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

Subject: SOI -- Electromagnetic Induction (EMI) Assistance **Date:** 18 June 1997

To: Darrel Dominick
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USDA-NRCS,
5 Godfrey Drive
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Purpose:
The purpose of this investigation was to map the spatial distribution of apparent conductivity within a long term research site at the Aroostook Farm, Presque Isle, Maine.

Participating Agencies:
University of Maine
USDA-Natural Resources Conservation Service

Participants:
Jim Doolittle, Research Soil Scientist, USDA-NRCS, Radnor, PA
Ron Olson, Soil Resource Specialist, USDA-NRCS, Bangor, ME
Gregory Porter, Associate Professor of Agronomy, University of Maine, Orono, ME

Activities:
All field activities were completed during the period of 2 to 4 June 1997.

Equipment:
The electromagnetic induction meters used in this study were the EM38 and EM31 manufactured by Geonics Limited.* These meters are portable and require one person to operate. Principles of operation have been described by McNeill (1980a, 1986). Ground contact is not required with these meters. Lateral resolution is approximately equal to the intercoil spacing of the meter. Each meter provides limited vertical resolution and depth information. The observation depth of an EMI meter is dependent upon intercoil spacing, transmission frequency, and dipole orientation. Table 1 lists the anticipated observation depths for the EM38 and EM31 meters with different dipole orientations.

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

TABLE 1

Depth of Measurement
(All measurements are in feet)

Meter	Intercoil Spacing	Depth of Measurement Horizontal	Vertical
EM38	3.2	2.5	5.0
EM31	12.0	9.8	19.7

The EM38 meter has a fixed intercoil spacing of about 3.2 feet. It operates at a frequency of 13.2 kHz. The EM38 meter has theoretical observation depths of about 2.5 and 5 feet in the horizontal and vertical dipole orientations, respectively (McNeill, 1986). The EM31 meter has a fixed intercoil spacing of about 12.7 feet. It operates at a frequency of 9.8 kHz. The EM31 meter has theoretical observation depths of about 10 and 20 feet in the horizontal and vertical dipole orientations, respectively (McNeill, 1980a). Values of apparent conductivity are expressed in milliSiemens per meter (mS/m).

To help summarize results, the SURFER for Windows program, developed by Golden Software, Inc.,* was used to construct two- and three-dimensional simulations. Grids were created using kriging methods with an octant search. All grids were smoothed using a cubic spline interpolation. Shadings and filled isoconductivity lines have been used in the enclosed plots to help emphasize spatial patterns. Other than showing trends and patterns in values of apparent conductivity (i.e., zones of higher or lower electrical conductivity), no significance should be attached to the shades themselves.

Introduction:

Several long term research projects are being carried out at the Aroostook Farm in Presque Isle, Maine. The *Potato Ecosystem Project* consists of ninety-six, 48 ft by 135 ft research plots. Three different management practices are being evaluated on these plots (conventional, biological, and reduced input).

Soil maps prepared by the USDA do not show in sufficient detail the variations in soil types and soil properties needed for this project. The *Potato Ecosystem Project* requires soil attribute maps prepared at a level of resolution that is comparable to the scale of management (0.1448 acre). Soil attribute maps need to be prepared at scales suitable for showing the variability of soils, soil properties, or capabilities across these units of management. Depth to bedrock is a critical soil attribute. The collection of these data by traditional methods is prohibitively expensive, time-consuming, and labor-intensive. Dr. Porter wishes to explore the use of geophysical methods to provide more precise maps of soils, soil depths, or other soil properties.

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Electromagnetic induction (EMI) is a noninvasive geophysical tool that has been used in high intensity surveys and for detailed site assessments. Electromagnetic induction uses electromagnetic energy to measure the apparent conductivity of earthen materials. Apparent conductivity is a weighted, average conductivity measurement for a column of earthen materials to a specific observation depth (Greenhouse and Slaine, 1983). Variations in apparent conductivity are produced by changes in the electrical conductivity of earthen materials. The electrical conductivity of soils is influenced by the type and concentration of ions in solution, the amount and type of clays in the soil matrix, the volumetric water content, and the temperature and phase of the soil water (McNeill, 1980b). The apparent conductivity of soils increases with increases in the concentrations of soluble salts, water, and/or clays (Kachanoski et al., 1988; Rhoades et al., 1976).

