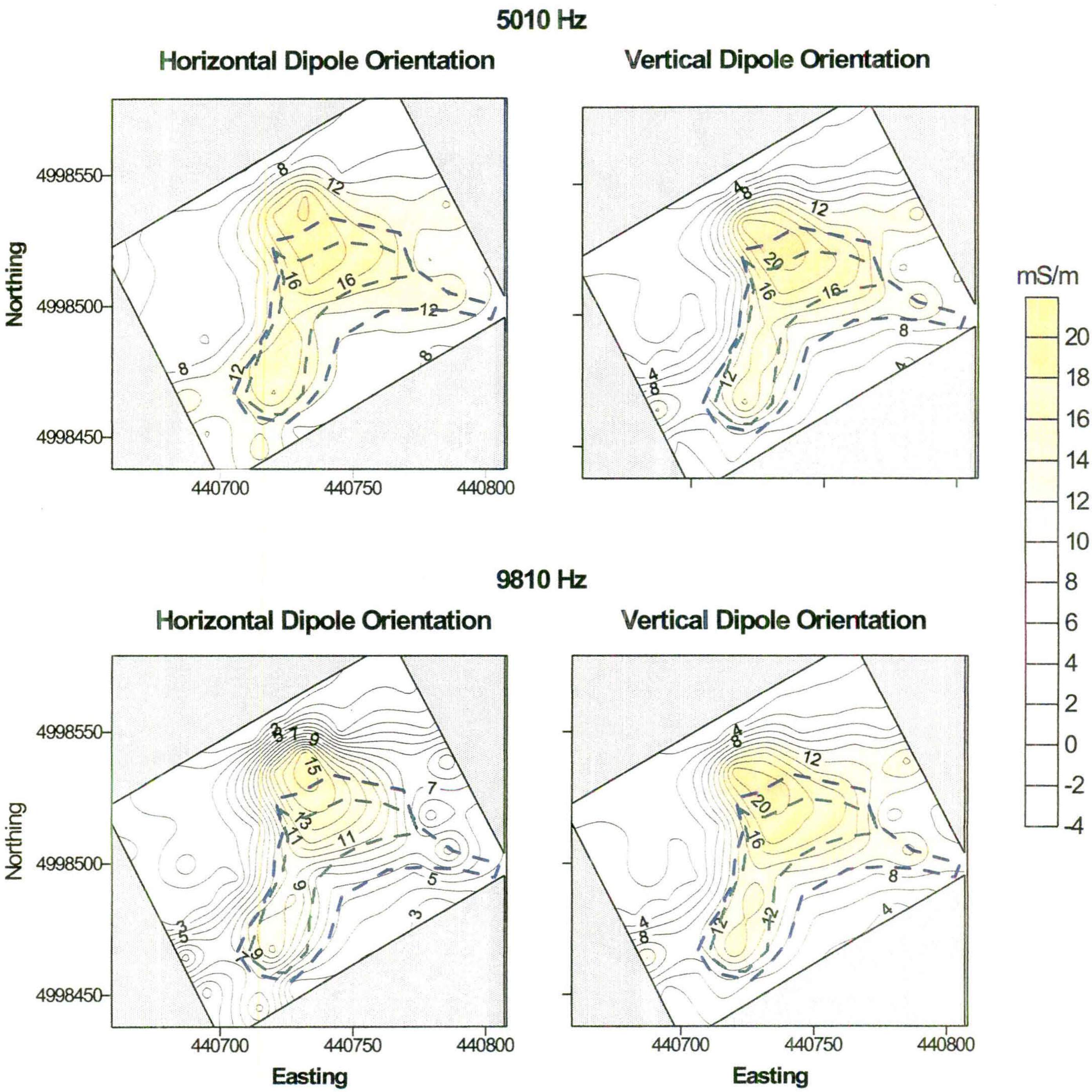


Figure 18

EMI SURVEY OF GRAVELY MOUNTAIN FEN
MADISON COUNTY, MONTANA
GEM300 SENSOR



File 19