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Purpose:
To use electromagnetic induction (EM) methods to map field scale variability of soils and soil properties. This study attempted to measure and addressed the influence of soil variability on nitrate movement transport.

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Activities:
Field work described in this report was completed during the period of 5 to 15 November 1995.

Introduction:
Electromagnetic induction is a non-invasive geophysical technique which uses electromagnetic energy to measure the apparent conductivity of earthen materials. Apparent conductivity is a weighted average measurement for a column of earthen materials to a specified observational depth (Greenhouse and Slaine, 1983). Variations in apparent conductivity are produced by changes in the electrical conductivity of soils and other earthen materials. The electrical conductivity of soils is influenced by the (i) volumetric water content, (ii) type and concentration of ions in solution, (iii) temperature and phase of the soil water, (iv) amount and type of clay in the soil matrix, and (v) the distribution of these parameters within the profile (McNeill, 1980a, Cook et al., 1989). The apparent conductivity of soils increases with increases in the exchange capacity, water content, and clay content (Kachanoski et al., 1988; Rhoades et al., 1976).

Soil scientists have used EM techniques principally to identify, map, and monitor soil salinity (Cook and Walker, 1992; Corwin and Rhoades, 1982, 1984, and 1990; Rhoades and Corwin, 1981; Rhoades et al., 1989; Slavich and Petterson, 1990; Williams and Baker, 1982; and Wollenhaupt et al., 1986). Recently, the use of this technology has been expanded to included the assessment and mapping of soil types and soil map units (Hoekstra et al., 1992; Jaynes et al., 1993, Doolittle et al., 1995b) and sodium-affected soils (Ammons et al., 1989; Nettleton et al., 1994), depths to claypans (Doolittle et al., 1994; Stroh et al., 1993; and Sudduth and Kitchen, 1993), thickness of alluvial sand deposits (Doolittle et al., 1995a), and edaphic properties important to forest site productivity (McBride et al., 1990).

Electromagnetic inductive methods measure vertical and lateral variations in the apparent electrical conductivity of earthen materials. The actual values of apparent conductivity measured are seldom diagnostic, but lateral and vertical variations in these measurements can be used to infer changes in soils and soil properties. Interpretations of the EM data are based on the identification of spatial patterns within data sets. Electromagnetic induction techniques are not suitable for use in all soil investigations. Generally, the use of EM techniques has been most successful in areas where subsurface properties are reasonably homogeneous, the effects of one property (e.g. clay, water, or salt content) dominates over the other properties, and variations in EM response can be related to changes in the dominant property (Cook et al., 1989).

Equipment:
The electromagnetic induction meters were the EM38, EM31, and EM34-3, manufactured by Geonics Limited*. These meters are portable and require either one or two persons to operate. Principles of operation have been described by McNeill (1980b, 1986). Each meter provides limited vertical resolution and depth information. For each meter, lateral resolution is approximately equal to the intercoil spacing. The observation depth of an EM meter is dependent upon intercoil spacing, transmission frequency, and coil orientation relative to the ground surface. Table 1 lists the anticipated observation depths for various meters with different intercoil spacings and coil orientations. Observation depths can be varied by changing coil orientation, intercoil spacing, and/or frequency.

TABLE 1

Depth of Measurement
(all measurements are in meters)

Meter	Intercoil Spacing	Depth of Measurement Horizontal	Vertical
EM38	1.0	0.75	1.5
EM31	3.7	2.75	6.0
EM34-3	10.0	7.5	15.0
	20.0	15.0	30.0
	40.0	30.0	60.0

The EM38 meter has a fixed intercoil spacing of about 1.0 m. It operates at a frequency of 13.2 kHz. The EM38 meter has effective observation depths of about 0.75 and 1.5 m in the horizontal and vertical dipole orientations, respectively (McNeill, 1986). The EM31 meter has a fixed intercoil spacing of 3.66 m. It operates at a frequency of 9.8 kHz. The EM31 meter has effective observation depths of about 3.0 and 6.0 m in the horizontal and vertical dipole orientations, respectively (McNeill, 1980b). The EM34-3 meter consists of two coils and three fixed reference cables with intercoil spacings of 10, 20, and 40 m. One of the coils serves as the transmitter, the other as the receiver. This meter operates at frequencies of 6.4 kHz (10-m spacing), 1.6 kHz (20-m spacing), and 0.4 kHz (40-m spacing). Observation depths range from 7.5 to 60 m (McNeill, 1980b). Values of apparent conductivity are expressed in milliSiemens per meter (mS/m).

To help summarize the results of this study, the SURFER for Windows program, developed by Golden Software, Inc.,* was used to develop two-dimensional simulations. Grids were created using kriging methods with an octant search. All grids were smoothed using a cubic spline interpolation.

Discussion:

1. Electromagnetic Induction and Topographic Surveys

This section discusses the results of topographic and electromagnetic induction surveys completed at each site. For each site, the survey procedures are described. The discussion attempts to characterize the topography, soils (as mapped and described by Hoffman and Dowd, 1974), and spatial distribution of apparent conductivity values within each site.

Site #1

The site was located in the SE 1/4 of Section 19, T. 23 S., R. 1 W. Within this site were delineated areas of Naron fine sandy loam, 1 to 4 percent slopes; Farnum loam, 0 to 1 percent slopes; and Farnum loam, 1 to 3 percent slopes (Hoffman and Dowd, 1974). The very deep, well drained Naron soil formed in wind-modified alluvium on paleo-terraces and is a member of the fine-loamy, mixed, thermic Udic Argiustolls family. The deep, well drained Farnum soil formed in loamy stratified alluvium and is a member of the fine-loamy, mixed, thermic Pachic Argiustolls family.

An irregularly-shaped, 200 by 400 meter grid was established across the site (about 8 hectares). Because of trees and dense vegetation the northwest corner of the site was not surveyed. The coordinates of the grid corners are listed in Table 2. Grid intervals were 20 and 40 meters. These intervals provided 126 grid intersections or observation points. At each observation point, survey flags were inserted in the ground. At each observation point measurements were taken with an EM38 and an EM31 meter placed on the ground surface in both the horizontal and vertical dipole orientations.

At each observation point, the relative elevation of the surface was determined using a level and stadia rod. Elevations were not tied to an elevation benchmark; the lowest observation point was recorded as the 450.0 m datum.

Table 2

Site #1
Coordinates of Grid Corners

SE	38^{o} 01′ 56.36" N. Lat.	96^{o} 27′ 49.26"
SW	38^{o} 01′ 58.95" N. Lat.	97^{o} 28′ 07.61"
NW	38^{o} 02′ 02.87" N. Lat.	97^{o} 28′ 07.59"
NW	38^{o} 02′ 05.60" N. Lat.	97^{o} 28′ 04.28"
NE	38^{o} 02′ 05.43" N. Lat.	97^{o} 27′ 51.19"

Figure 1 is a two-dimensional contour plot of the study site. The contour interval is 0.25 m. Within the study site, relief was about 4.2 m. The lowest-lying areas are located near the southeast corner of the site. In this portion of the site, the surface is relatively level and is inclined towards the east and West Emma Creek. A broad, relatively level, higher-lying surface occurs in the western portion of the site. These surfaces are believed to represent the remnants of two paleo-terraces. Between these two surfaces is an undulating area of low mounds and ridges. Figure 2 is a three-dimensional surface net diagram of the site. In this figure, the vertical exaggeration is about 23 times the horizontal scale.

Basic statistics for the EM data collected at the Site #1 are displayed in Table 3. Variations in each meters response can be related to differences in soil types and landscape positions. Differences in soil types are related to the presence, arrangement, depth, and thickness of contrasting materials. In general, apparent conductivity increases and becomes more variable with increasing observation depths.

Table 3
Site #1 - Harvey County, Kansas
(all values are in mS/m)

				Quartiles			
Meter	Orientation	Minimum	Maximum	1st	Median	3rd	Average
EM38	Horizontal	4.5	29.1	7.9	10.3	11.7	10.3
EM38	Vertical	8.3	35.6	12.1	14.8	18.6	15.7
EM31	Horizontal	15.0	49.0	23.5	27.0	33.5	29.0
EM31	Vertical	21.0	74.0	32.5	36.5	43.0	38.9
EM34-3	Horizontal	38.0	68.0	40.0	43.0	46.0	45.5
EM34-3	Vertical	30.0	46.0	37.0	39.0	41.0	39.0

Figures 3 and 4 are two-dimensional plots of data collected with the EM38 meter in the horizontal and vertical dipole orientations, respectively. Figures 5 and 6 are two-dimensional plots of data collected with the EM31 meter in the horizontal and vertical dipole orientations, respectively. In each of these plots, the isoline interval is 4 mS/m.

Figure 3 represents the spatial distribution of apparent conductivity measurements for the upper 75 cm of the soil profile. These measurements are relatively low and invariable across the site. However, measurements were slightly higher on each of the paleo-terraces and lower on the undulating area between the paleo-terraces. These patterns were assumed to primarily reflect the presence of finer-textured soil materials nearer to the soil surface on each of the paleo-terraces. The lower measurements on the undulating areas between the paleo-terraces, suggested the prevalence of more coarser-textured materials.

The spatial patterns appearing in figures 4 to 6 are remarkably similar. In general, patterns obtained with these deeper-sensing meters and/or orientations were more complex and variable over short distances than those obtained with the shallow-sensing, EM38 meter in the horizontal dipole orientation (see Figure 3). Measurements of apparent conductivity continued to be higher on each of the paleo-terraces and lower on the undulating area between the paleo-terraces. However, several small included areas having higher values of apparent conductivity are evident within the undulating area of low mounds and ridges. These included areas suggest the presence of contrasting soils presumably with layers of finer-textured soil materials near the surface.

In figures 3 to 6, values of apparent conductivity increase with each increasing deep of observation (responses in the horizontal dipole orientation were typically greater than those in vertical dipole orientation and measurements taken with the EM38 meter were less than those obtained with the deeper sensing EM31 meter). This vertical trend reflects changes in soil properties with depth (principally increases in clay, water, and carbonate contents), and supports the occurrence of a finer-textured paleosol at lower soil depths. The general increase in EM responses with increasing depth conforms with the basic conceptual model of the site. For the purpose of this investigation, the site was assumed to consist of two principal layers: a coarse- and moderately coarse-textured wind-modified mantle overlying medium- and moderately fine-textured alluvial materials. The alluvium has higher clay and water contents and was presumed to have higher apparent conductivity values than the overlying wind-modified materials.

Figures 7 and 8 are two-dimensional plots of data collected with the EM34-3 meter in the horizontal and vertical dipole orientations, respectively. These plots were prepared from data collected at 62 equally spaced (40 m) observation points. A 40-m intercoil spacing was used. This spacing provided observation depths of 30 and 60 m in the horizontal and vertical dipole orientations, respectively. In each of these plots, the isoline interval is 4 mS/m.

With a 40-m intercoil spacing, the volumes of earthen materials sampled in the horizontal and vertical dipole orientations were considerably greater than those sampled with the other meters. At these greater observation depths, to be detected, strata need to be more unique (electrically) and strongly contrasting, thicker, and/or have larger cross-sectional areas than similar strata at shallower depths.

In Figure 7, higher values of apparent conductivity occur in the western portion of the site. These values appear to delineate the higher-lying paleo-terrace. Measurements taken in the vertical dipole orientation (see Figure 8) were lower and less variable than those obtained in the horizontal dipole orientation (see Figure 7). The lower values of apparent conductivity recorded in the vertical dipole orientation suggest the presence of more resistive materials at lower observation depths. Measurements collected with the EM34-3 meter in the vertical dipole orientation were less variable possibly indicating the effects of greater volume averaging and/or more homogeneous materials at these greater depths. In addition, spatial patterns appearing in the data set collected in the vertical dipole orientation were more ambiguous and could not be associated with any features on the present landscape.

Site #2

The site was located in the SW 1/4 of Section 23, T. 23 S., R. 3 W. The site was located in a delineation of Pratt-Carwile complex (Hoffman and Dowd, 1974). The deep, somewhat poorly drained Carwile soil formed in clayey alluvium and loamy eolian materials and is a member of the fine, mixed, thermic Typic Argiaquolls family. The Carwile soils are in lower-lying areas and in depressions. The deep, well drained Pratt soil formed in sandy eolian deposits and is a member of the sandy, mixed, thermic Psammentic Haplustalfs family. The Pratt soils are on higher-lying areas.

A 260 by 260 meter grid was established across the site (about 6.8 hectares). The coordinates of the grid corners are listed in Table 4. The grid interval was 20 meters. This interval provided 196 grid intersections or observation points. At each observation point, survey flags were inserted in the ground. At each observation point measurements were taken with an EM38 and an EM31 meter placed on the ground surface in both the horizontal and vertical dipole orientations.

At each observation point, the relative elevation of the surface was determined using a level and stadia rod. Elevations were not tied to an elevation benchmark; the lowest observation point was recorded as the 450.0 m datum.

Table 4

Site #2
Coordinates of Grid Corners

SE	38° 01′ 58.98" N. Lat.	96° 37′ 26.57"
SW	38° 01′ 58.78" N. Lat.	97° 37′ 37.26"
NW	38° 02′ 07.26" N. Lat.	97° 37′ 37.82"
NE	38° 02′ 07.30" N. Lat.	97° 37′ 27.03"

Figure 9 is a two-dimensional contour plot of the study site. In this plot, the contour interval is 0.25 m. Within the study site, relief was about 1.7 m. A conspicuous drainageway extended across the site from near the southwest to the northeast corner. A low ridge extends in an east-west direction across the north-central portion of the site. This ridge separates the drainageway from a low-lying area located along the northern border of the site. Figure 10 is a three-dimensional surface net diagram of the site. In this figure, the vertical exaggeration is about 19 times the horizontal scale.

Table 5
Site #2 - Harvey County, Kansas
(all values are in mS/m)

				Quartiles			
Meter	Orientation	Minimum	Maximum	1st	Median	3rd	Average
EM38	Horizontal	9.9	61.6	14.5	17.6	24.2	20.8
EM38	Vertical	15.4	86.2	21.8	27.6	37.7	30.9
EM31	Horizontal	20.0	85.5	35.0	43.0	51.0	43.7
EM31	Vertical	29.5	86.5	40.5	48.5	54.0	47.8

Basic statistics for the EM data collected at the Site #2 are displayed in Table 5. Variations in each meters response can be related to differences in soil types and landscape positions. Differences in soil types are related to the presence, arrangement, depth, and thickness of contrasting materials. Values of apparent conductivity greater than 40 to 45 mS/m are believed to reflect soils having high concentrations of exchangeable sodium. Soils having apparent conductivity values greater than 60 mS/m are believed to be saline. In general, apparent conductivity increases and becomes more variable with increasing observation depths.

Figures 11 and 12 are two-dimensional plots of data collected with the EM38 meter in the horizontal and vertical dipole orientations, respectively. Figures 13 and 14 are two-dimensional plots of data collected with the EM31 meter in the horizontal and vertical dipole orientations, respectively. In each of these plots, the isoline interval is 4 mS/m.

In figures 11 to 14, conspicuous and repeating spatial patterns occur. Values of apparent conductivity are higher in the drainageway and in lower-lying areas. The highest EM responses are found in the lowest portion of the study site (see figure 9). These areas are presumed to be wetter and to have higher concentrations of clay and soluble salts than nearby, higher-lying areas. Carwile and included areas of sodium-affected soils are assumed to be more prevalent on these segments of the landscape. Values of apparent conductivity are lower on the slightly higher-lying ridges. These areas often have a thicker mantle of coarse- and moderately coarse-textured eolian materials overlying a medium- or moderately fine-textured paleosol. Soils on these low uplands are presumed to be drier and have less clay and soluble salt contents. Areas of Pratt soils are more prevalent on these segments of the landscape.

In general, values of apparent conductivity increase with increasing observation depths (see figures 11 to 14). With each increment in profiling depth, the definition of the drainageway and ridge becomes less distinct. It is probable that this pattern reflects increased concentrations of soluble salts and/or the presence of the water table or a relatively thick and continuous strata of more conductive materials underlying the site. The higher apparent conductivity of this inferred underlying material(s) is attributed to higher moisture, clay, and/or soluble salt contents.

Site #5

The site was located in the NW 1/4 of Section 8, T. 24 S., R. 1 W. Within this site were delineated areas of Pratt-Carwile complex, and Pratt loamy fine sand, 1 to 5 percent slopes (Hoffman and Dowd, 1974).

Table 6

Site #5
Coordinates of Grid Corners

SE	37^{o} 58′ 47.70" N. Lat.	97^{o} 27′ 33.56"
SW	37^{o} 58′ 47.62" N. Lat.	97^{o} 27′ 40.14"
NW	37^{o} 58′ 53.43" N. Lat.	97^{o} 27′ 40.24"
NE	37^{o} 58′ 53.45" N. Lat.	97^{o} 27′ 33.58"

A 180 by 160 meter grid was established across the site (about 2.9 hectares). The coordinates of the grid corners are listed in Table 6. The grid interval was 20 meters. This interval provided 90 grid intersections or observation points. At each observation point, survey flags were inserted in the ground. At each observation point measurements were taken with an EM38 and an EM31 meter placed on the ground surface in both the horizontal and vertical dipole orientations.

At each observation point, the relative elevation of the surface was determined using a level and stadia rod. Elevations were not tied to an elevation benchmark; the lowest observation point was recorded as the 450.0 m datum.

Figure 15 is a two-dimensional contour plot of the study site. The contour interval is 0.5 m. Within the study site, relief was about 9.7 m. A distinct ridge was located in the center of the study site. The ridge had the appearance of a large dune and was assumed to be covered by a thick mantle of coarse- and moderately coarse-textured eolian materials. A portion of a prominent depression was located along the southern boundary of the site. Figure 16 is a three-dimensional surface net diagram of the site. In this figure, the vertical exaggeration is about 5.56 times the horizontal scale.

Basic statistics for the EM data collected at the Site #5 are displayed in Table 7. Electromagnetic responses obtained at this site were similar to those obtained at Site #1. Variations in each meters response can be related to differences in soil types and landscape positions. Differences in soil types are related to the presence, arrangement, depth, and thickness of contrasting materials. In general, apparent conductivity increases and becomes more variable with increasing observation depths.

Table 7
Site #5 - Harvey County, Kansas
(all values are in mS/m)

				Quartiles			
Meter	Orientation	Minimum	Maximum	1st	Median	3rd	Average
EM38	Horizontal	5.7	26.8	9.2	11.0	13.4	12.0
EM38	Vertical	10.2	40.8	14.0	16.5	19.6	18.0
EM31	Horizontal	18.9	54.5	23.6	28.1	32.5	29.2
EM31	Vertical	26.2	63.9	33.0	38.8	44.0	39.7

Figures 17 and 18 are two-dimensional plots of data collected with the EM38 meter in the horizontal and vertical dipole orientations, respectively. Figures 19 and 20 are two-dimensional plots of data collected with the EM31 meter in the horizontal and vertical dipole orientations, respectively. In each of these plots, the isoline interval is 4 mS/m.

A conspicuous linear zone having higher apparent conductivity values is apparent in figures 17 to 20. This belt bends in a northeast to west direction and extends across the ridge. The higher values of apparent conductivity within this belt were assumed to reflect higher clay contents and shallower depths to the medium- or moderately fine-textured paleosol. Lower values to the north and south of this zone were believed to reflect soils with lower clay contents or greater depths to the paleosol. Slightly higher values of apparent conductivity were recorded adjacent to the depression forming a portion of the sites southern border.

Site #7

The site was located in the SW 1/4 of Section 21, T. 24 S., R. 2 W. Kisiwa Creek was located about 800 m northwest of the site. Within the site were delineated areas of Naron fine sandy loam, 0 to 1 percent slopes; Carwile fine sandy loam; and Farnum-Slickspots complex (Hoffman and Dowd, 1974). Special symbols appearing on the soil map indicated the occurrence of small areas of saline soils within the Carwile map unit. Slickspots represent areas having a puddled or crusted, nearly impervious surface. These areas have high concentrations of exchangeable sodium and other more soluble salts. The Farnum soils associated with slickspots are often sodium-affected.

A 200 by 200 meter grid was established across the site (about 4.0 hectares). The coordinates of the grid corners are listed in Table 8. The grid interval was 25 meters. This interval provided 81 grid intersections or observation points. At each observation point, survey flags were inserted in the ground. At each observation point measurements were taken with an EM38 and an EM31 meter placed on the ground surface in both the horizontal and vertical dipole orientations.

At each observation point, the relative elevation of the surface was determined using a level and stadia rod. Elevations were not tied to an elevation benchmark; the recorded observation point was lowest as the 450.0 m datum.

Table 8

Site #7
Coordinates of Grid Corners

SE	37^{O} 56′ 43.42" N. Lat.	97^{O} 33′ 07.92"
SW	37^{O} 56′ 43.55" N. Lat.	97^{O} 33′ 16.28"
NW	37^{O} 56′ 50.10" N. Lat.	97^{O} 33′ 15.66"
NE	37^{O} 56′ 49.95" N. Lat.	97^{O} 33′ 07.52"

Figure 21 is a two-dimensional contour plot of the study site. The contour interval is 0.25 m. Within the study site, relief was about 1.6 m. Slopes were level. Slightly higher-lying areas were located in the western and northwestern portions of the site. Soil cores obtained at this site provided some indications that the surface was leveled for irrigation. Figure 22 is a three-dimensional surface net diagram of the site. In this figure, the vertical exaggeration is about 15 times the horizontal scale.