Electromagnetic induction methods map spatial variations in apparent conductivity. 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 has been used extensively to identify, map, and monitor soil salinity (Cook and Walker, 1992; Corwin and Rhoades, 1982 and 1990; Rhoades and Corwin, 1981; Rhoades et al., 1989; Slavich and Peterson, 1990; and Wollenhaupt et al., 1986). This technology has also been used to assess and map sodium-affected soils (Ammons et al., 1989; Nettleton et al., 1994), depths to claypans (Doolittle et al., 1994; Stroh et al., 1993; Sudduth and Kitchen, 1993; and Sudduth et al., 1995), regional differences in soil mineralogy (Doolittle et al., 1995), and edaphic properties important to forest site productivity (McBride et al., 1990). In addition, electromagnetic induction has been used to measure soil water contents (Kachanoski et al., 1988), cation exchange capacity (McBride et al., 1990), and leaching rates of solutes (Jaynes et al., 1995b).

Apparent conductivity can be used as a measure of within-field variability. Apparent conductivity has been associated with changes in soils and soil map units (Doolittle et al., 1996; Hoekstra et al., 1992; Jaynes et al., 1993). Electromagnetic induction integrates the bulk physical and chemical properties of soils into a single value for a defined observation depth. The inherent physical and chemical properties of each soil, as well as temporal variations in soil water and temperature, establish a unique and characteristic range of apparent conductivity values. This range is influenced by differences in use and management practices (Sudduth and Kitchen, 1993, Sudduth et al., 1995).

Electromagnetic induction is ideally suited to high intensity surveys or research projects. Recently, EMI has been used in the Midwest to map soil attributes for precision farming (Jaynes, 1995; Jaynes et al., 1995a; Sudduth et al., 1995). This technique is relatively fast, inexpensive, and can provide the comprehensive coverage needed for precision farming. Results from EMI surveys have been used to map soils and soil properties, guide sampling, and facilitate site assessments.

Electromagnetic induction is not appropriate for use on all soils. The use of EMI is often inappropriate in areas having varied soils with complex and highly variable properties and spatial distributions. In these areas, relationships between apparent conductivity and soils or soil properties are weakened and results are more ambiguous. Generally, the use of EMI has been most successful in areas where soils and subsurface properties are reasonably homogeneous. This technique has been most effective in areas where the effects of one property (e.g., clay, water, or salt content) dominate over

the other properties. In these areas, variations in EMI response can be directly related to changes in the dominant property (Cook et al., 1989).

Predictive models constructed from EMI data are more accurate in areas having a minimal sequence of dissimilar horizontal layers. The predictive accuracy of EMI data decreases with increasing numbers of subsurface layers. In addition, an EMI meter must be sensitive to the differences existing between soil layers. In other words, a meter must be able to detect differences in electromagnetic properties between the layers. The Caribou soils observed within the Aroostook Farm displayed low values and a narrow range of apparent conductivity. The overlying till contained numerous coarse fragments and was electrically similar to the underlying shale and limestone bedrock. These factors would limit the effectiveness of EMI for predicting bedrock depths.

Some dissimilar materials have similar values of apparent conductivity and therefore produce non-unique (equivalent) solutions. This occurs where differences in apparent conductivity caused by changes in one property (e.g., layer thickness; soluble salt, clay or water contents) are offset by variations in another property. Many soils have subsurface layers that vary in thickness and in chemical and physical properties, but have closely similar conductivity values. Where these dissimilar layers occur in the same landscape, they can produce equivalent solutions or measurements. Equivalent solutions are caused by the simultaneous change in two or more properties (e.g., layer thickness; soluble salt, clay or water contents). The resulting apparent conductivity is the summation of concurrent changes in more than one soil property. Equivalent solutions obscured results and limited the effectiveness of EMI. In this study the effects of different management practices and the presence and variations in the thickness of coarser-textured, water reworked till weakened and obscured relationships between apparent conductivity and depth to bedrock.

Study Site:

The site is located on the Aroostook Experiment Farm about 1 mile south of Presque Isle, Aroostook County, Maine (see Figure 1).

The selected research plots are located in an area that had been mapped as Caribou gravelly loam, 2 to 8 percent slopes (Arno, 1964). Caribou soils are members of the fine-loamy, mixed, frigid Typic Haplorthods family. This very deep, well-drained soil formed in calcareous till. Depths to shale or limestone bedrock range from 36 to 60 inches. The surface layers are variable in texture (gravelly very fine sandy loam, gravelly loam, and gravelly silt loam) and thickness because of erosion. The till is texturally varied. In some areas, the underlying till contains strata of water-reworked materials.

Field Procedures:

Twelve research plots were surveyed. These plots were grouped into three sites. Site #1 consisted of research plots 201, 202, 203, and 204. Site #2 consisted of research plots 205, 206, 207, and 208. Site #3 consisted of research plots 401, 402, 403, and 404. Survey grids were established across each site (0.1448 acre). The grid interval was 12 feet. This interval created a grid with 12 rows and 17 columns, and 204 grid intersections or observation points.

At each observation point, measurements were taken with an EM38 meter placed on the ground surface in both the horizontal and vertical dipole orientations. At each observation point, measurements were taken with an EM31 meter in both the horizontal and vertical dipole orientations. For each measurement, the EM31 meter was held at hip height (about 36 inches above the ground surface).

Soil profiles were observed with a soil auger at nine grid intersections within Site #1. At each of these observation sites, a brief profile description was prepared. These descriptions included the depth, thickness, texture, and colors of each soil horizon to a depth of auger refusal or bedrock. These data were used to confirm interpretations and relationships.

Results:

Fluctuations and minor drifts in measurements were observed with each meter (but especially the EM38 meter) in the field. Fluctuations were believed to be caused by interference from *atmospherics* and radio transmissions. Slight drifts in measurements were caused by warming temperatures. These fluctuations and drifts were sources of measurement errors. These errors were conspicuous at the low values of apparent conductivity measured within the sites.

Basic statistics for the collected apparent conductivity data are displayed in Tables 2 to 4. Measurements were exceedingly low, invariable, and similar among the three sites. Site #3 (see table 4) was the most variable; Sites #2 and #3 were the least variable. Variability tended to increase with included relief.

Table 2

Basic Statistics for EMI Survey of Site #1
Grid Interval = 12 feet
N = 204

(all values are in mS/m)

				Quartiles				Standard
Meter	Orientation	Minimum	Maximum	1st	Median	3rd	Average	Deviation
EM38	Horizontal	2.0	5.2	2.8	3.4	4.1	3.44	0.7415
EM38	Vertical	2.1	6.2	3.3	4.1	4.6	4.00	0.8187
EM31	Horizontal	3.0	5.4	4.0	4.4	4.8	4.37	0.4779
EM31	Vertical	4.6	6.8	5.4	5.8	6.2	5.81	0.5333

The apparent conductivity data (see tables 2 to 4) indicate that, at each site, values of apparent conductivity increase and become slightly less variable with increasing soil depths. Values of apparent conductivity measured with the deeper-sensing EM31 meter were greater and slightly less variable than those measured with the EM38 meter. This relationship was believed to reflect the greater and more unifying influence of the underlying bedrock on measurements taken with the EM31 meter. For each meter, measurements obtained in the deeper-sensing, vertical dipole orientation were higher

than those obtained in the shallower-sensing, horizontal dipole orientation. For the shallower-sensing EM38 meter, this vertical trend supports the greater acidity of surface layers and greater alkalinity of the substratum. For the deeper-sensing EM31 meter, this vertical trend could reflect increases in calcium carbonate and/or moisture contents with increasing soil depths.