Basic statistics for the EM data collected at the Site #7 are displayed in Table 9. Variations in each meters response can be related principally to differences in soil types and concentrations of soluble salts within the soil profiles. Though unconfirmed at this time, soils having apparent conductivity values between 40 and 80 are believed to be sodium-affected. Soils having apparent conductivity values greater than 60 mS/m are believed to be saline.

Table 9
Site #7 - Harvey County, Kansas
(all values are in mS/m)

				Quartiles			
Meter	Orientation	Minimum	Maximum	1st	Median	3rd	Average
EM38	Horizontal	12.6	77.2	21.8	31.2	45.4	35.9
EM38	Vertical	19.9	110.4	31.3	44.5	64.8	49.9
EM31	Horizontal	37.0	138.0	48.0	63.2	81.6	68.0
EM31	Vertical	36.5	145.0	50.5	67.2	83.8	69.8

In general, apparent conductivity increases and becomes more variable with increasing observation depths. In areas of saline soils, an increase in apparent conductivity values with increasing soil depths is referred to as a "normal" salt profile. This trend suggest that salts are being translocated upwards in the soil profile. An "inverted" salt profile occurs when apparent conductivity values decrease with increasing soil depths (Corwin and Rhoades, 1984). This trend suggests that salts are being translocated downwards in the profile. Such a profile often occurs from the application (irrigation or floods) of water having a relatively high concentration of soluble salts to the soil surface. At this and similar sites, assessments of the depths to paleosol are indeterminate because of the overwhelming influence of saline, sodic, or calcareous soil conditions on EM responses.

Figures 23 and 24 are two-dimensional plots of data collected with the EM38 meter in the horizontal and vertical dipole orientations, respectively. Figures 25 and 26 are two-dimensional plots of data collected with the EM31 meter in the horizontal and vertical dipole orientations, respectively. In each of these plots, the isoline interval is 4 mS/m.

The spatial patterns appearing in figures 23 to 26 are remarkably similar. These patterns are relatively complex and variable over short distances. Relatively broad, bifurcating, sinuous strands of higher apparent conductivity values can be discerned in each of these figures. These strands of higher apparent conductivity are separated by lineaments with lower apparent conductivity values. Within these strands are nodes of even higher apparent conductivity values. As the observation depth is increased, the locations of these nodes appear to remain static and their values to increase. During the course of this field investigation, this pattern was to recur at other sites having areas of saline and sodium-affected soils.

Site #8
The site was located in the NW 1/4 of Section 29, T. 24 S., R. 2 W. Within this site are delineated areas of Carwile fine sandy loam, and Pratt loamy fine sand, 1 to 5 percent slopes (Hoffman and Dowd, 1974). Special symbols appearing on the soil map denote small included areas of saline soils within the Carwile map unit and a small area of severely eroded soils within the Pratt map unit.

A 175 by 400 meter grid was established across the site (about 7.0 hectares). The coordinates of the grid corners are listed in Table 10. The grid interval was 25 meters. This interval provided 136 grid intersections or observation points. At each observation point, survey flags were inserted in the ground. At each observation point measurements were taken with an EM38 and an EM31 meter placed on the ground surface in both the horizontal and vertical dipole orientations.

At each observation point, the relative elevation of the surface was determined using a level and stadia rod. Elevations were not tied to an elevation benchmark; the lowest observation point was recorded as the 450.0 m datum.

Table 10

Site #8
Coordinates of Grid Corners

SE	37° 56′ 08.48" N. Lat.	97° 33′ 57.50"
SW	37° 56′ 08.48" N. Lat.	97° 34′ 13.70"
NW	37° 56′ 14.14" N. Lat.	97° 34′ 13.83"
NE	37° 56′ 14.12" N. Lat.	97° 33′ 57.49"

Figure 27 is a two-dimensional contour plot of the study site. The contour interval is 0.5 m. Within the study site, relief was about 10.1 m. A southeast to northwest trending ridge extends across the central portion of the study site. The summit of this ridge consists of a comparatively wide and uneven area mapped as Pratt soils. The west-facing slope of this ridge is steeper than the east-facing slope. Both slopes descend into areas mapped as Carwile soils. The east-facing slope descends into a shallow depression. Figure 28 is a three-dimensional surface net diagram of the site. In this figure, the vertical exaggeration is about 5.9 times the horizontal scale.

Basic statistics for the EM data collected at the Site #8 are displayed in Table 11. Variations in each meters response can be related to differences in soil types, landscape positions, depth to paleosols, and concentrations of soluble salts in the soil profile. In general, apparent conductivity increases with increasing observation depths.

Table 11
Site #8 - Harvey County, Kansas
(all values are in mS/m)

				Quartiles			
Meter	Orientation	Minimum	Maximum	1st	Median	3rd	Average
EM38	Horizontal	12.6	67.5	21.2	28.8	39.0	31.8
EM38	Vertical	15.7	90.1	27.3	35.7	53.5	41.4
EM31	Horizontal	23.1	105.8	37.6	46.7	63.5	51.9
EM31	Vertical	28.3	110.4	43.1	49.2	66.8	56.0

Figures 29 and 30 are two-dimensional plots of data collected with the EM38 meter in the horizontal and vertical dipole orientations, respectively. Figures 31 and 32 are two-dimensional plots of data collected with the EM31 meter in the horizontal and vertical dipole orientations, respectively. In each of these plot, the isoline interval is 4 mS/m.

The spatial patterns appearing in figures 29 to 32 are remarkably similar. In each of these figures, similar areas of higher or lower apparent conductivity occur in the same general locations. The only obvious difference in these figures is the tendency towards increasing conductivity with increasing observation depths and variations in the gradients. The patterns appearing in these plots are relatively complex and variable over short distances. In general, the highest values of apparent conductivity were recorded in areas mapped as Carwile soils. In areas of Carwile soils, the comparatively high and irregular spatial patterns suggest the presences of soluble salts. Lower values of apparent conductivity were recorded in areas mapped as Pratt soils and in the shallow depression along the eastern border of the site. The lower values within the shallow depression is considered to suggest the downward leaching of soluble salts rather than the absences of finer-textured soil materials.

The summit area was surprisingly variable and displayed an exceedingly complex spatial pattern of apparent conductivity values. Values recorded on the ridge were higher than anticipated and atypical for eolian deposits. As noted earlier, a small area of severely eroded soils was mapped within the Pratt unit on the ridge summit. However, on some areas of the ridge, apparent conductivity values are too high to be attributed to shallower depths to finer-textured materials or the paleosol alone. These values are considered to reflect shallow depths to paleosol, concentrations of soluble salts, and/or buried artifacts.

Site #10

The site was located in the NW 1/4 of Section 32, T. 24 S., R. 3 W. Within this site were delineated areas of Naron fine sandy loam, 0 to 1 percent slopes; Farnum loam, 0 to 1 percent slopes; and Farnum-Slickspots complex (Hoffman and Dowd, 1974). Special symbols appearing on the soil map indicated small included areas of saline soils within the Farnum map unit. Slickspots represent areas having a puddled or crusted, nearly impervious surface. These areas have high concentrations of exchangeable sodium and other more soluble salts. Farnum soils associated with slickspots are often sodium-affected.

Table 12

Site #10
Coordinates of Grid Corners

SE	37° 55′ 28.03" N. Lat.	97° 40′ 43.00"
SW	37° 55′ 28.11" N. Lat.	97° 40′ 52.83"
NW	37° 55′ 34.56" N. Lat.	97° 40′ 53.36"
NE	37° 55′ 34.55" N. Lat.	97° 40′ 43.54"

A 200 by 240 meter grid was established across the site (about 4.8 hectares). The coordinates of the grid corners are listed in Table 12. The grid interval was 20 meters. This interval provided 143 grid intersections or observation points. At each observation point, survey flags were inserted in the ground. At each observation point measurements were taken with an EM38 and an EM31 meter placed on the ground surface in both the horizontal and vertical dipole orientations.

At each observation point, the relative elevation of the surface was determined using a level and stadia rod. Elevations were not tied to an elevation benchmark; the lowest observation point was recorded as the 450.0 m datum.

Figure 33 is a two-dimensional contour plot of the study site. The contour interval is 0.25 m. Within the study site, relief was about 5.8 m. A prominent terrace extends across the site in a southeast to northwest direction. Higher-lying areas of Naron soils are located in the western and southern portion of the site on the level, terrace tread and nearly level, terrace riser. Lower-lying areas of Farnum soils are located at the base of the terrace in the northeastern portion of the site. Figure 33 is a three-dimensional surface net diagram of the site. In this figure, the vertical exaggeration is about 11.3 times the horizontal scale.

Basic statistics for the EM data collected at the Site #10 are displayed in Table 13. Variations in each meters response can be related to differences in soil types and landscape positions. Differences in soil types are related to the presence, arrangement, depth, and thickness of contrasting materials. In general, apparent conductivity increases and becomes more variable with increasing observation depths.

Table 13
Site #10 - Harvey County, Kansas
(all values are in mS/m)

				Quartiles			
Meter	Orientation	Minimum	Maximum	1st	Median	3rd	Average
EM38	Horizontal	5.5	128.6	8.4	13.6	27.2	21.9
EM38	Vertical	5.2	168.3	8.0	17.2	39.0	28.1
EM31	Horizontal	11.0	178.5	13.8	28.6	59.8	40.5
EM31	Vertical	12.6	136.0	16.0	34.4	68.5	44.8

Figures 35 and 36 are two-dimensional plots of data collected with the EM38 meter in the horizontal and vertical dipole orientations, respectively. Figures 37 and 38 are two-dimensional plots of data collected with the EM31 meter in the horizontal and vertical dipole orientations, respectively. In each of these plots, the isoline interval is 4 mS/m.

The spatial patterns appearing in figures 35 to 38 are remarkably similar and conform to the landscape. In general values of apparent conductivity are lowest on the terrace tread and the higher-lying slopes of the terrace riser. These low values suggest low concentrations of soluble salts and clays. It was inferred that soils on these surfaces, compared with soils on the lower base level, are deeper to water table, coarser textured, and have thicker eolian mantles over paleosols. Isoline lines on the tread and riser are orientated parallel with the terrace.

Spatial patterns on the lower base level are complex and variable over short distances. Nodes of higher apparent conductivity values occur on this lower base level and suggest areas of saline and sodium-affected soils. As indicated earlier, soils having apparent conductivity values between 40 and 80 are believed to be sodium-affected. Soils having apparent conductivity values greater than 60 mS/m are believed to be saline. In general, within the soil profile (0 to 2 m) values of apparent conductivity increase and become more variable with increasing observation depths. This trend suggests that salts are being translocated upwards in the profile. However, at lower depths (see Figure 38), though the general trend is towards increased apparent conductivity, values decline in areas having maximum conductivity (generally in those inferred to be the most saline).

In figures 35 to 38, similar areas of higher or lower apparent conductivity occur in the same general locations. The only obvious difference in these figures is the tendency towards increasing conductivity with increasing observation depths and variations in gradients.

Site #12

The site was located in the SW 1/4 of Section 16, T. 24 S., R. 3 W. Within this site were delineated areas of Farnum-Slickspots complex and Farnum loam, 0 to 1 percent slopes (Hoffman and Dowd, 1974). The Farnum-Slickspots complex was mapped in the lower-lying sections of the site (northern part of survey area). Slickspots represent areas having a puddled or crusted, nearly impervious surface. These areas have high concentrations of exchangeable sodium and other more soluble salts. Farnum soils associated with slickspots are often sodium-affected. A portion of a small intermittent pond was located in the northern portion of the site. Though dry at the time of the survey, this area is covered by water during part of the year.

A 225 by 225 meter grid was established across the site (about 5.1 hectares). The coordinates of the grid corners are listed in Table 14. The grid interval was 25 meters. This interval provided 100 grid intersections or observation points. At each observation point, survey flags were inserted in the ground. At each observation point measurements were taken with an EM38 and an EM31 meter placed on the ground surface in both the horizontal and vertical dipole orientations.

Table 14

Site #12
Coordinates of Grid Corners

37° 57′ 34.29" N. Lat.	97° 39′ 37.59"
37° 57′ 31.98" N. Lat.	97° 39′ 28.85"
37° 57′ 25.19" N. Lat.	97° 39′ 32.25"
37° 57′ 27.48" N. Lat.	97° 39′ 40.93"

At each observation point, the relative elevation of the surface was determined using a level and stadia rod. Elevations were not tied to an elevation benchmark; the lowest observation point was recorded as the 450.0 m datum.

Figure 39 is a two-dimensional contour plot of the study site. The contour interval is 0.25 m. Within the study site, relief was about 1.5

m. Higher-lying areas are located in the southeast and south portions of the site. A conspicuous depression is located in the northern corner of the site. This features was mapped as an intermittent pond and contained wetter and finer-textured soil materials. Figure 40 is a three-dimensional surface net diagram of the site. In this figure, the vertical exaggeration is about 17 times the horizontal scale.

Basic statistics for the EM data collected at the Site #12 are displayed in Table 15. Variations in each meters response can be related to differences in soil types and landscape positions. Differences in soil types are related to the presence, arrangement, depth, and thickness of contrasting materials. In general, within the soils profile, apparent conductivity increases and becomes more variable with increasing observation depths. At lower depths, values of apparent conductivity decrease and become slightly less variable.

Table 15
Site #12 - Harvey County, Kansas
(all values are in mS/m)

				Quartiles			
Meter	Orientation	Minimum	Maximum	1st	Median	3rd	Average
EM38	Horizontal	11.9	75.0	19.5	25.4	35.2	29.1
EM38	Vertical	19.9	98.5	27.9	35.0	48.9	40.5
EM31	Horizontal	27.0	126.0	37.5	45.0	59.5	50.5
EM31	Vertical	27.0	124.5	37.5	42.0	54.0	48.6

Figures 41 and 42 are two-dimensional plots of data collected with the EM38 meter in the horizontal and vertical dipole orientations, respectively. Figures 43 and 44 are two-dimensional plots of data collected with the EM31 meter in the horizontal and vertical dipole orientations, respectively. In each of these plots, the isoline interval is 4 mS/m.

The spatial patterns appearing in figures 41 to 44 are complex and variable over short distances. The highest and most variable recorded measurements were obtained in the delineated area of the Farnum-Slickspots complex. The spot-like patterns appearing in the northern and northeastern parts of the site are indicative of saline and sodium-affected soils. Values were high within the intermittent pond. However, the highest values were consistently measured along the periphery of this shallow depression. This pattern suggest a "wicking-up" and deposition of soluble salts in areas surrounding this depression. In areas of Farnum loam, 0 to 1 percent slopes, values of apparent conductivity appear less variable and more consistent over larger areas. Patterns are more linear and extensive in the southern and southeastern portion of the site.

Site #13

The site was located in the NE 1/4 of Section 5, T. 24 S., R. 3 W. Within this site were delineated areas of Carwile fine sandy loam, and Farnum-Slickspots complex (Hoffman and Dowd, 1974). The Carwile soils had been mapped along a small drainageway in the lowest-lying portions of the site. The drainageway bisected the survey site. Special symbols appearing on the soil map denote small included areas of saline soils within the Carwile map unit. Slickspots represent areas having a puddled or crusted, nearly impervious surface. These areas have high concentrations of exchangeable sodium and other more soluble salts. Farnum soils associated with slickspots are often sodium-affected.

Table 16

Site #13
Coordinates of Grid Corners

SE	37° 59′ 46.85" N. Lat.	97° 40′ 12.77"
SW	37° 59′ 46.91" N. Lat.	97° 40′ 20.89"
NW	37° 59′ 53.34" N. Lat.	97° 40′ 20.93"
NE	37° 59′ 53.32" N. Lat.	97° 40′ 12.83"

A 200 by 200 meter grid was established across the site (about 4.0 hectares). The coordinates of the grid corners are listed in Table 16. The grid interval was 20 meters. This interval provided 121 grid intersections or observation points. At each observation point, survey flags were inserted in the ground. At each observation point measurements were taken with an EM38 and an EM31 meter placed on the ground surface in both the horizontal and vertical dipole orientations. At each observation point, the relative elevation of the surface was determined using a level and stadia rod. Elevations were not tied to an elevation benchmark; the lowest observation point was recorded as the 450.0 m datum.

Figure 45 is a two-dimensional contour plot of the study site. The contour interval is 0.25 m. Within the study site, relief was about 1.0 m. The site is traverses from near the southeast to the northwest corners by a drainageway. Slightly higher-lying areas are located on either side of this drainageway. Figure 46 is a three-dimensional surface net diagram of the site. In this figure, the vertical exaggeration is about 14 times the horizontal scale.

Basic statistics for the EM data collected at the Site #13 are displayed in Table 17. Variations in each meters response can be related to differences in soil types and landscape positions. Differences in soil types are related to the presence, arrangement, depth, and thickness of contrasting materials. In general, apparent conductivity increases and becomes more variable with increasing observation depths.

Table 17
Site #13 - Harvey County, Kansas
(all values are in mS/m)

					Quartiles		
Meter	Orientation	Minimum	Maximum	1st	Median	3rd	Average
EM38	Horizontal	4.4	76.5	17.1	23.5	30.3	25.7
EM38	Vertical	9.3	102.8	22.0	30.9	40.2	34.8
EM31	Horizontal	16.4	109.7	28.8	37.0	45.2	41.1
EM31	Vertical	23.0	95.0	30.9	37.1	44.1	41.2

Figures 47 and 48 are two-dimensional plots of data collected with the EM38 meter in the horizontal and vertical dipole orientations, respectively. Figures 49 and 50 are two-dimensional plots of data collected with the EM31 meter in the horizontal and vertical dipole orientations, respectively. In each of these plots, the isoline interval is 4 mS/m.

The spatial patterns appearing in figures 47 to 50 are complex and variable over short distances. The lowest values of apparent conductivity were measured within the drainageway. It is inferred that this area is composed of coarser-textured materials and/or contains lower concentrations of soluble salts. The highest and most variable measurements were obtained in areas of the Farnum-Slickspots complex. Spot-like patterns, indicative of saline and sodium-affected soils, are most prevalent along the periphery of the drainageway. This pattern suggest a "wicking-up" and deposition of soluble salts in areas surrounding this feature.

2. Modeling EM Data:

In many areas of the country, quantification and mapping of the field-scale variability of soils and soil properties are important components for water-quality research and non-point source contamination investigations. Collection of such data with a soil probe or auger is highly tedious and labor intensive, making it impractical to collect the large quantities of data needed to implement comprehensive mapping studies over large areas. This study was undertaken to evaluate the appropriateness of using EM techniques to study the field-scale variability of soils and soil properties, and to compare data collected by EM methods with data collected by conventional sampling methods.

Field Methods

During the course of this investigation, soils were observed at selected observation points within each of the eight study sites. At most of these observation points, brief profile descriptions were obtained from soil cores extracted with a powered probe. In addition, measurements of apparent conductivity were obtained with an EM38 meter, placed on the ground surface, in both the horizontal and vertical dipole orientations. At seventy observation points, the depths to argillic horizon, finer-textured (greater than 18 percent clay) materials, and paleosol were recorded. In some profiles, these features were equivalent and the recorded depths were identical. However, in most profiles, each of these features were unique and occurred at slightly different depths. Soil probe and EM data were compared and used to develop a predictive model and to help characterize variations in soils and soil properties.

Variability of Soils

The eight study sites were located in southwest portion of Harvey County. These sites were located in delineated areas of the Carwile-Pratt (4 sites), the Farnum-Slickspots-Naron (3 sites) and the Farnum-Hobbs-Geary (1 site) associations (Hoffman and Dowd, 1974). Included within these sites were delineated areas of Carwile fine sandy loam; Farnum loam, 0 to 1 percent slopes; Farnum loam, 1 to 3 percent slopes; Farnum-Slickspots complex; Naron fine sandy loam, 0 to 1 percent slopes; Naron fine sandy loam, 1 to 4 percent slopes; Pratt loamy fine sand, 1 to 5 percent slopes; and Pratt-Carwile complex (Hoffman and Dowd, 1974).

Within the study sites, soils and near-surface stratigraphy were highly complex and variable over short distances. During the course of this investigation, seventeen different soil series were observed within the eight study sites. The taxonomic classifications of these soils are listed in Table 18.

Table 18
Taxonomic Classification of Observed Soils

Attica	coarse-loamy, mixed, mesic Udic Haplustalfs
Carbika	fine, montmorillonitic, thermic Vertic Argiaquolls
Carway	fine-loamy, mixed, mesic Aeric Epiaqualfs
Darlow	fine-loamy, mixed, mesic Vertic Natrustalfs
Dilhut	sandy over loamy, mixed, mesic Aquic Ustorthents
Elmer	fine-loamy, mixed, mesic Typic Natrustolls
Hayes	coarse-loamy, mixed, mesic Udic Haplustalfs
Farnum	fine-loamy, mixed, mesic Pachic Argiustolls
Funmar	fine-loamy, mixed, mesic Pachic Argiustolls
Kaskan	fine-loamy, mixed mesic Cumulic Haplustolls
Naron	fine-loamy, mixed, mesic Udic Argiustolls
Punkin	fine, mixed, mesic Vertic Natrustolls
Saltcreek	fine-loamy, mixed, mesic Udic Argiustolls
Solvay	fine-loamy, mixed, thermic Aquic Haplustalfs
Taver	fine, montmorillonitic, mesic Udertic Argiustolls
Tobin	fine-silty, mixed, mesic Cumulic Haplustolls
Turon	sandy, mixed, mesic Psammentic Haplustalfs

Within a given geographic area, apparent conductivity values can be used to infer soil types and changes in soil properties. As EM measurements integrate the bulk physical and chemical properties for a defined observational depth into a single value, responses have been associated with changes in soils and soil map units (Hoekstra et al., 1992; Jaynes et al., 1993). For each soil, the inherent variability in physical and chemical properties, as well as temporal variations in soil water and temperature, will establish a characteristic range of observable apparent conductivity values.

Within a given geographic area, most similar soils should have comparable EM responses. Dissimilar soils should have disparate EM responses. However, the conductivities of some similar and dissimilar soils will overlap. This occurs where contrasts in EM responses caused by differences in one property are offset by differences in another property. Table 19 list the average, minimum, and maximum conductivity for the seventeen soils observed within the study sites. This table is based on seventy observations. Admittedly, for most soils, the number of observations is too small to describe statistically valid relationships. However, several tendencies can be inferred from the data.

In general, soils with average apparent conductivity values less than 20 mS/m (in both orientations) are well drained and have relatively coarser textures (belong to the sandy, coarse-loamy, or fine-loamy particle-size classes). Soils with average apparent conductivity values greater than 20 mS/m in the horizontal dipole orientation and/or greater than 30 mS/m in the vertical dipole orientation are usually wetter (belong to aquic suborders or subgroups), finer textured (belong to fine-loamy or fine particle-size classes), and/or have natric horizons. Soils with average apparent conductivity values greater than 40 mS/m in the horizontal dipole orientation and greater than 50 mS/m in the vertical dipole orientation belong to the fine particle-size classes and have natric horizon or soluble salts.

Table 19

Apparent Conductivity Values for Observed Soils
(in mS/m)

Soil	Observations	EM38H			EM38V		
		Avg.	Min.	Max	Avg.	Min.	Max
Attica	5	11.1	5.0	14.8	14.7	8.3	19.0
Turon	1	11.4			15.9		
Kaskan	1	11.4			17.1		
Naron	4	10.4	5.4	13.8	17.8	8.7	23.9
Hayes	16	12.0	5.7	19.6	17.9	10.2	31.2
Funmar	4	13.2	9.5	19.0	21.3	14.7	31.2
Elmer	3	21.9	18.7	23.5	28.0	22.7	35.0
Saltcreek	4	23.2	17.6	27.8	33.2	26.2	37.5
Solvay	8	23.8	15.2	37.1	33.4	23.3	49.1
Dilhut	4	21.3	16.6	28.8	33.6	26.6	44.1
Tobin	1	29.1			35.6		
Darlow	3	30.6	22.6	40.3	35.9	27.6	44.0
Carbika	4	24.9	12.2	32.7	36.6	17.1	45.6
Carway	1	17.2			37.7		
Farnum	1	37.5			52.1		
Tavar	6	41.1	28.9	53.7	58.3	40.2	76.8
Punkin	4	68.4	45.6	77.2	93.9	63.7	110.4

Exceptions to these relationships can be noted in Table 19. The apparent conductivity values for several soils, such as Elmer and Carway, appear to reflect varying textures and concentrations of calcium carbonates, exchangeable sodium, and/or other soluble salts. Further analysis of these relationships should be performed to better understand and characterize the inferred ranges in soils and soil properties from EM responses.

Modeling EM Data

Electromagnetic induction is an imperfect tool. This tool is not equally suitable for use in all soil investigations. Generally, the use of EM techniques has been most successful in areas where subsurface properties are reasonably homogeneous, the effects of one parameter (clay, water, or salt content) dominates over the other parameters, and variations in EM response can be related to changes in the dominant parameter (Cook et al., 1989). In such areas, information is gathered on the dominant parameter, and assumptions are made concerning the behavior of the other parameters (Cook and Walker, 1992).

For most earth models, the number of possible constructed models is almost infinite. Models constructed from EM data are most accurate in areas having a minimal sequence of dissimilar horizontal layers. The accuracy of models decreases with increasing numbers of layers. In addition, the principal layers should be electromagnetically dissimilar and each have unique EM responses. Electromagnetic induction methods must be sensitive to the differences existing between the layers. In other words, a meter must be able to detect differences in electromagnetic properties between the layers. Some subsurface layers have varying thicknesses and properties, but closely similar conductivity values. These dissimilar layers produce equivalent solutions which seriously reduce the accuracy and limit the effectiveness of models. In Harvey County, several undesirable soil parameters (variable soluble salt and clay contents) fostered ambiguous EM interpretations and lessened the applicability of geoelectric models over broad areas.

In Harvey County, the parent materials are variable. Pleistocene epoch braided and meandering stream systems deposited alluvial sediments over much of the County. Changes in erosion and depositional processes, and sediments produced, over short distances, highly complex and variable soils and depositional landforms. Later, these paleosols and landforms were reworked by winds, and eolian materials were deposited in varying amounts on a new soil surface (Hoffman and Dowd, 1974). The eolian materials have increased the variability of soils and added complexity to the landscape.

Soil horizons and stratigraphic layers are variable in thickness, texture (ranged from sands to clay), and electrical conductivity. In an attempt to reduce the number of layers and to simplify the data for modeling, several soil horizons or layers were grouped. Because of differences in clay content, contrasts in electrical conductivity were assumed to exist between the surface layers and the argillic horizons, between the overlying coarse- and moderately coarse-textured eolian materials and the underlying medium- or moderately fine-textured alluvial materials; and between the reworked eolian mantle and the paleosol. Variations in the thickness and contrasts in electrical conductivity between these layers were assumed to influence EM responses. However, vertical and horizontal variations in clay and soluble salt contents occurred within each of these principal layers and increased the ambiguity of interpretations.

The eolian materials are predominantly coarse- and moderately coarse-textured. These wind-reworked materials are principally loamy sands, loamy fine sands, fine sandy loam, and loam. As a result of differential deposition and erosion these layers are variable in thickness and texture.

Underlying the coarse- and moderately coarse-textured eolian materials are medium- and moderately fine-textured alluvial materials. In most soils, a paleosol occurs at the contact of the eolian and alluvial materials and in the upper part of the alluvium. Paleosols vary in horizon nomenclature, depth, thickness, and texture. Typically, paleosols are loam, clay loam, sandy clay loam, sandy loam, fine sandy loam, or silt loam.

The soils, formed in these wind-reworked alluvial materials, have either a cambic, argillic, or natric horizon. Depth and composition (soluble salt, clay, and moisture contents) of subsoils were variable. Subsoils are fine sandy loam, loam, sandy clay loam, clay loam, or silty clay loam.

In this study, variations in the number, arrangement, thickness, and texture of soil layers and the concentrations of calcium carbonates, exchangeable sodium, and/or other soluble salts offset variations in the depths to measured soil layers (argillic horizon, finer-textured materials, and paleosol). This variability produced ambiguous EM interpretations and inconclusive results.

Predictive Equations

Data was compiled from brief profile descriptions recorded at fifty observation points in five of the eight study sites. This data set excluded calcareous, sodium-affected, and saline soils. The apparent conductivities of these excluded soils were conspicuously higher because of greater concentrations of soluble salts. Within this restricted data set, depths to the argillic horizon averaged 35 cm, and ranged from 0 cm to 109 cm. Depths to fine-loamy materials (greater than 18 percent clay) averaged 71 cm, and ranged from 0 cm to 244 cm. Depths to paleosol averaged 87 cm, and ranged from 15 cm to 199 cm.

At the fifty observations points, values of apparent conductivity averaged 16.7 mS/m and ranged from 5.0 mS/m to 44.6 mS/m in the horizontal dipole orientation. In the vertical dipole orientation, values of apparent conductivity averaged 24.9 mS/m and ranged from 8.3 mS/m to 56.6 mS/m. The higher readings in the vertical dipole orientation suggest that apparent conductivity increased with soil depth. This relationship was believed to be a manifestation of increasing clay, soluble salt, and volumetric moisture contents with increasing soil depth.

Tables 20 and 21 list the sample correlation coefficients between depths to soil layers (argillic horizon, fine-loamy materials, paleosol) and values of apparent conductivity collected with the EM38 meter in the horizontal and vertical dipole orientations, respectively. Apparent conductivity values were inversely related to both the depths to fine-loamy materials and paleosol. The strength of these relationships varied among the sites and with soils. Within most sites, no relationship was found between values of apparent conductivity and depths to the argillic

Table 20

Sample Correlation Coefficients
between
Soil Depths and Apparent Conductivity
EM38 Meter (Horizontal Dipole Orientation)

Site #	# Obs.	Depth to Bt Horizon	Depth to Fine-loamy materials	Depth to Paleosol
1	19	-0.006	-0.554	-0.218
2	19	-0.132	-0.700	-0.797
5	3	-0.888	-0.888	-0.888
7	5	-0.368	-0.368	-0.368
8	4	0.135	-0.954	-0.654
All	50	-0.037	-0.490	-0.538

horizon. Based on fifty observations, the sample correlation coefficient, r, between the depths to fine-loamy materials and values of apparent conductivity was -0.490 (significant at the 0.001 level) in the horizontal dipole orientation and -0.488 (significant at the 0.001 level) in the vertical dipole orientation. Slightly stronger relationships were achieved between the depths to paleosol and values of apparent conductivity. The sample correlation coefficient between the depths to paleosol and values of apparent conductivity was -0.538 (significant at the 0.001 level) in the horizontal dipole orientation and -0.585 (significant at the 0.001 level) in the vertical dipole orientation.

Table 21

Sample Correlation Coefficients
between
Soil Depths and Apparent Conductivity
EM38 Meter (Vertical Dipole Orientation)

Site #	# Obs.	Depth to Bt Horizon	Depth to Fine-loamy materials	Depth to Paleosol
1	19	0.245	-0.542	-0.459
2	19	-0.055	-0.798	-0.802
5	3	-0.801	-0.801	-0.801
7	5	-0.277	-0.277	-0.829
8	4	0.117	-0.937	-0.615
ALL	50	0.075	-0.488	-0.585

Though relatively weak, the inverse relationships between depths to measured soil layers (finer-textured materials and paleosol) and EM responses were considered favorable. Large variations in the number, arrangement, thickness, and texture of soil layers and the concentrations of calcium carbonates, exchangeable sodium, and/or other soluble salts reduced correlations, produced ambiguous EM interpretations, and fostered imprecise predictions. Though imprecise, models constructed using this data, can be illustrative and used to describe general tendencies and patterns over extensive areas.

At the fifty observation points, values of apparent conductivity obtained with the different coil orientations were strongly inter-dependent ($r = 0.948$). Since the strongest relationship was found between the apparent conductivity values obtained with the EM38 meter in the vertical dipole orientation and the depth to paleosol, these values were used to develop a regression equation to predict depth to paleosol from values of apparent conductivity. Based on data collected at the fifty observation points, the following equation was developed:

Linear regression ($r^2 = 0.342$):

$$D = 1.4713 + (-0.02439 * X) \qquad [1]$$

where "D" is depth to paleosol (m) and "X" is the apparent conductivity measured by the EM38 meter in the vertical dipole orientation (mS/m).

The relationship between the observed and predicted depth to paleosol for the 50 observation points is shown in the scatter plot in Figure 51. This plot suggests that, for greater depths (> 100 cm), the predictive equation appears to underestimate depths to the paleosol. For lesser depths (< 100 cm) the equation appears to overestimate depths to paleosol. In addition, data points appear to be more dispersed at lower values. This dispersion suggests that in areas where the paleosol is shallow (0 to 50 cm) or moderately deep (50 to 100 cm), differences in soil types and properties exert greater influence on EM responses. Negative values for the predicted depths to paleosol were obtained (from entire data set, 70 observations; not shown) in areas of saline and sodium-affected soils (having apparent conductivity values greater than 60 mS/m).

Equation [1] was used to predict the depths to paleosol at each of the fifty observation points. Based on Equation [1] and measurements taken with the EM38 meter in the vertical dipole orientation, sixty-four percent of the predicted depths were within 0.25 m of the observed depths to paleosol. The difference between the observed and the predicted depths to paleosol ranged from -0.87 to 0.70 m. The average predicted depth to paleosol was estimated to be 0.86 m with a range of 0.09 to 1.27 m. One-half of the observations had predicted depths to paleosol between 0.66 and 1.07 m. The average observed depth to paleosol was 0.87 m with a range of 0.15 to 1.99 m. One-half of the observations had observed depths to paleosol between 0.56 and 1.17 m.

Table 22

Basic Statistics
for
Predicted Depths to Paleosol

Site	Observations	Depth to Paleosol (m)					
					Quartiles		
		Avg.	Min.	Max	1st	2nd	3rd
1	118	1.09	0.60	1.27	1.02	1.11	1.18
2	196	0.72	0.00	1.10	0.54	0.79	0.93
5	90	1.03	0.48	1.22	0.99	1.06	1.13
7	81	0.25	0.00	0.99	0.00	0.36	0.70
8	136	0.46	0.00	1.09	0.16	0.60	0.80
10	143	0.79	0.00	1.34	0.52	1.04	1.28
12	100	0.48	0.00	0.99	0.27	0.62	0.79
13	121	0.62	0.00	1.24	0.49	0.72	0.92

Figures 52 to 59 are two-dimensional plots of the estimated depths to paleosols within each of the study sites. In each of these plots the isoline interval is 25 cm. In areas having high values of apparent conductivity (greater than 60 mS/m), the depths to paleosol were assumed to be zero. Soils in these areas were either finer-textured or had high concentrations of soluble salts. Table 22 summarizes some of the basic statistics for the estimated depths to paleosol within each of the sites. Table 23 list the distribution of paleosols within each site by soil depth-classes. The depth classes are shallow (0 to 50 cm), moderately deep (50 to 100 cm), and deep (100 to 150 cm).

For each site, three-dimensional surface net diagram showing the distribution of the depths to paleosol with the topography of surface were prepared (figures 60 to 67). In each plot, the isoline interval is 25 cm. These plots can be used to show variations in the depth to the paleosol, suggest directions of lateral water flow, and facilitate the location of sampling sites.

Table 23

Depth-Class Distribution of Paleosol

Site	Shallow	Moderately Deep	Deep
1	0	21	79
2	20	66	14
5	1	28	71
7	59	41	0
8	43	52	5
10	23	24	53
12	40	60	0
13	27	58	15

Results:

1. This field investigation provided participants with additional training and exposure to the uses of EM techniques. Results from this study have been tabulated, graphed, and briefly summarized in this report. A more comprehensive review of this data will be accomplished by Richard Sleezer.

2. Attempts to use EM techniques to estimate depths to finer-textured soil materials and/or paleosol were moderately successful. While anticipated relationships were attained, the strengths of the derived correlations and the predictiveness of constructed equations and models were weaker than anticipated.

In Harvey County, several undesirable and variable soil parameters fostered ambiguous EM interpretations and lessened the applicability of geoelectric models over broad areas. The variability of several soil properties were sighted as reasons for the weak correlations. Additional studies are recommended to better understand the influence of these properties on EM responses. These studies will help ascertain the soils and soil conditions most suitable for EM investigations.

3. Though relatively weak, the inverse relationships between depths to measured soil layers (finer-textured materials and paleosol) and EM responses were considered favorable. Large variations in the number, arrangement, thickness, and texture of soil layers and the concentrations of calcium carbonates, exchangeable sodium, and/or other soluble salts reduced correlations, produced ambiguous EM interpretations, and fostered imprecise predictions. Though imprecise, models constructed using this data, can be illustrative and used to describe general tendencies and patterns over extensive areas.

4. The reliability of EM techniques must always be appraised based on verifiable results from ground-truth observation and measurements.

It was my pleasure to work with your staff.

With kind regards

James A. Doolittle
Research Soil Scientist

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HARVEY COUNTY, KANSAS
SITE 1