Table 3

Basic Statistics for EMI Survey of Site #2
Grid Interval = 12 feet
N = 204

(all values are in mS/m)

Meter	Orientation	Minimum	Maximum	Quartiles 1st	Median	3rd	Average	Standard Deviation
EM38	Horizontal	1.8	5.3	2.6	3.2	4.0	3.35	0.8534
EM38	Vertical	1.8	6.0	3.0	3.6	4.4	3.68	0.9227
EM31	Horizontal	3.2	5.4	4.0	4.4	4.6	4.33	0.4601
EM31	Vertical	4.2	6.6	5.4	5.8	6.2	5.71	0.5112

Table 4

Basic Statistics for EMI Survey of Site #3
Grid Interval = 12 feet
N = 204

(all values are in mS/m)

Meter	Orientation	Minimum	Maximum	Quartiles 1st	Median	3rd	Average	Standard Deviation
EM38	Horizontal	1.5	7.0	2.9	3.5	4.4	3.66	1.1067
EM38	Vertical	1.6	7.8	3.5	4.4	5.2	4.48	1.3227
EM31	Horizontal	3.4	7.4	4.6	5.6	6.0	5.35	0.8894
EM31	Vertical	4.0	8.4	5.8	7.0	7.4	6.56	1.1530

Figures 2 through 4 contain plots that simulate the spatial distribution of apparent conductivity collected with different meters and coil orientations within each site. In each figure, the upper left-hand plot shows the field numbers. Each plot shows the spatial distribution of apparent conductivity for a different depth interval. In each plot, the isoconductivity line interval is 1 mS/m. In general, observation errors are assumed to be less than 2 mS/m. Therefore, the minimum isoconductivity interval shown should be greater than or equal to 2 mS/m. However, at the Aroostook Farm, the low range in apparent conductivity necessitated the use of a 1 mS/m interval. The reader is cautioned as to this source of error and its possible expression in Figures 2 to 4.

Figure 2 shows the spatial distribution of apparent conductivity for Site #1. Figure 3 shows the spatial distribution of apparent conductivity for Site #2. Figure 4 shows the spatial distribution of apparent conductivity for Site #3. Trends can be seen at each site. The EM38 meter, with a theoretical observation depth of 0 to 60 inches, is the most appropriate tool for this research project. Measurements collected with the EM38 meter are more sensitive to soil conditions especially properties within the upper 16 inches. Patterns of apparent conductivity measured with the EM38 meter at each site appear to more closely conform to the plots or units of management. Areas with high apparent conductivity were assumed to be less acidic, more nutrient enriched, and deeper to bedrock.

The EM31 meter, with a theoretical observation depth of 0 to about 20 feet, is considered the more appropriate tool for bedrock mapping. Measurements collected with the EM31 meter are more sensitive to the underlying bedrock and especially to conditions within the upper 5 feet. Patterns of apparent conductivity measured with the EM31 meter at each site were assumed to follow broad trends in the underlying bedrock and were least affected by management practices. Areas with low apparent conductivity were believed to be shallower to bedrock.

The patterns appearing in Figures 2 through 4 are believed to be related principally to variations in management and the depth to bedrock. Areas having low values of apparent conductivity are assumed to have shallower depths to bedrock.

Attempts to correlate apparent conductivity with observable soil properties were unsuccessful. Soil profiles were observed with a shovel and auger at nine grid intersections in Site #1. Soil properties (horizon nomenclature, thickness, color, and texture; and depth to bedrock or auger refusal) were compared with apparent conductivity measured at each of these observation points. A comparison of soil auger and EMI data collected at these observation points revealed no to exceedingly weak relationships between the depth to bedrock or auger refusal and apparent conductivity. Coefficients of determination (r^2) ranged from 0.001 to 0.257. Apparent conductivity, measured with the EM38 meter in the vertical dipole orientation, was the most strongly related with depth to bedrock or auger refusal ($r^2 = 0.257$). Relationships were weakened by the uncertainty as to the depth to bedrock and variations in soil properties (e.g., number, arrangement, texture, and thickness of soil layers; and moisture contents). In addition, measurement error was introduced into the data set because of differences in the area profiled with the meters versus the point of soil observed with the shovel and auger.

Conclusions:

1. Results from the EMI survey at the Aroostook Farm were initially disappointing. Observation errors, the extremely low apparent conductivity of the Caribou soil, the lack of a significant contrast between the till and the underlying bedrock, and the affects of management weakened predictive relationships and produced ambiguous interpretations. Equivalent solutions may have obscured results.

2. Variations in apparent conductivity are related to changes in the physical and chemical properties of soils. While no association was found between apparent conductivity and the soil properties measured at nine observation points, relationships

do exits. The data set included with this report can be compared with other soil characterization data collected within each plot. Relationships may be found.