RELATIVE TOPOGRAPHY
CONTOUR INTERVAL = 0.25 M

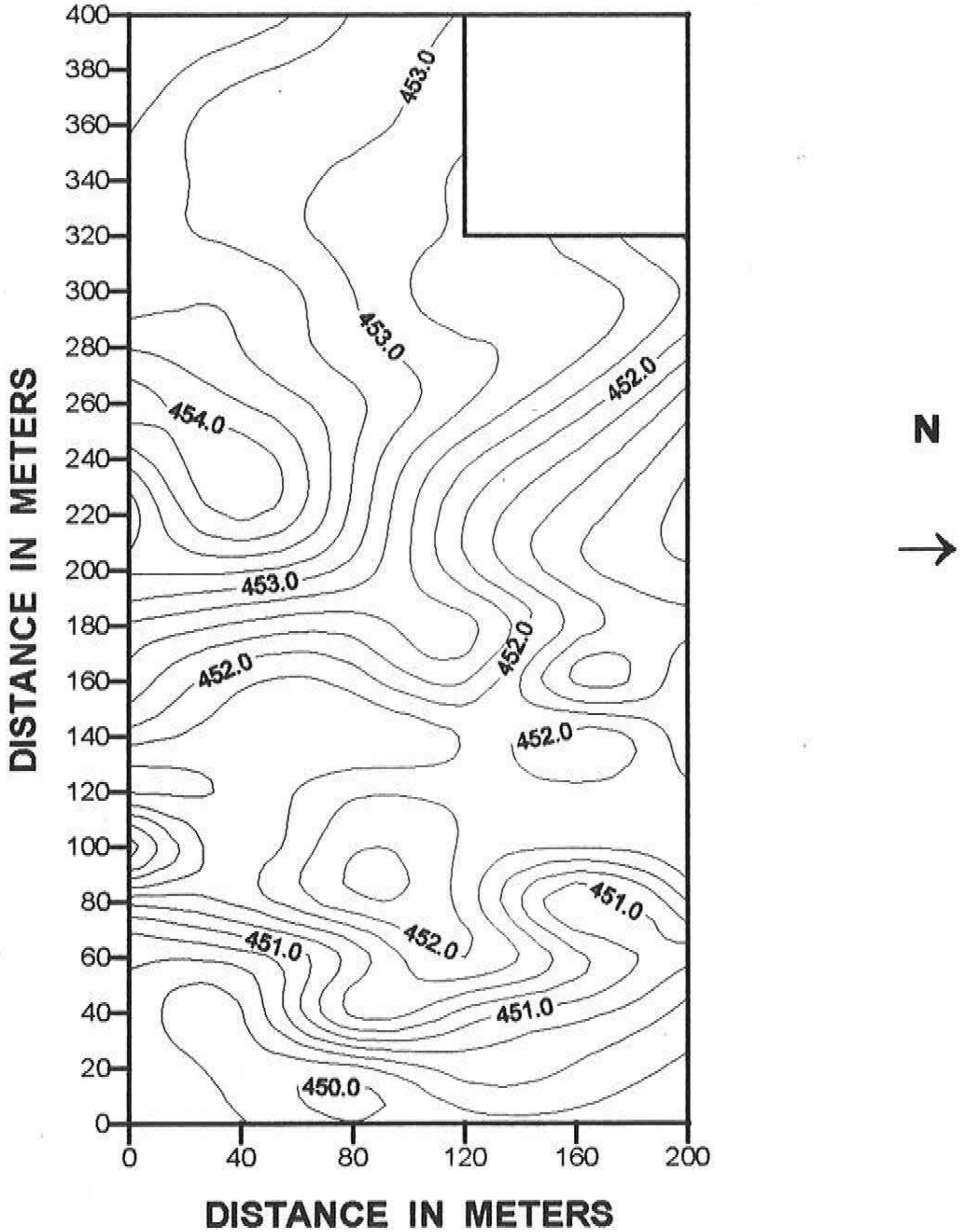


FIGURE 1

HARVEY COUNTY, KANSAS
SITE 1

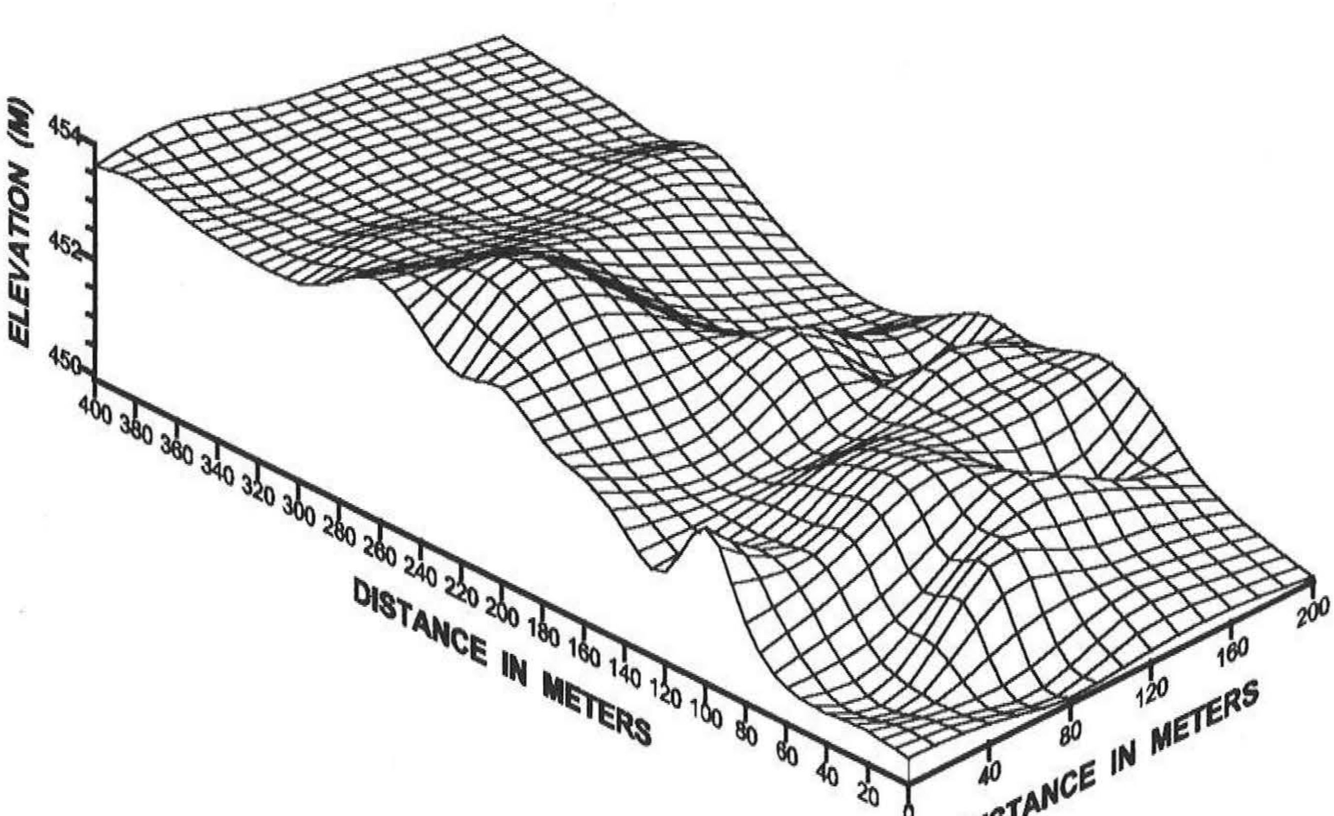


FIGURE 2

HARVEY COUNTY, KANSAS
SITE 1

EM38 METER
HORIZONTAL DIPOLE ORIENTATION

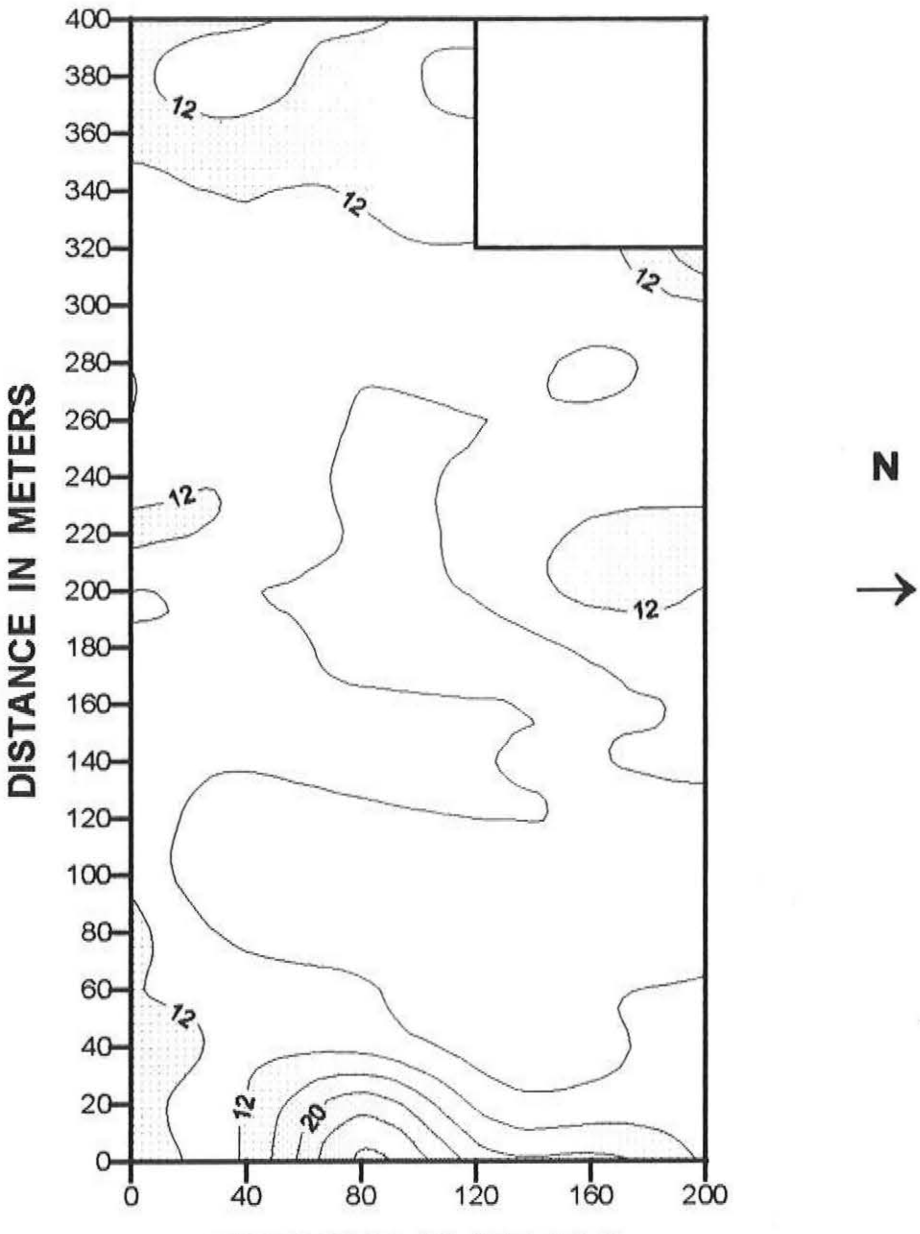


FIGURE 3

HARVEY COUNTY, KANSAS
SITE 1

EM38 METER
VERTICAL DIPOLE ORIENTATION

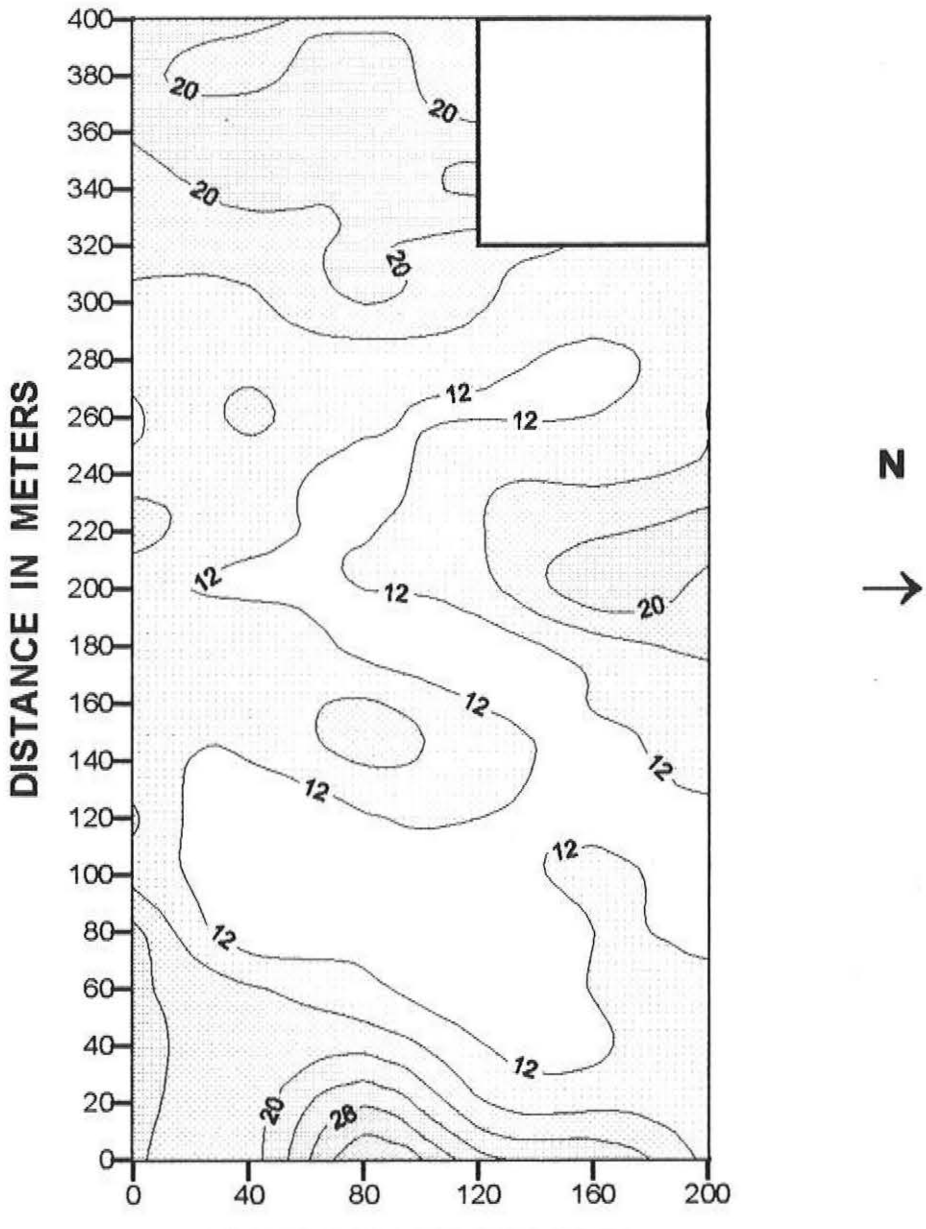


FIGURE 4

HARVEY COUNTY, KANSAS
SITE 1

EM31 METER
HORIZONTAL DIPOLE ORIENTATION

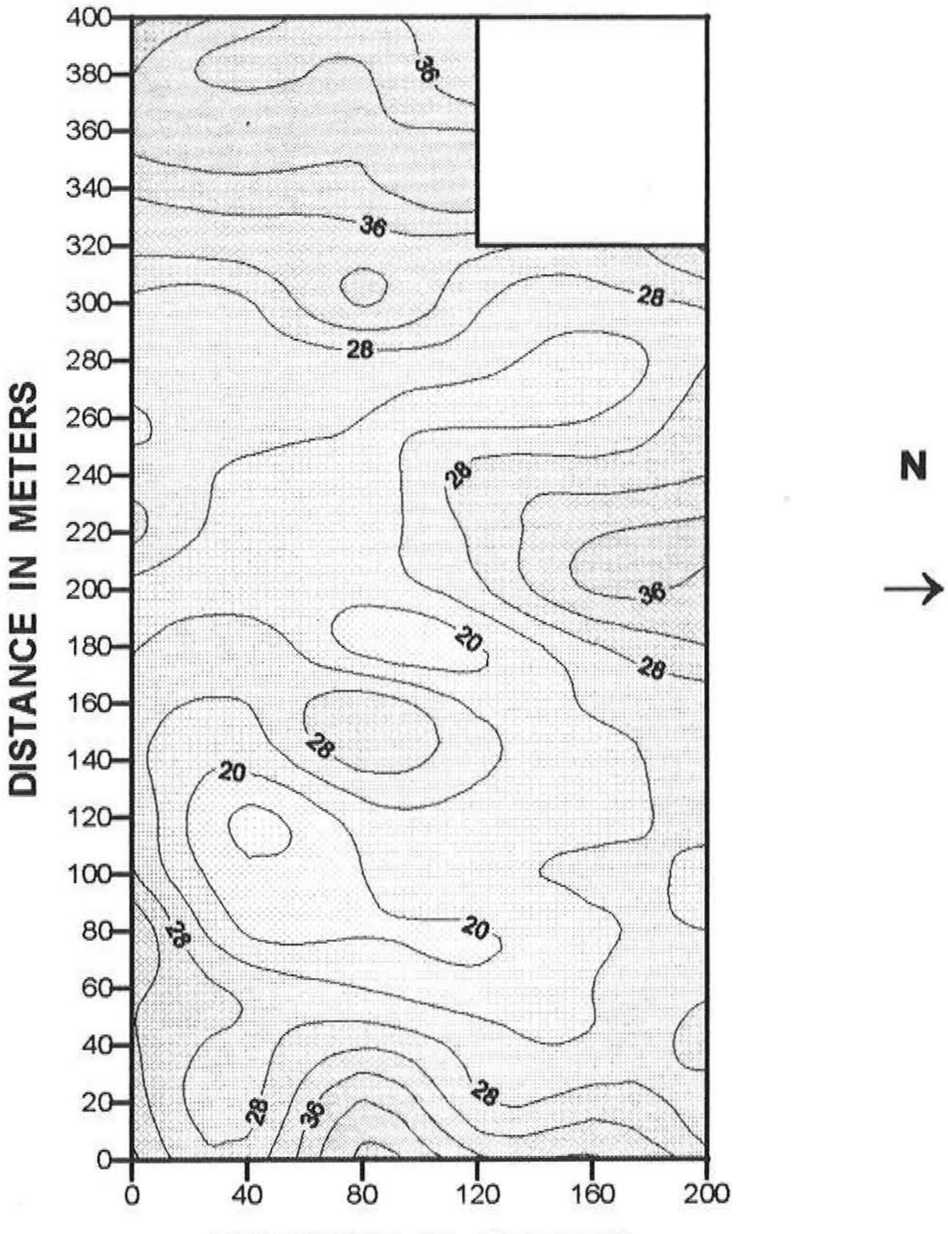


FIGURE 5

HARVEY COUNTY, KANSAS
SITE 1

EM31 METER
VERTICAL DIPOLE ORIENTATION

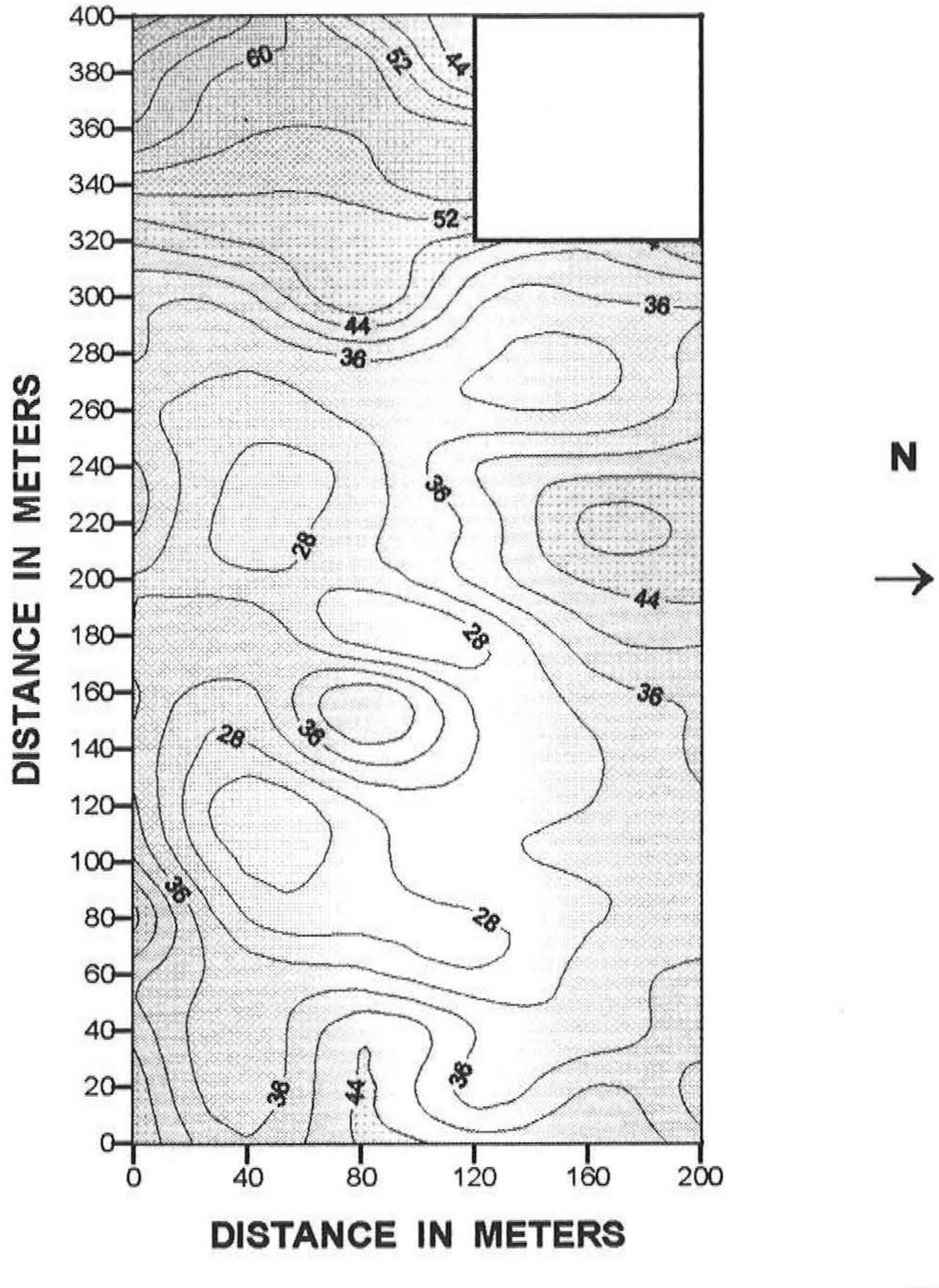


FIGURE 6

HARVEY COUNTY, KANSAS
SITE 1

EM34 METER
HORIZONTAL DIPOLE ORIENTATION

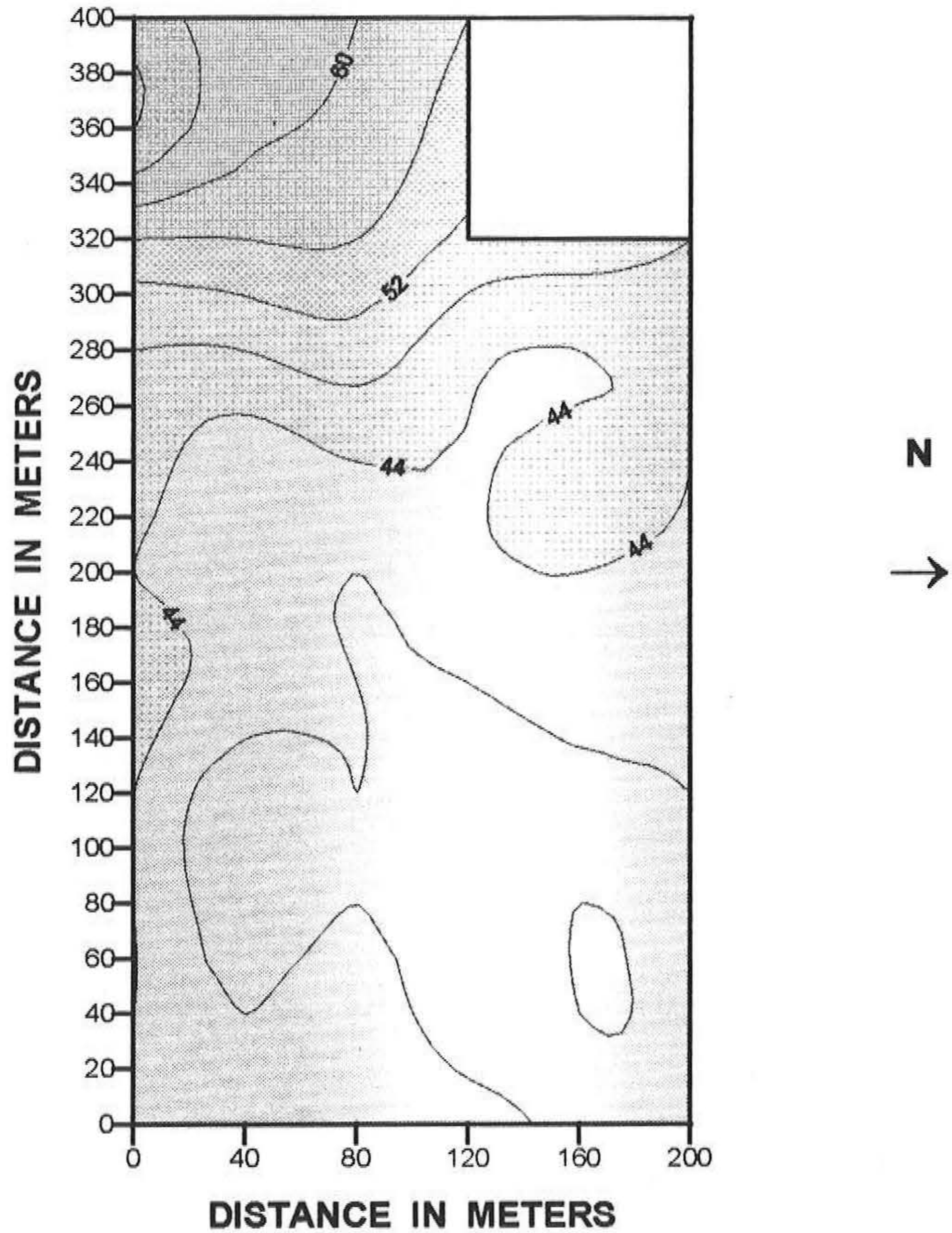


FIGURE 7

HARVEY COUNTY, KANSAS
SITE 1

EM34 METER
VERTICAL DIPOLE ORIENTATION

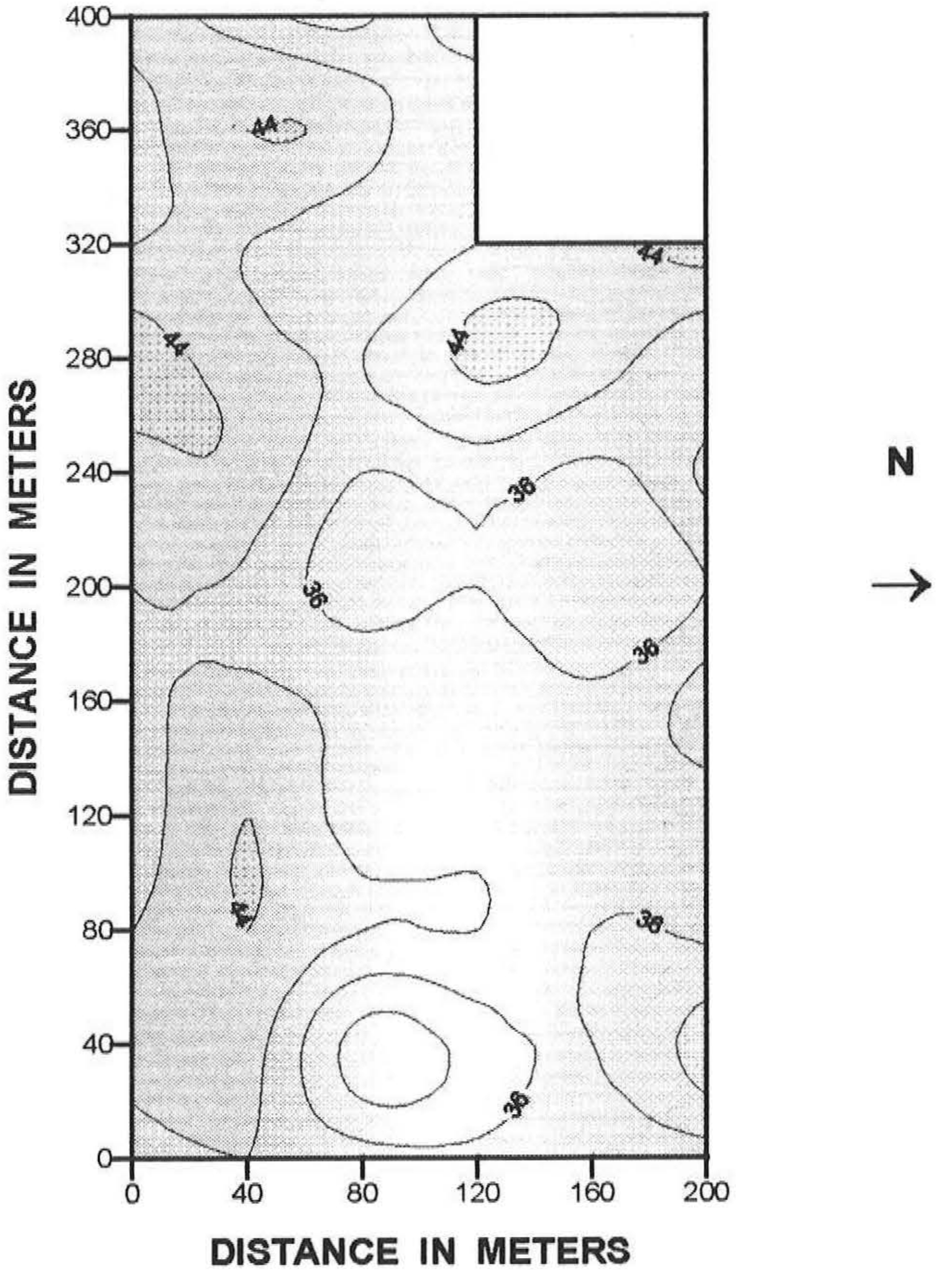


FIGURE 8

HARVEY COUNTY, KANSAS
SITE 2

RELATIVE TOPOGRAPHY
CONTOUR INTERVAL = 0.25 M

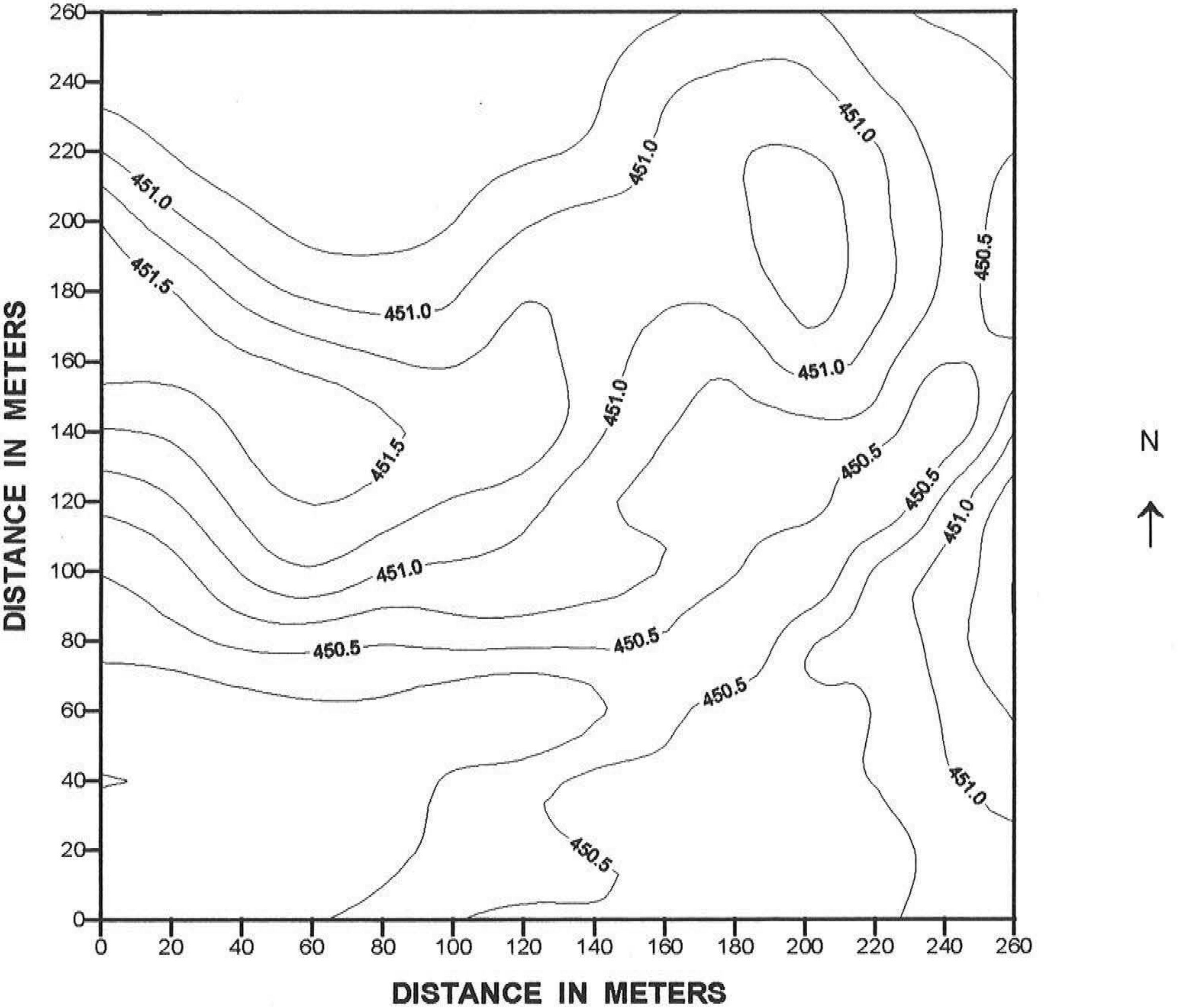


FIGURE 9

HARVEY COUNTY, KANSAS
SITE 2

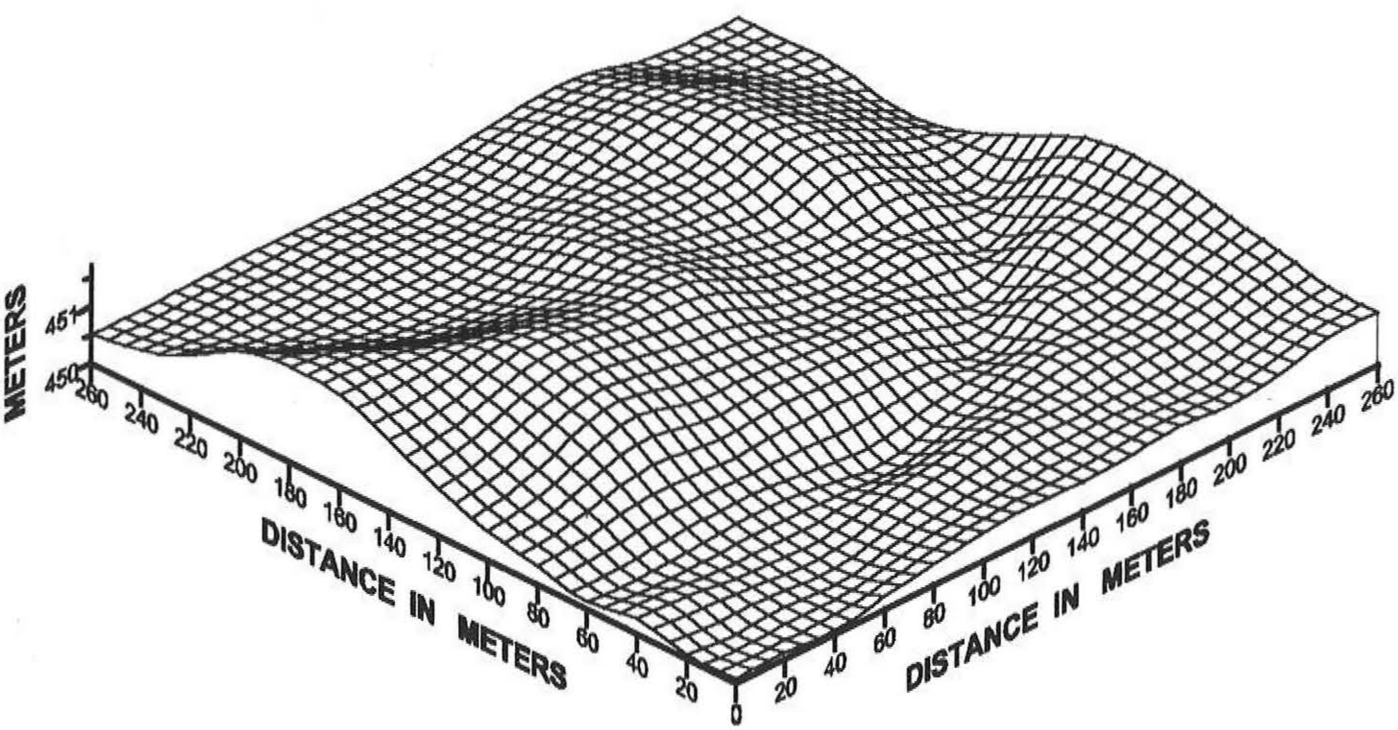


FIGURE 10

HARVEY COUNTY, KANSAS
SITE 2

EM38 METER
HORIZONTAL DIPOLE ORIENTATION

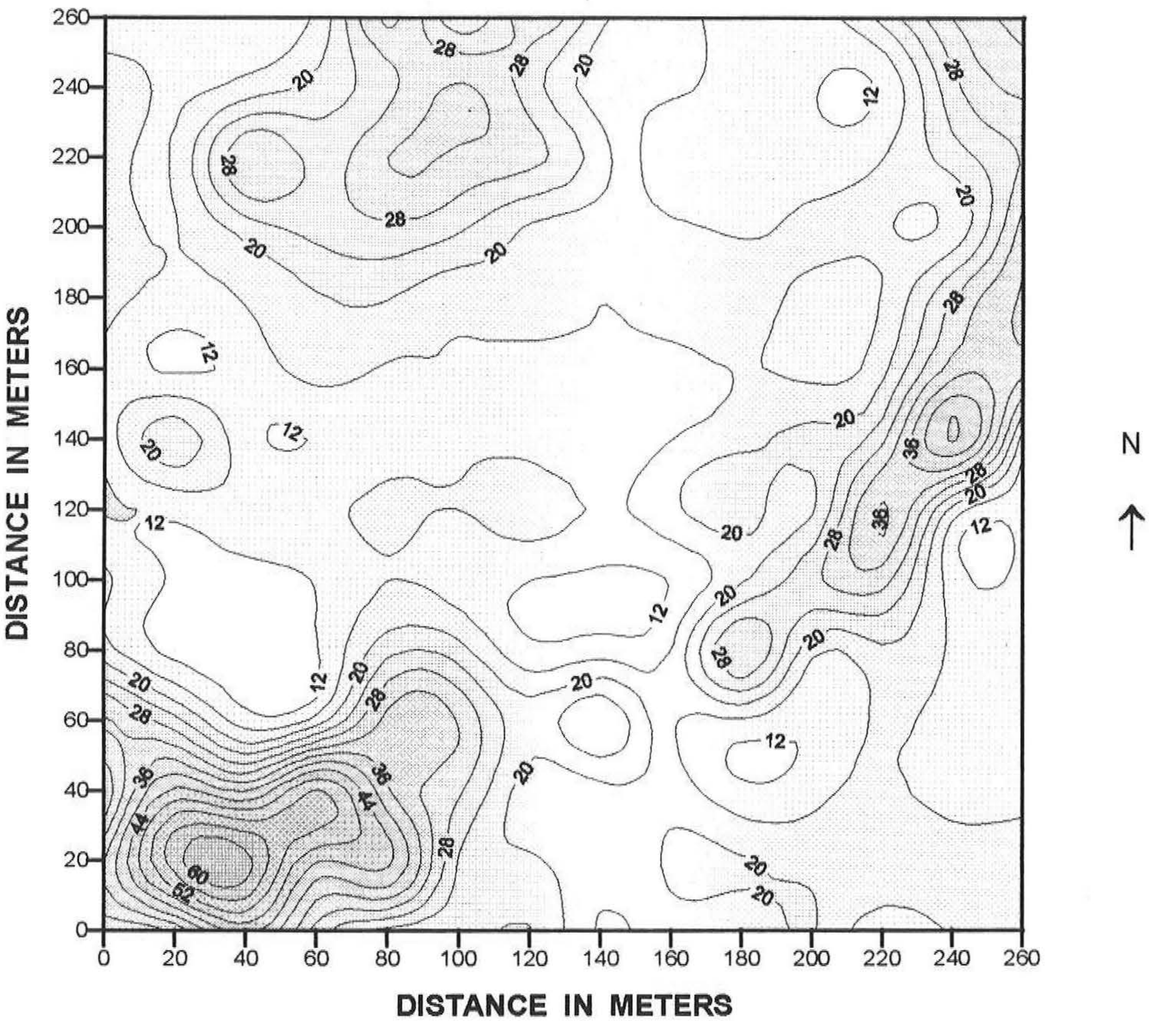


FIGURE 11

HARVEY COUNTY, KANSAS
SITE 2

EM38 METER
VERTICAL DIPOLE ORIENTATION

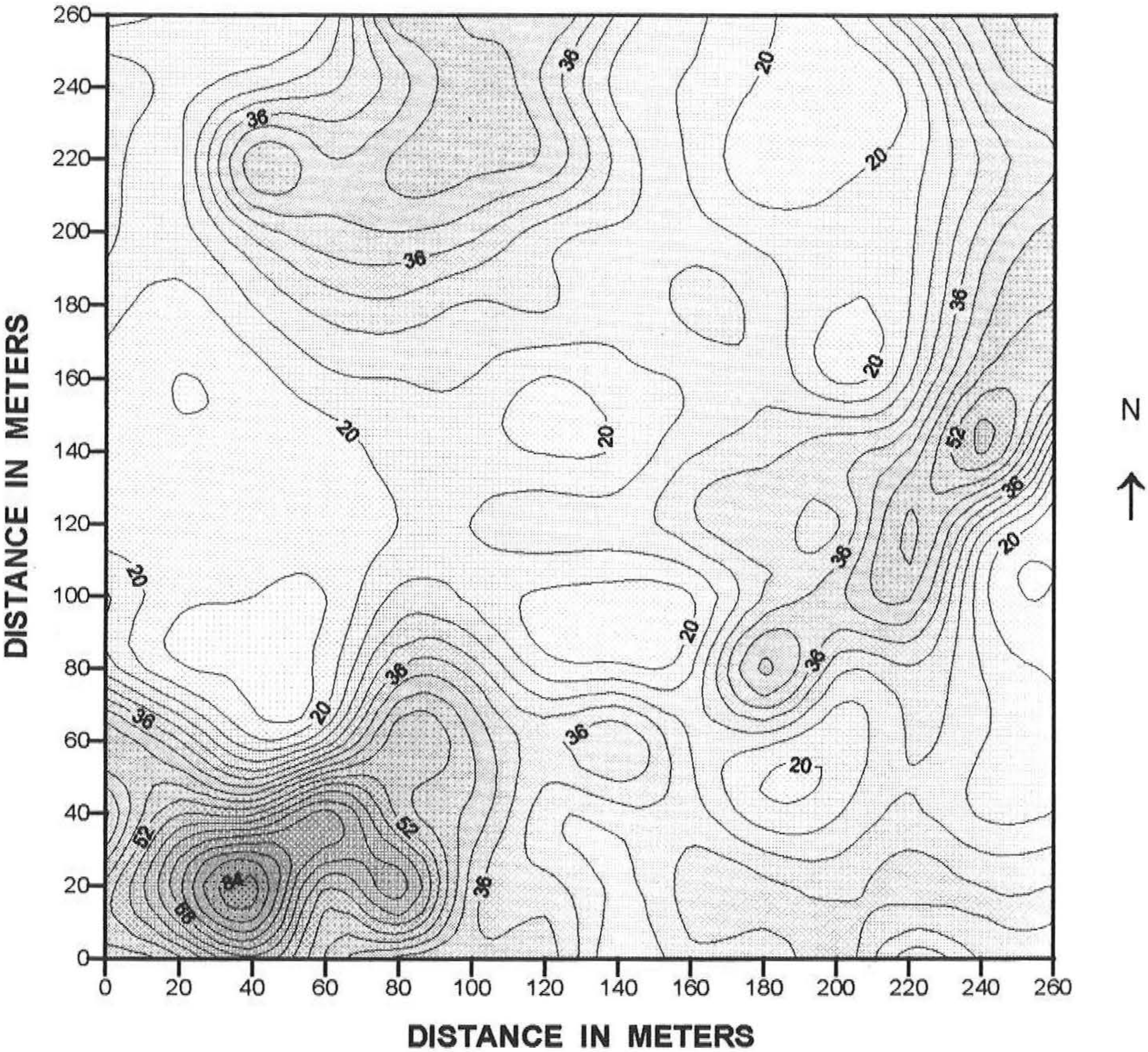


FIGURE 12

HARVEY COUNTY, KANSAS
SITE 2