3. The spatial patterns shown in Figures 2 to 4 appear to correspond with plot boundaries and suggest the influence of differences in management practices. If this can be confirmed, EMI may be an effective tool for assessing the affects of management.

4. Results of this survey are enclosed in this report and have been stored on disc. This information should be reviewed by Dr. Porter and hopefully integrated with existing soil and yield data. The successful integration and analysis of these data sets can increase our understanding of the variability of soils within soil map units and the affects of management on EMI.

It was my pleasure to work in Maine and to be of assistance to your staff.

With kind regards,

James A. Doolittle
Research Soil Scientist

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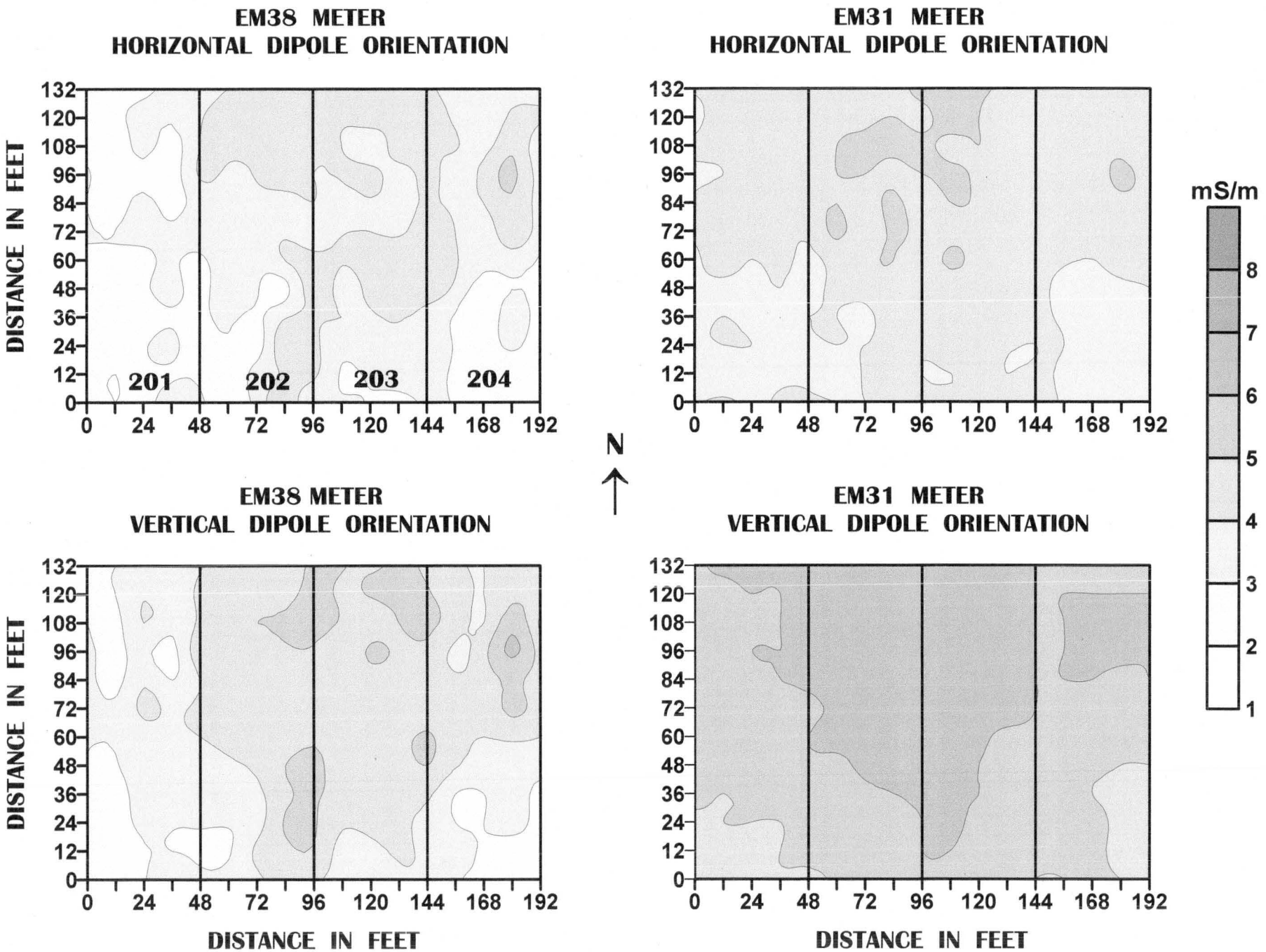
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Figure 2