EM31 METER
HORIZONTAL DIPOLE ORIENTATION

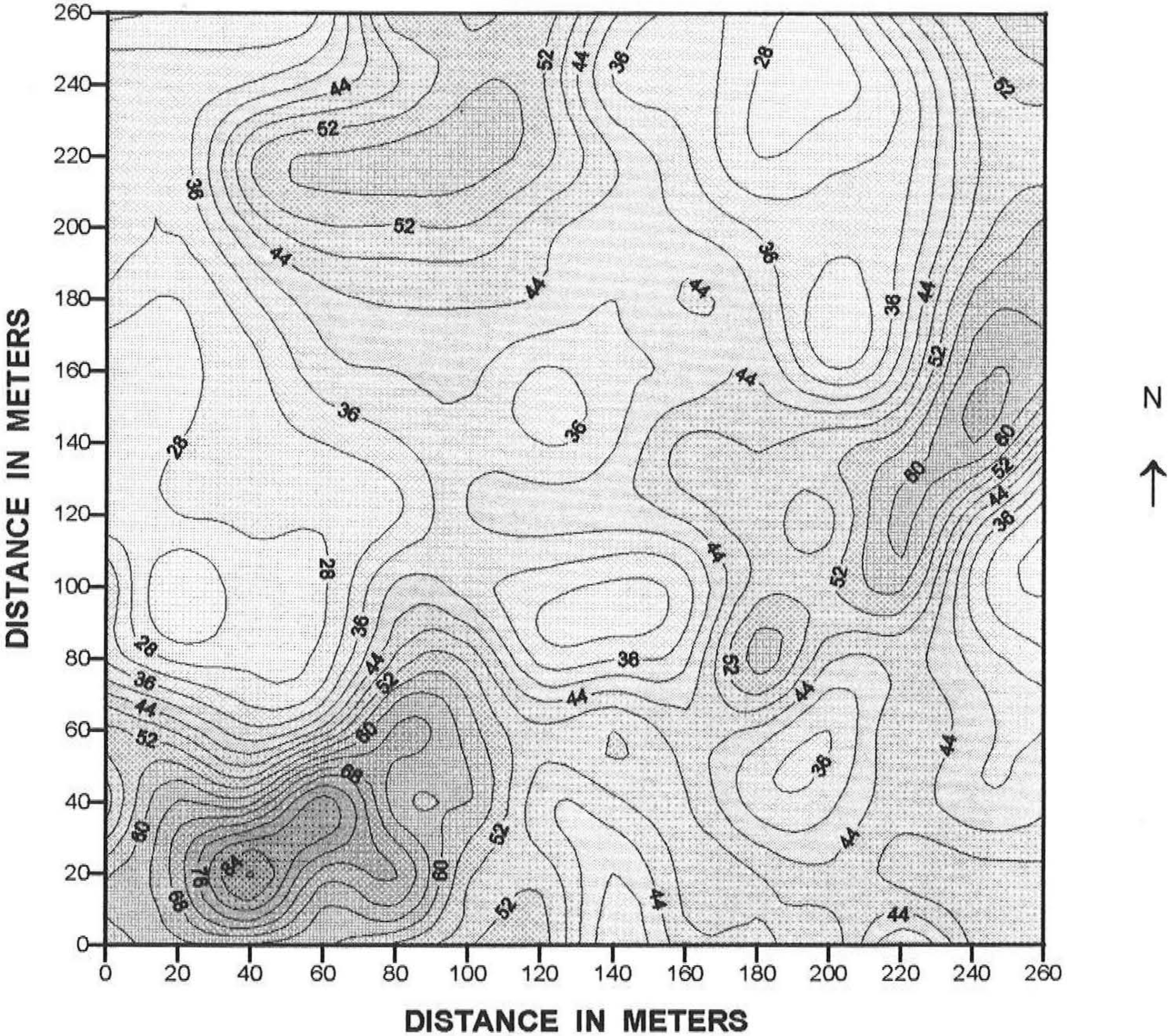


FIGURE 13

HARVEY COUNTY, KANSAS
SITE 2

EM31 METER
VERTICAL DIPOLE ORIENTATION

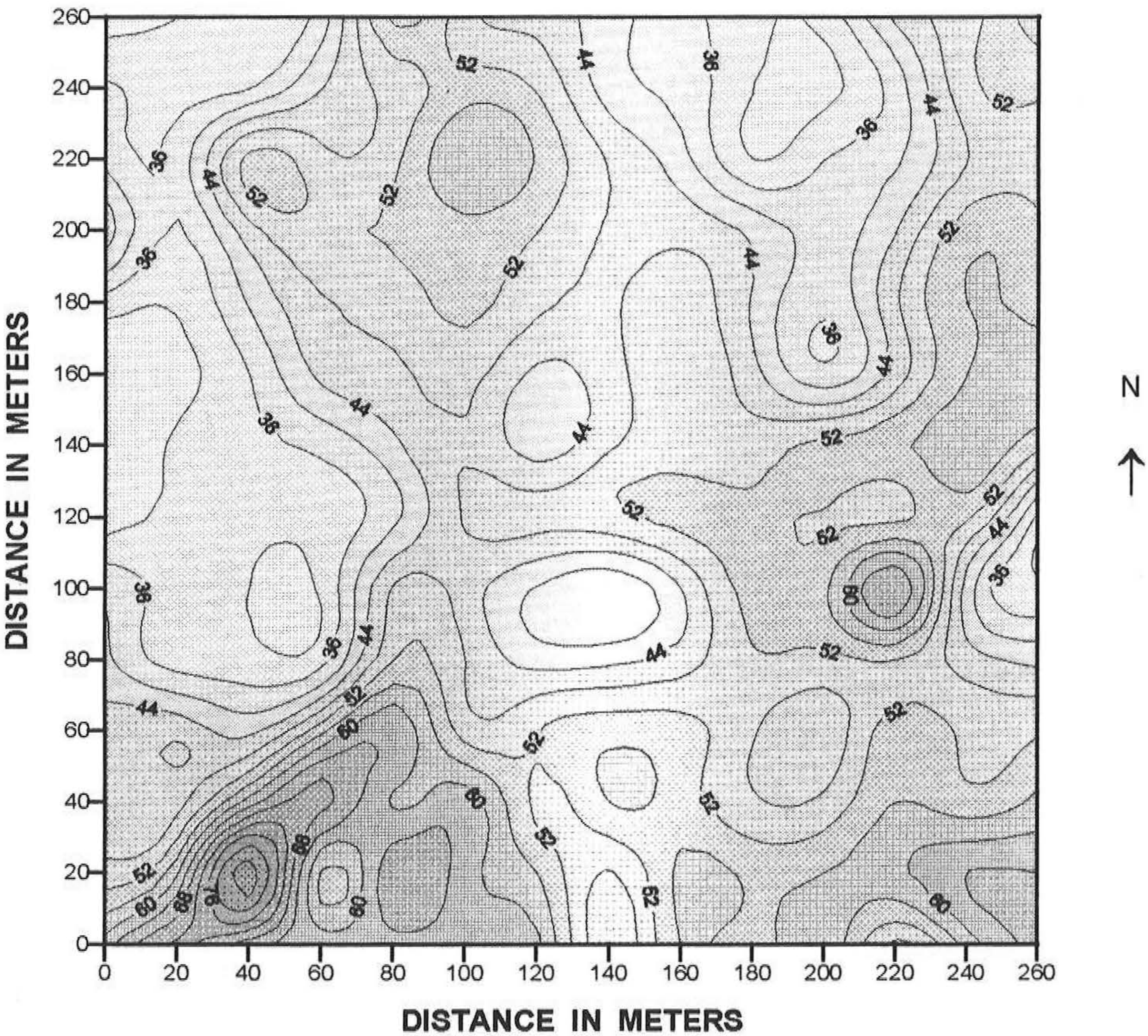


FIGURE 14

HARVEY COUNTY, KANSAS
SITE 5

RELATIVE TOPOGRAPHY
CONTOUR INTERVAL = 0.50 M

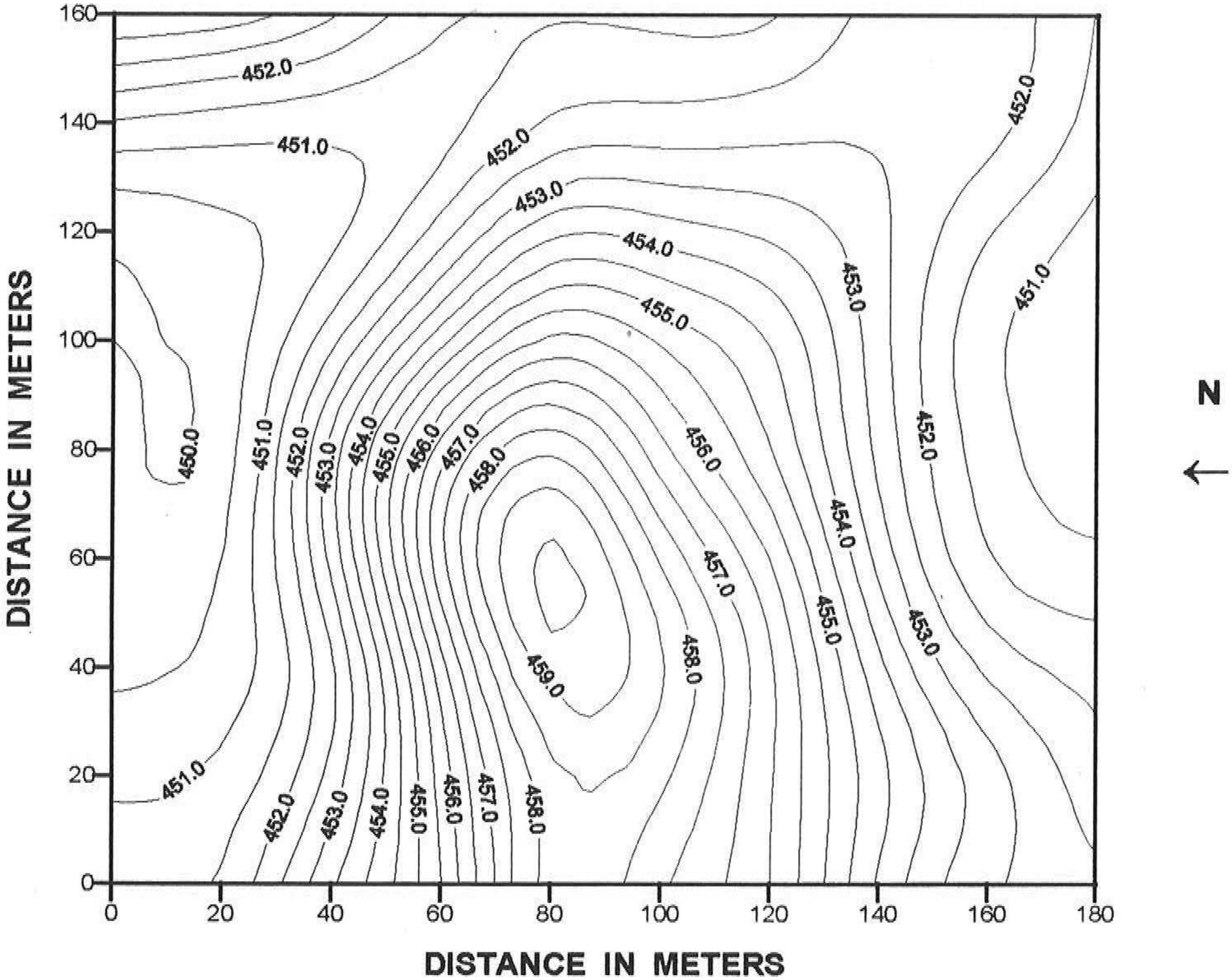


FIGURE 15

HARVEY COUNTY, KANSAS
SITE 5

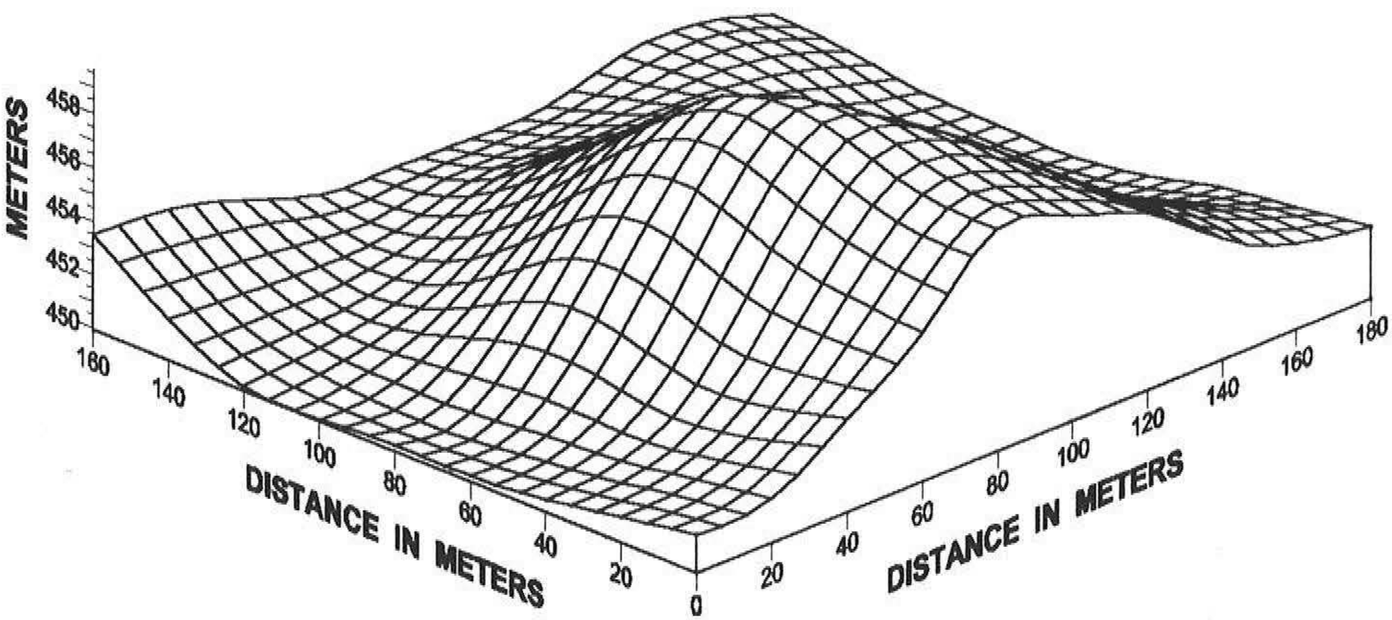


FIGURE 16

HARVEY COUNTY, KANSAS
SITE 5

EM38 METER
HORIZONTAL DIPOLE ORIENTATION

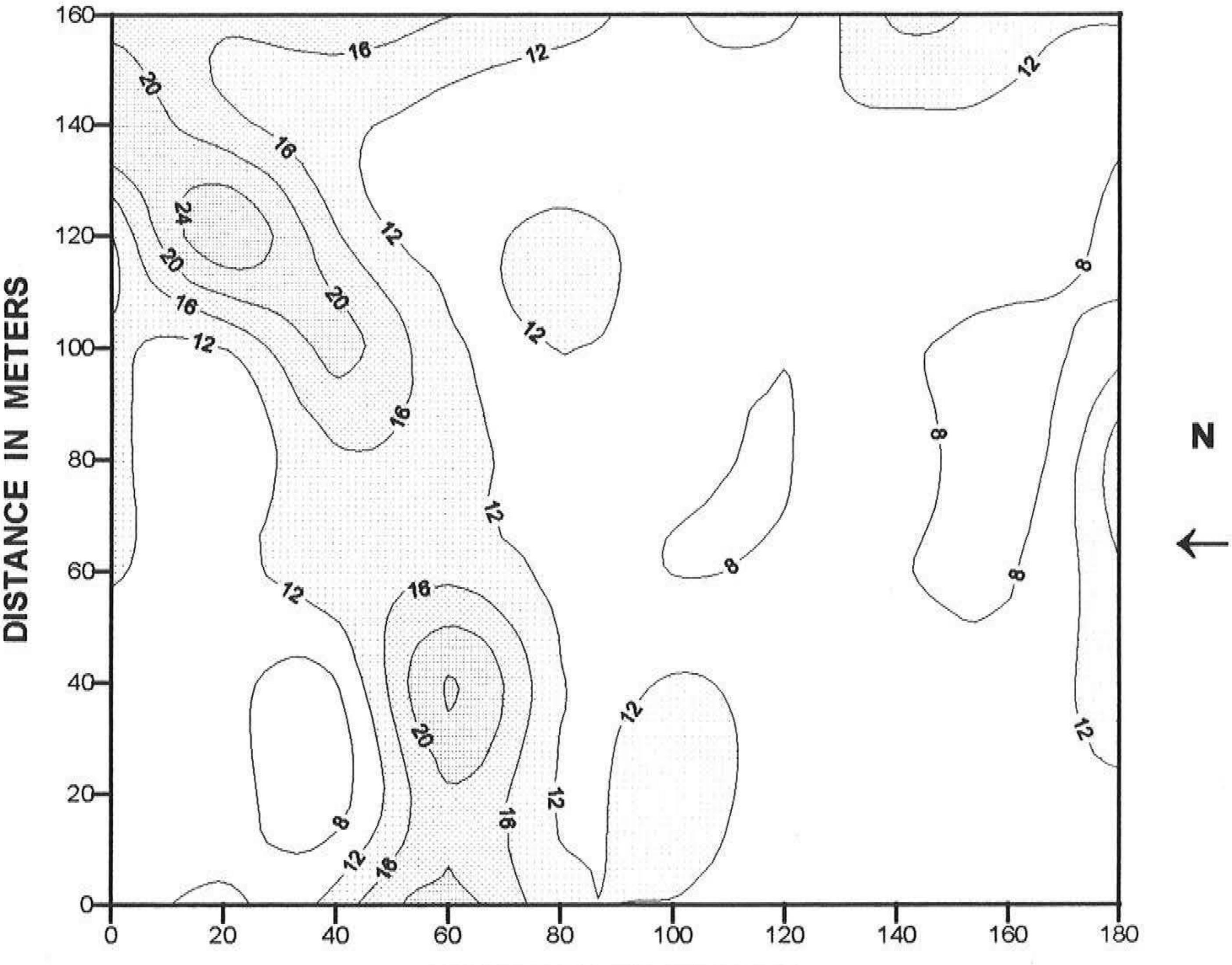


FIGURE 17

HARVEY COUNTY, KANSAS
SITE 5

EM38 METER
VERTICAL DIPOLE ORIENTATION

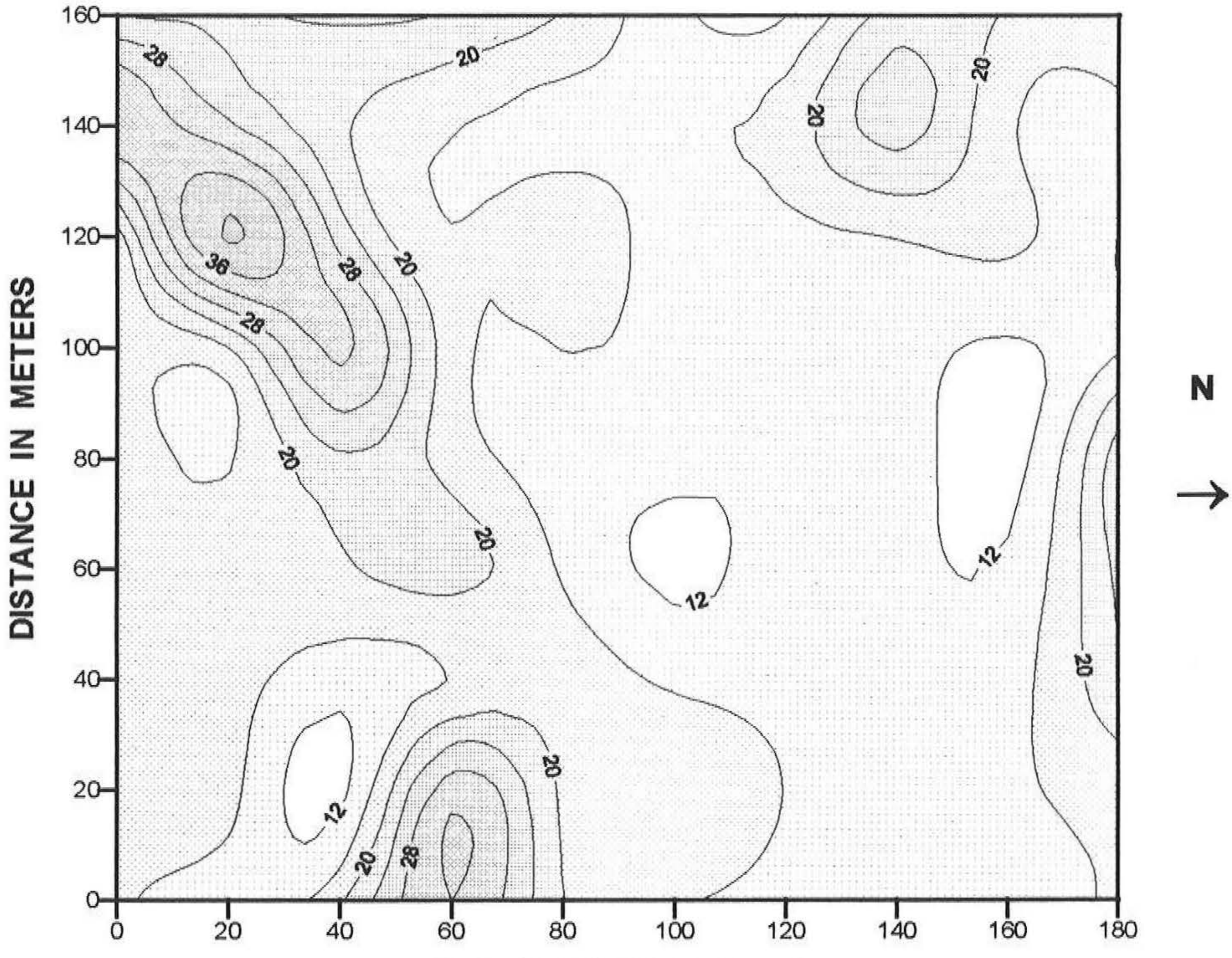


FIGURE 18

HARVEY COUNTY, KANSAS
SITE 5

EM31 METER
HORIZONTAL DIPOLE ORIENTATION

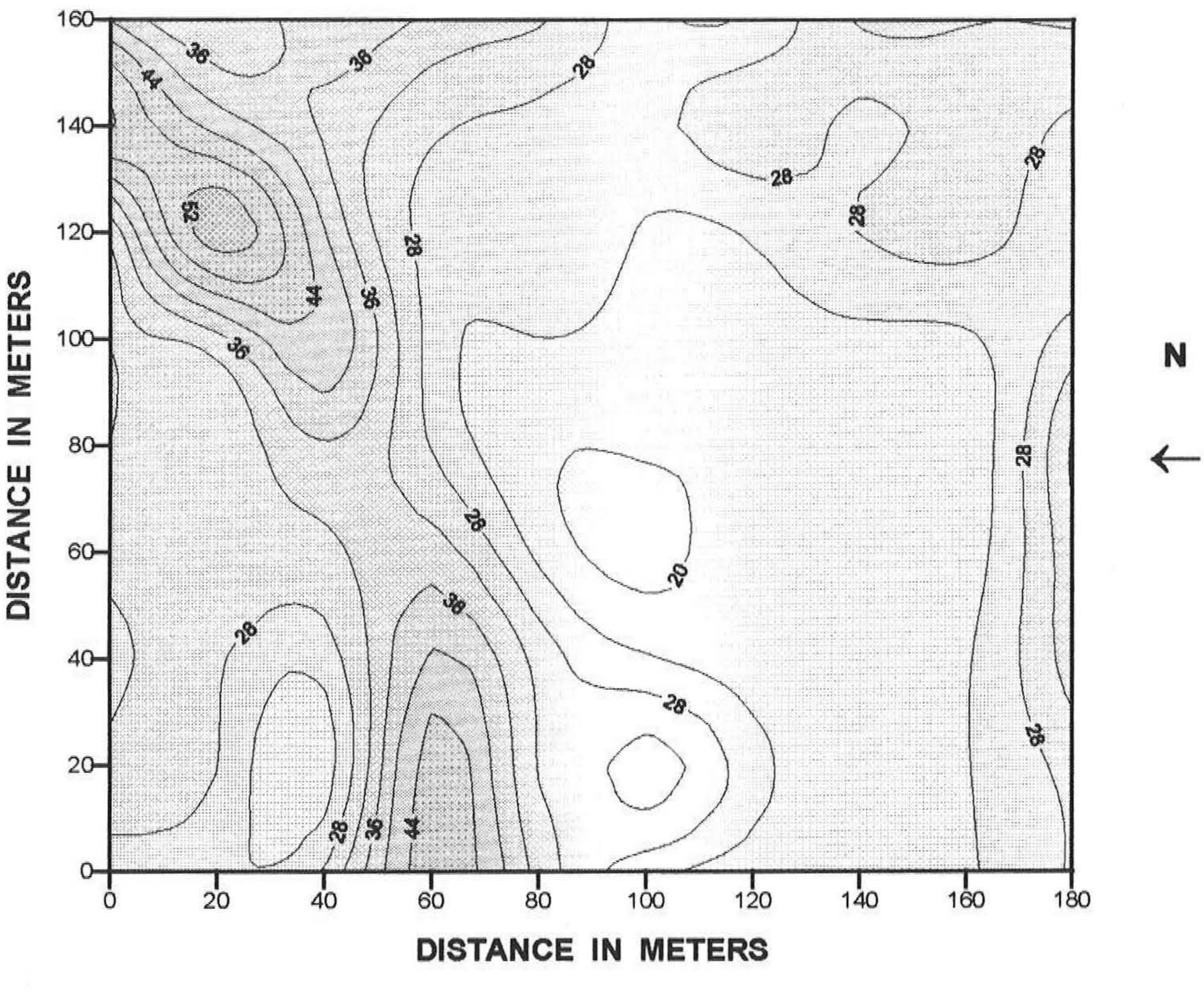


FIGURE 19

HARVEY COUNTY, KANSAS
SITE 5

EM31 METER
VERTICAL DIPOLE ORIENTATION

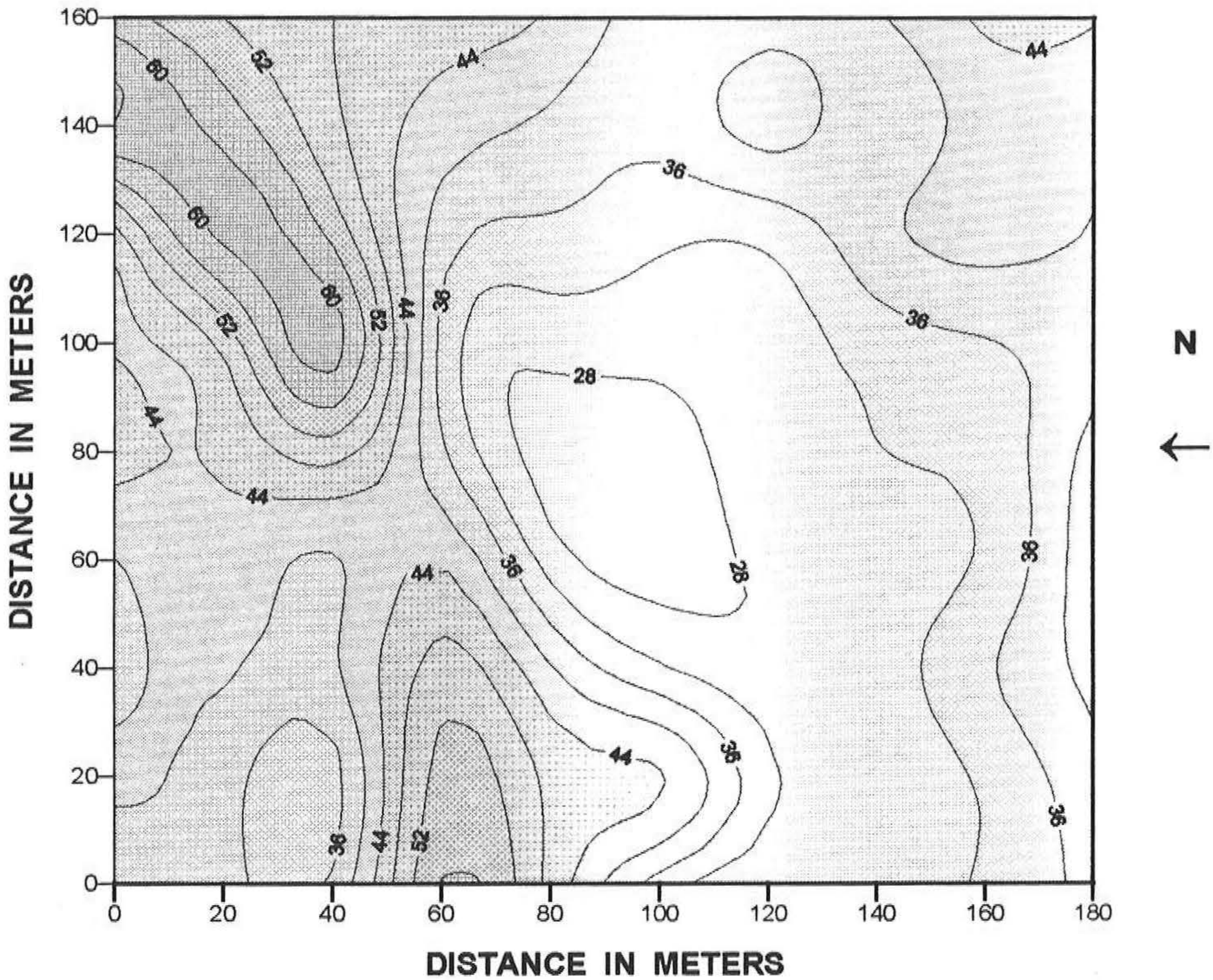


FIGURE 20

HARVEY COUNTY, KANSAS
SITE 7

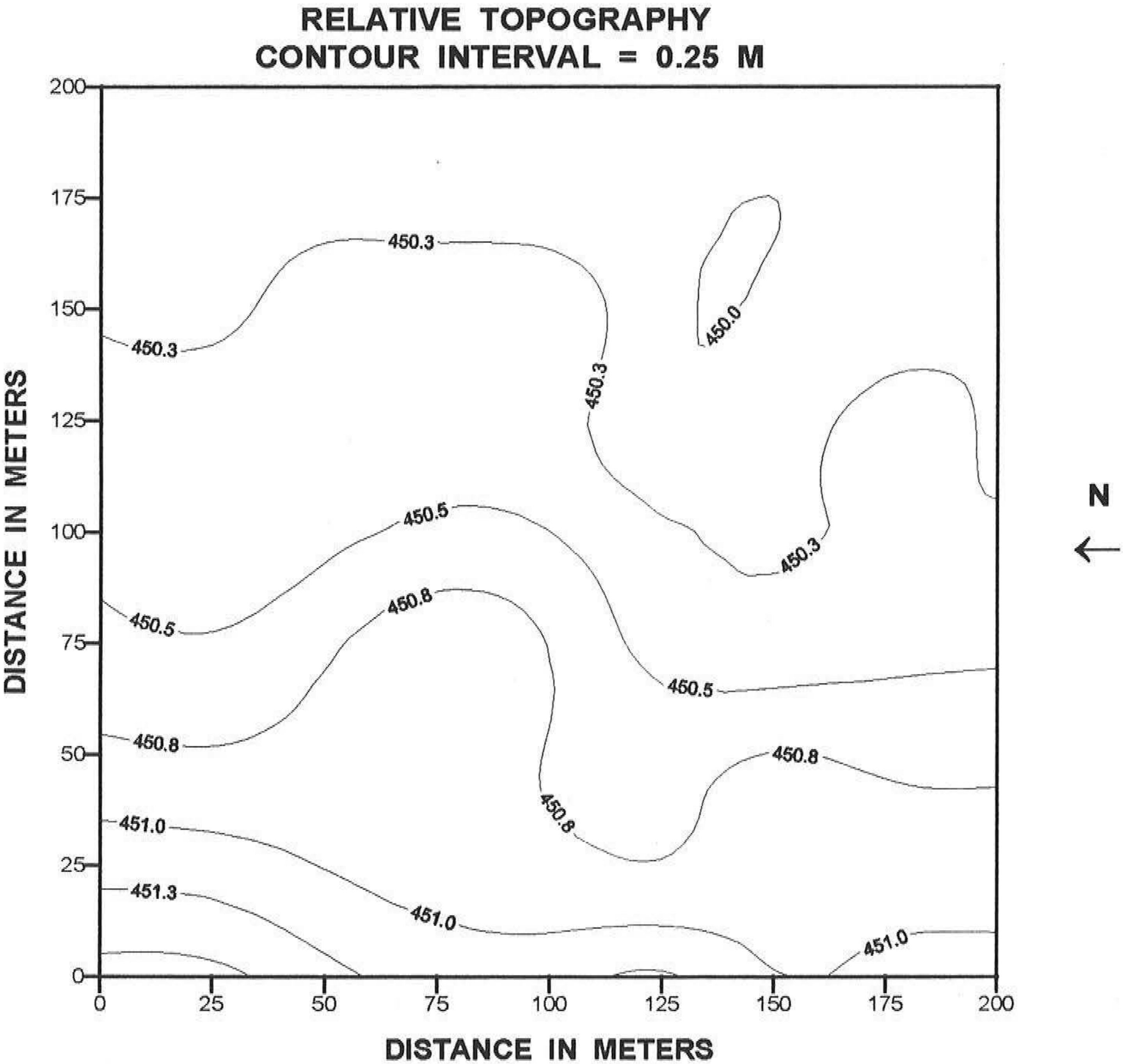


FIGURE 21

HARVEY COUNTY, KANSAS
SITE 7

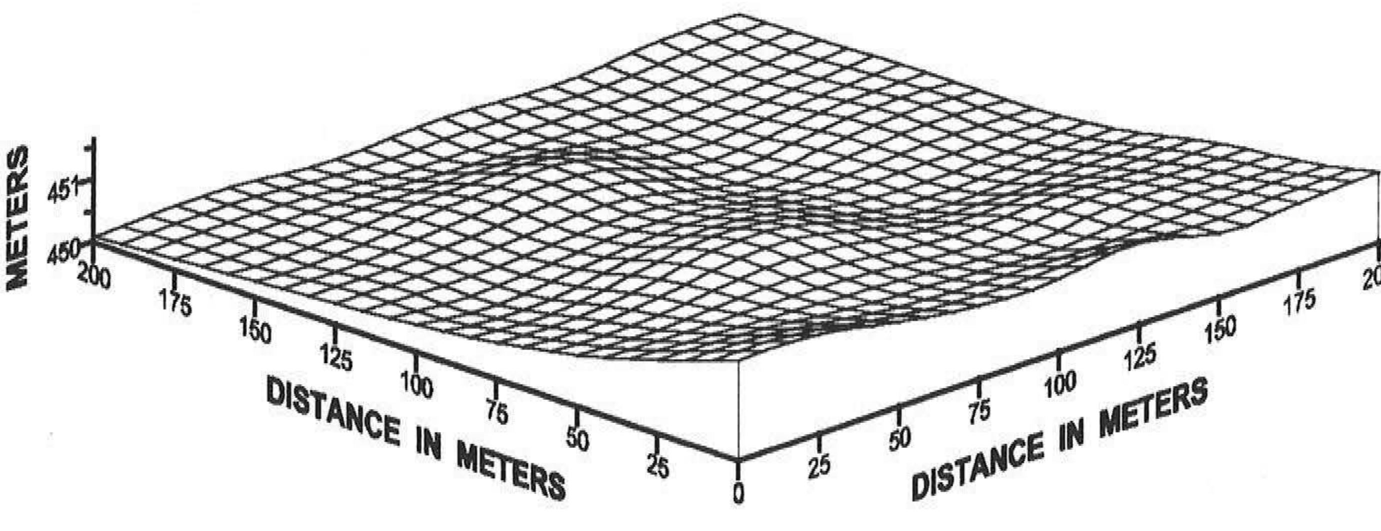


FIGURE 22

HARVEY COUNTY, KANSAS
SITE 7

EM38 METER
HORIZONTAL DIPOLE ORIENTATION

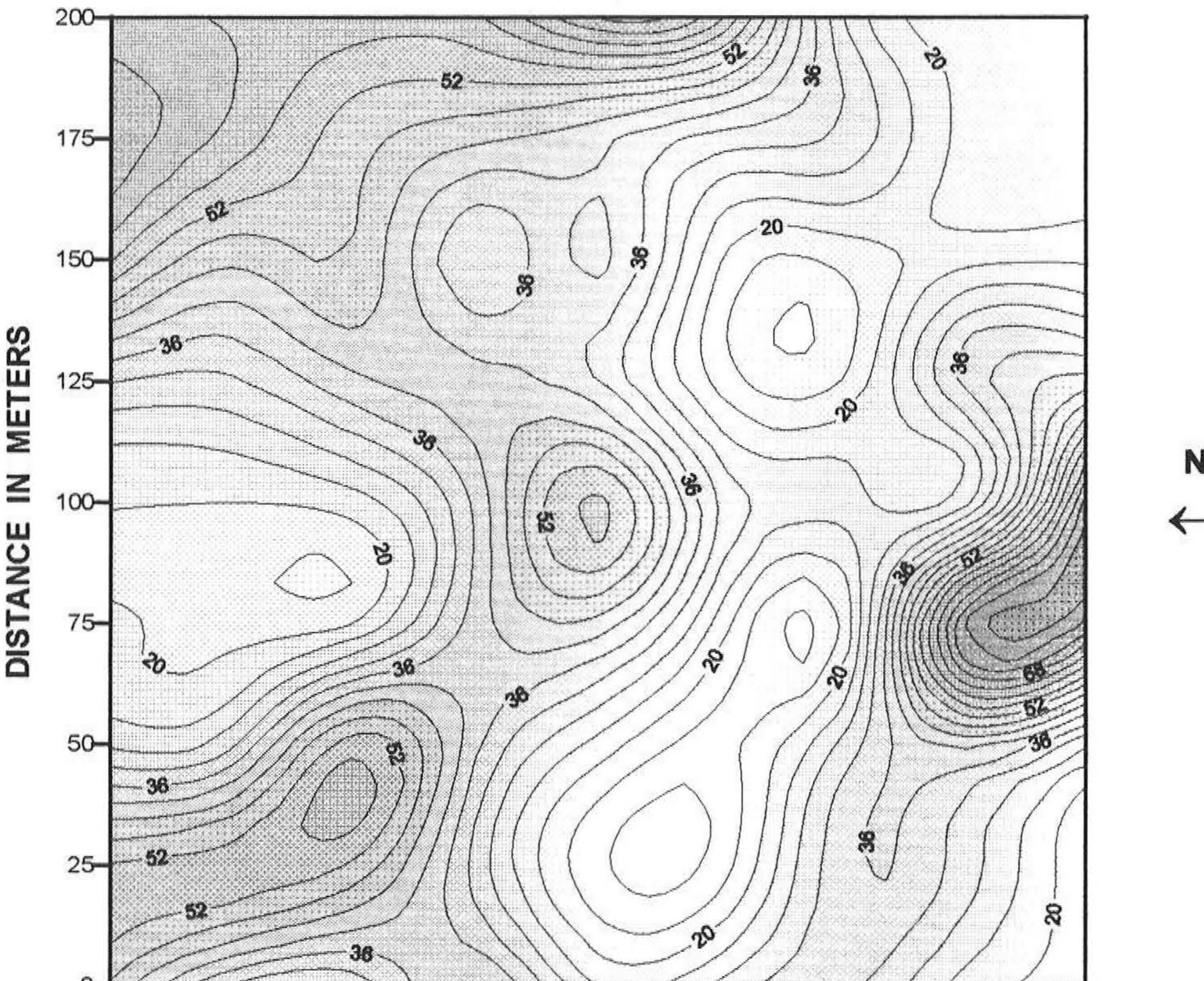


FIGURE 23

HARVEY COUNTY, KANSAS
SITE 7

EM38 METER
VERTICAL DIPOLE ORIENTATION

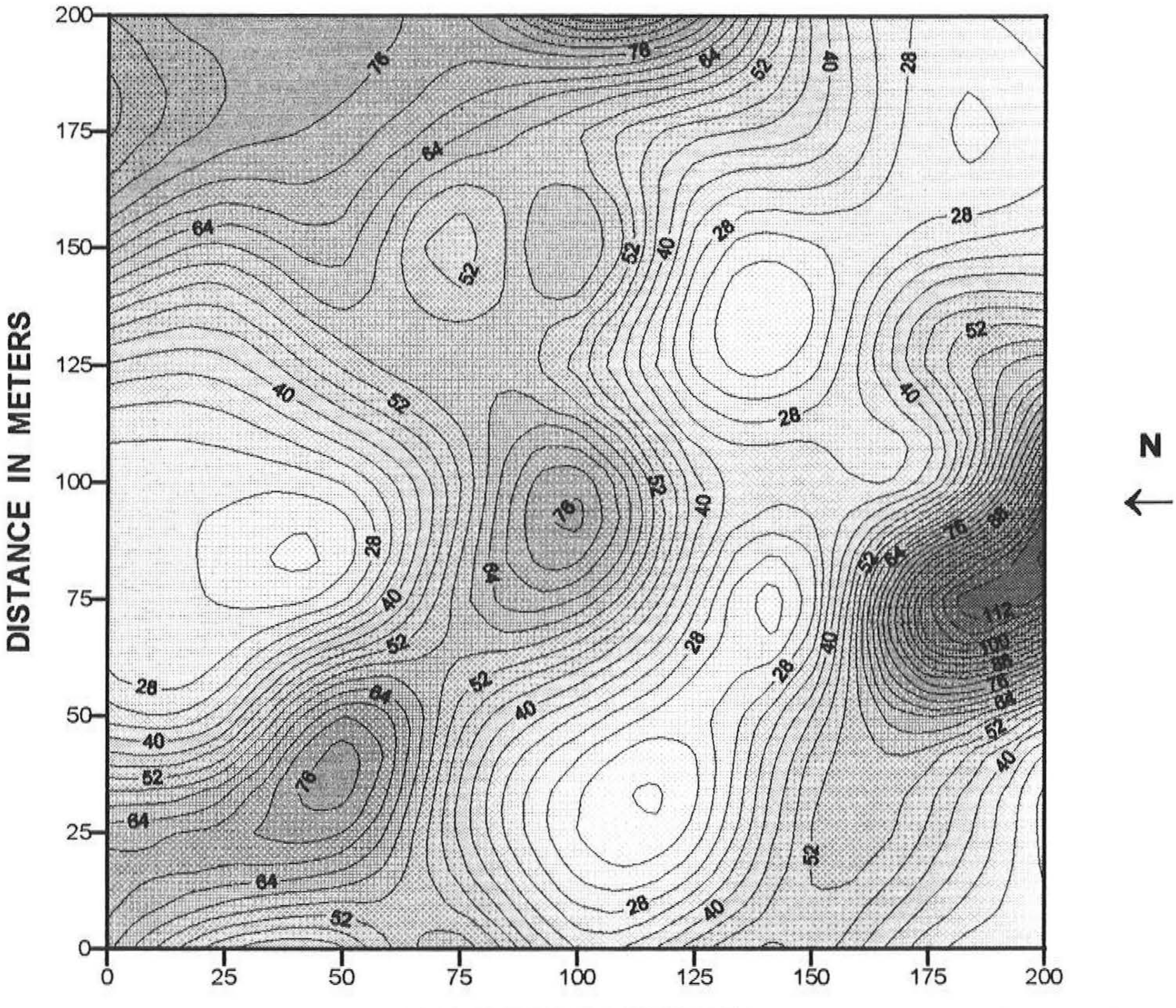


FIGURE 24

HARVEY COUNTY, KANSAS
SITE 7

EM31 METER
VERTICAL DIPOLE ORIENTATION