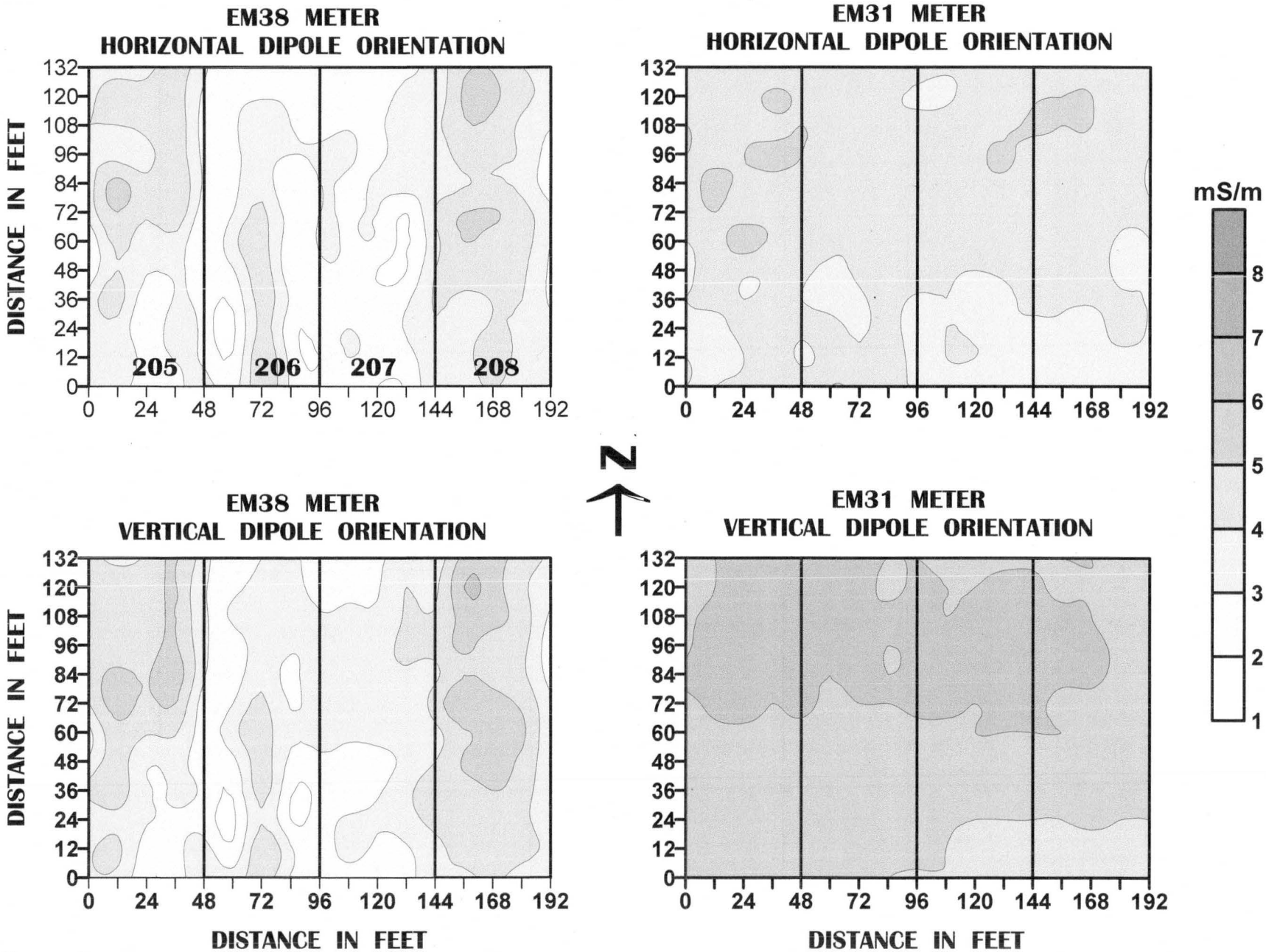
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Figure 3

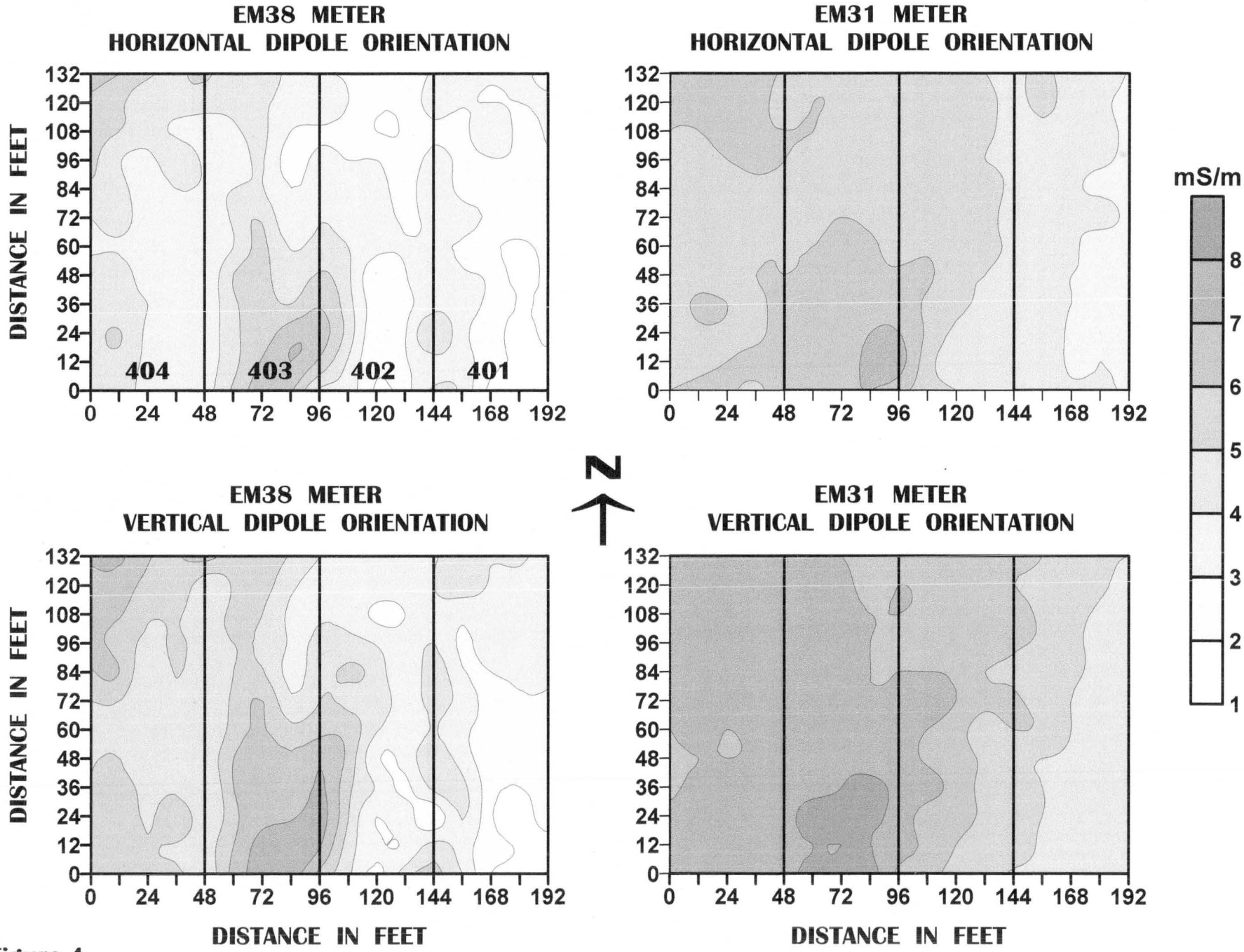
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Figure 4