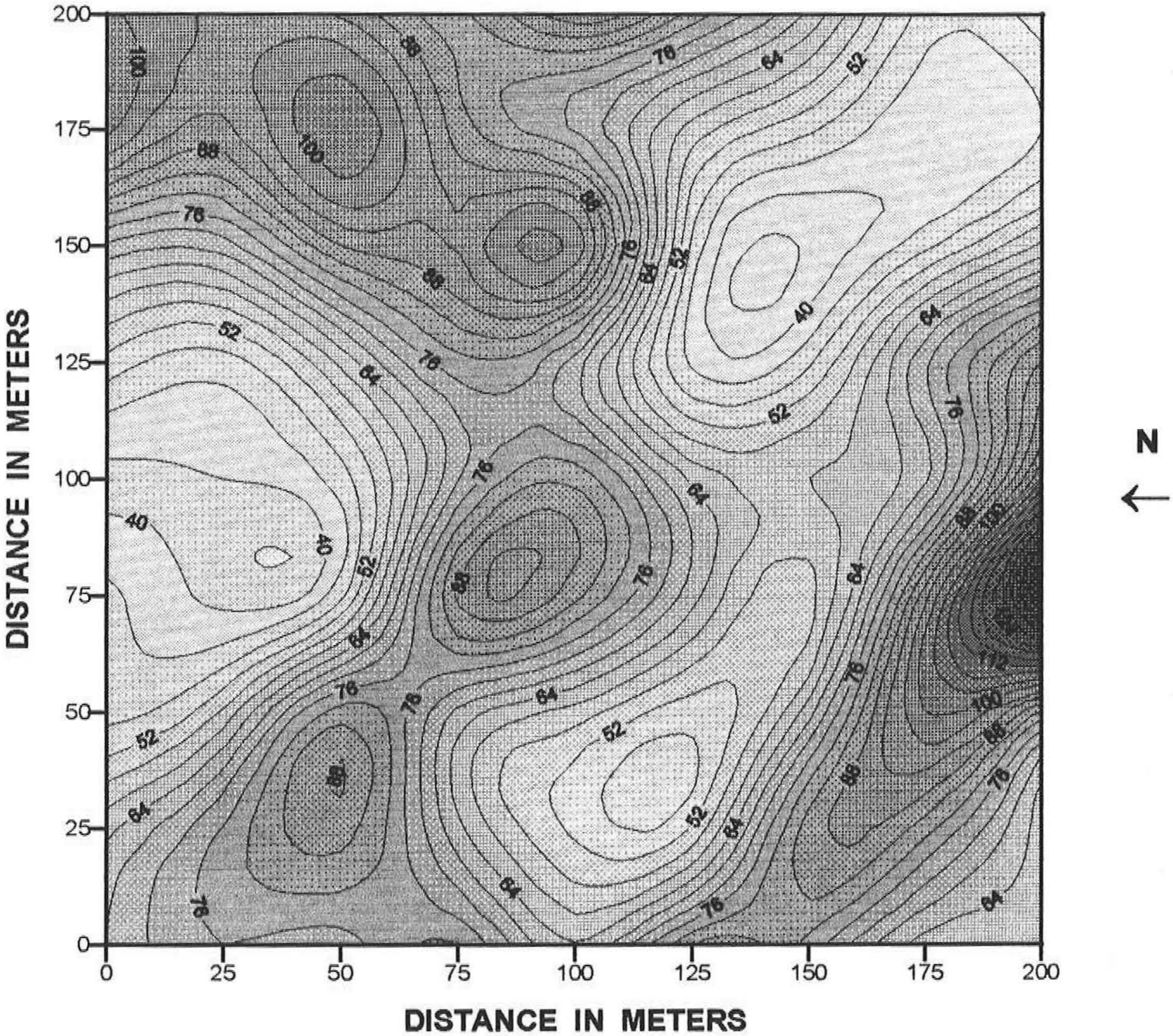


FIGURE 26

HARVEY COUNTY, KANSAS
SITE 7

EM31 METER
HORIZONTAL DIPOLE ORIENTATION

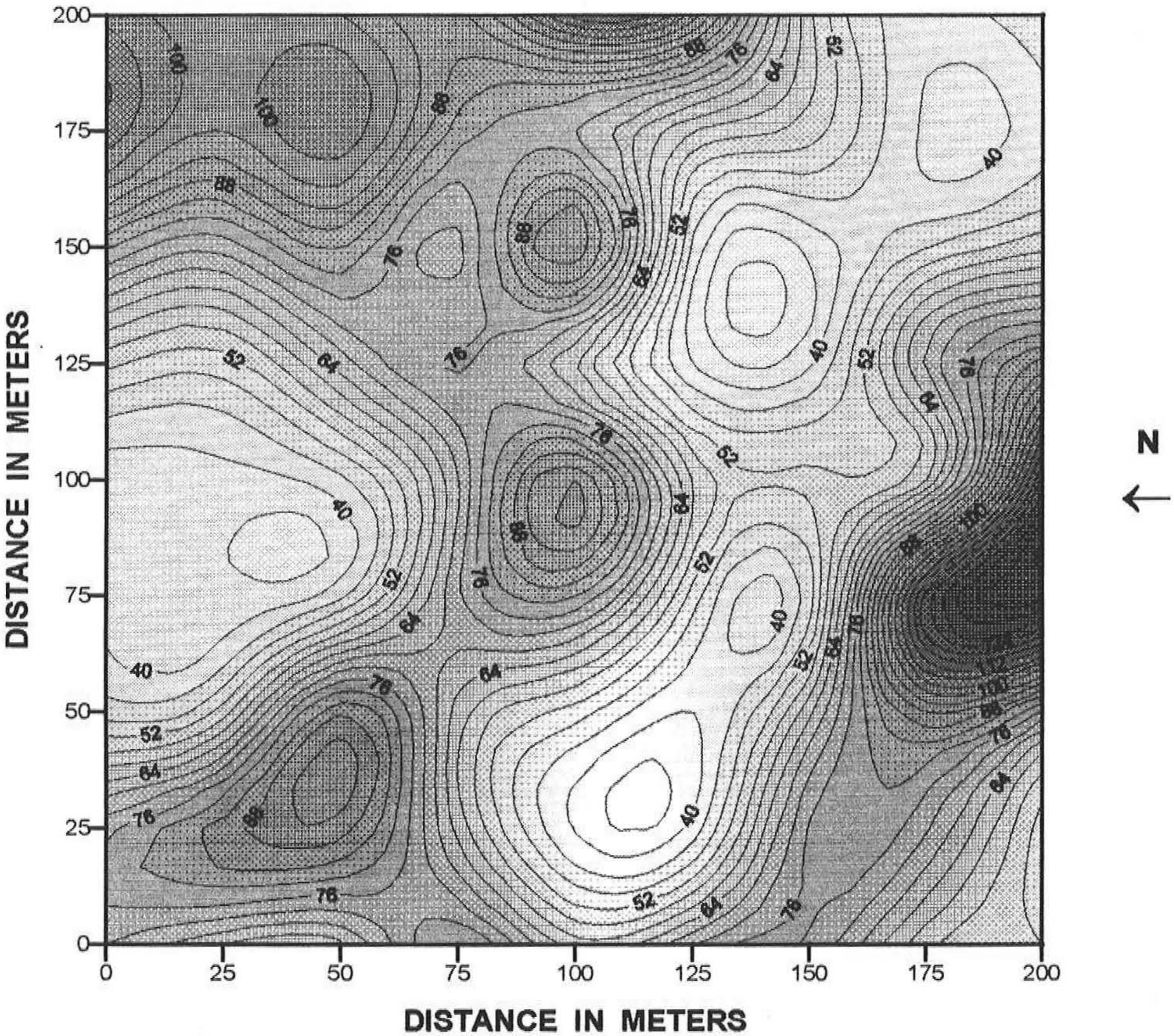


FIGURE 25

HARVEY COUNTY, KANSAS
SITE 8

RELATIVE TOPOGRAPHY
CONTOUR INTERVAL = 0.50 M

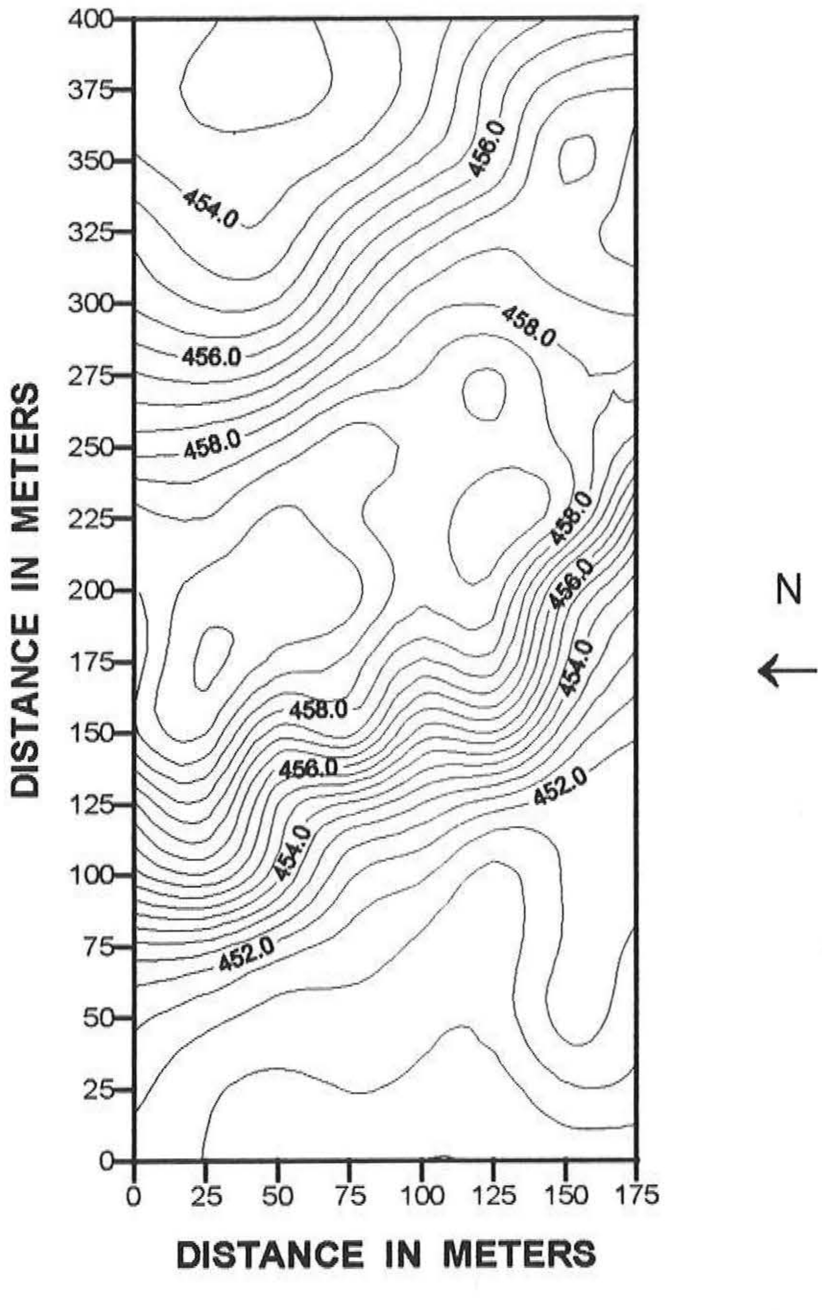


FIGURE 27

HARVEY COUNTY, KANSAS
SITE 8

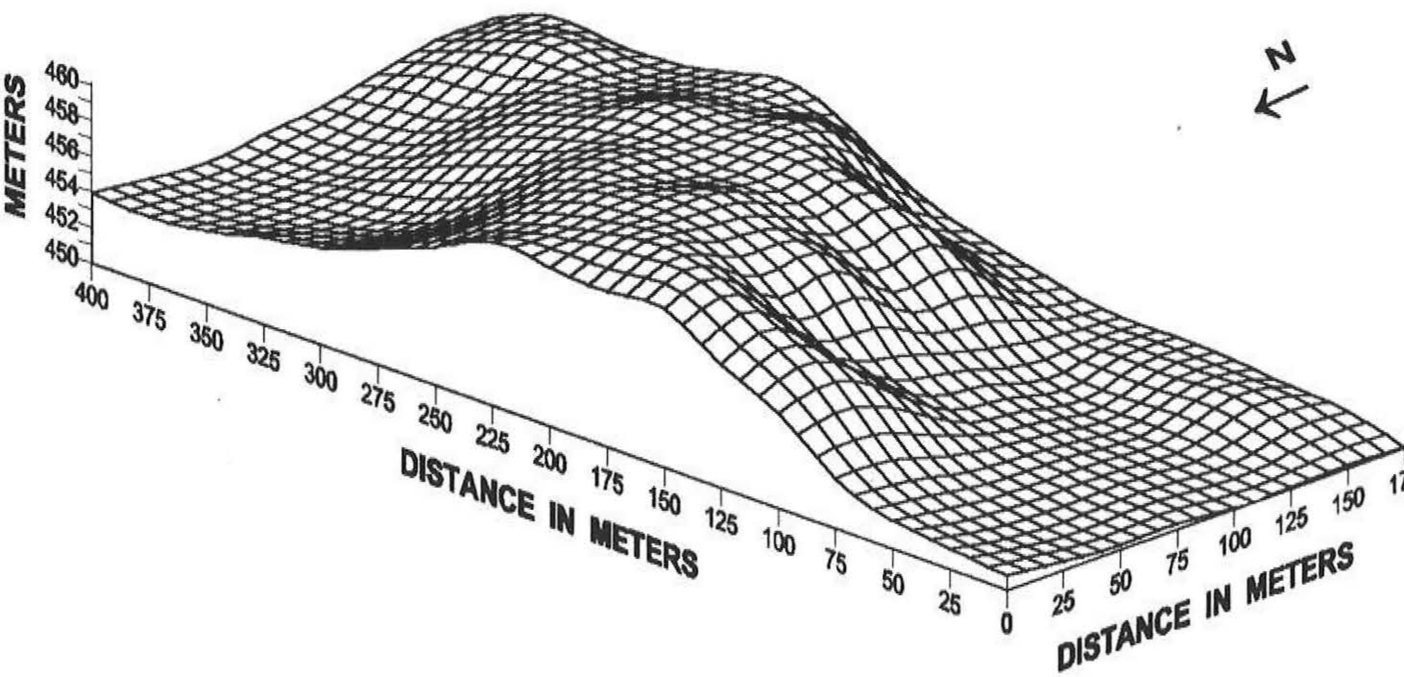


FIGURE 28

HARVEY COUNTY, KANSAS
SITE 8

EM38 METER
HORIZONTAL DIPOLE ORIENTATION

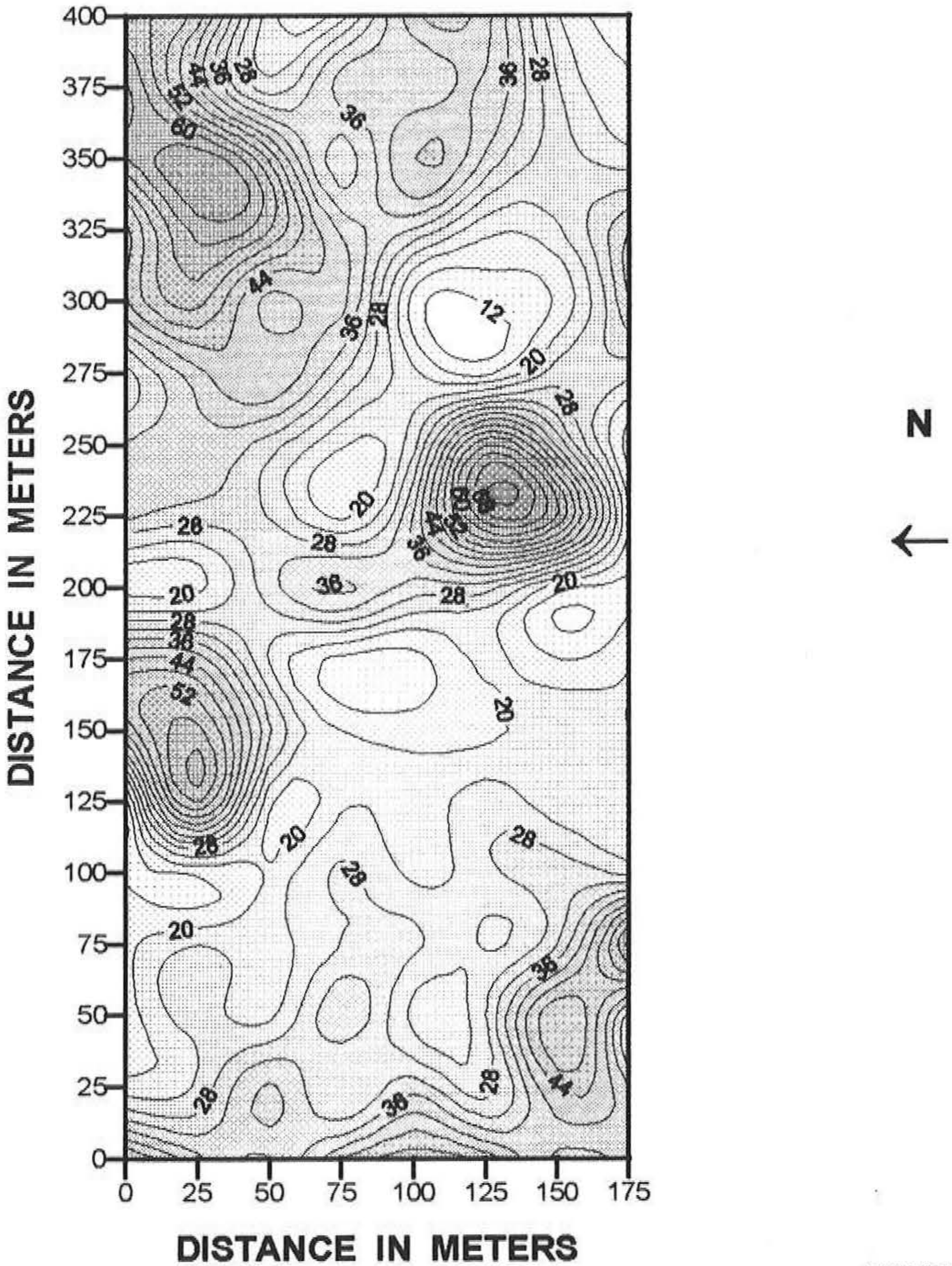


FIGURE 29

HARVEY COUNTY, KANSAS
SITE 8

EM31 METER
VERTICAL DIPOLE ORIENTATION

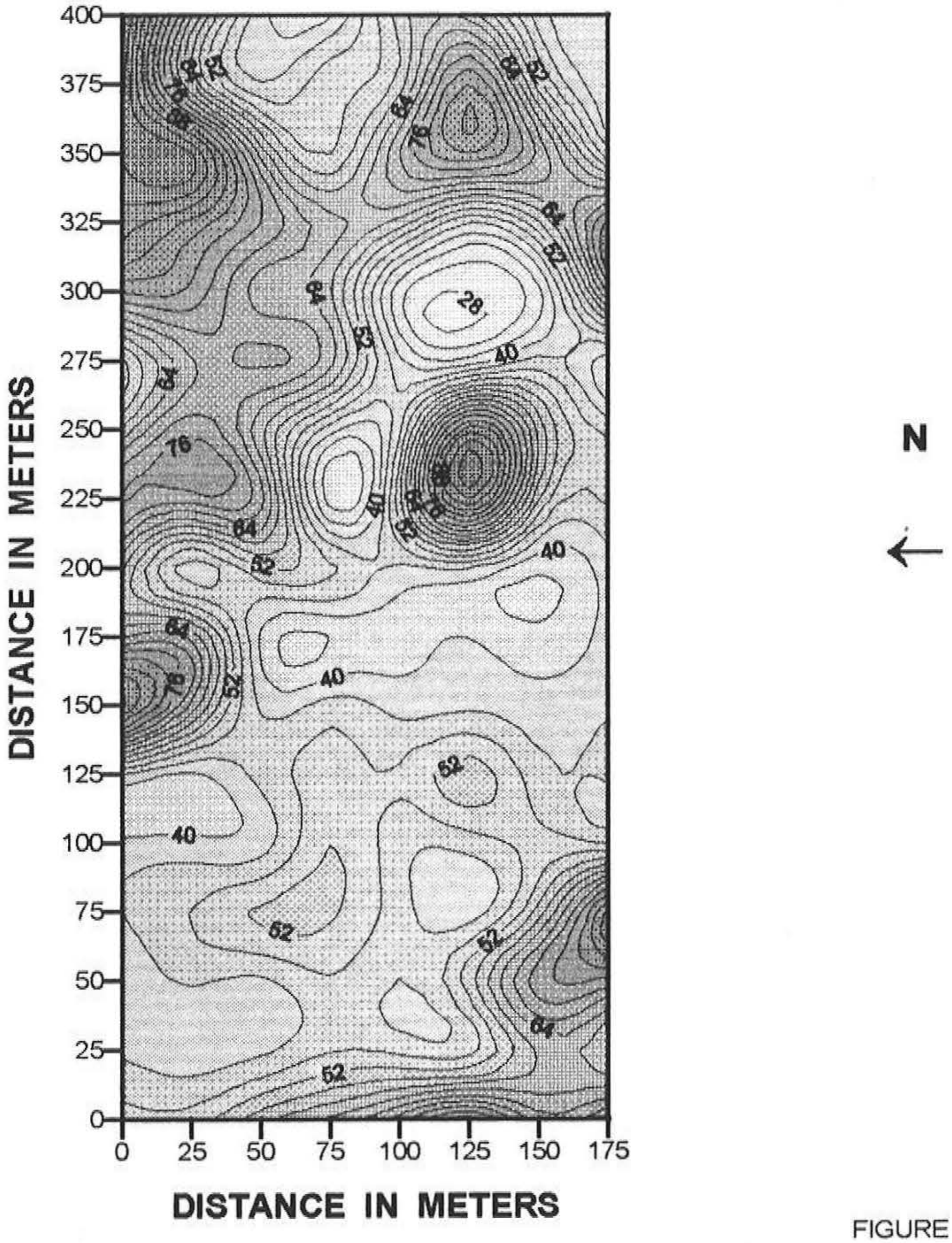


FIGURE 32

HARVEY COUNTY, KANSAS
SITE 8

EM31 METER
HORIZONTAL DIPOLE ORIENTATION

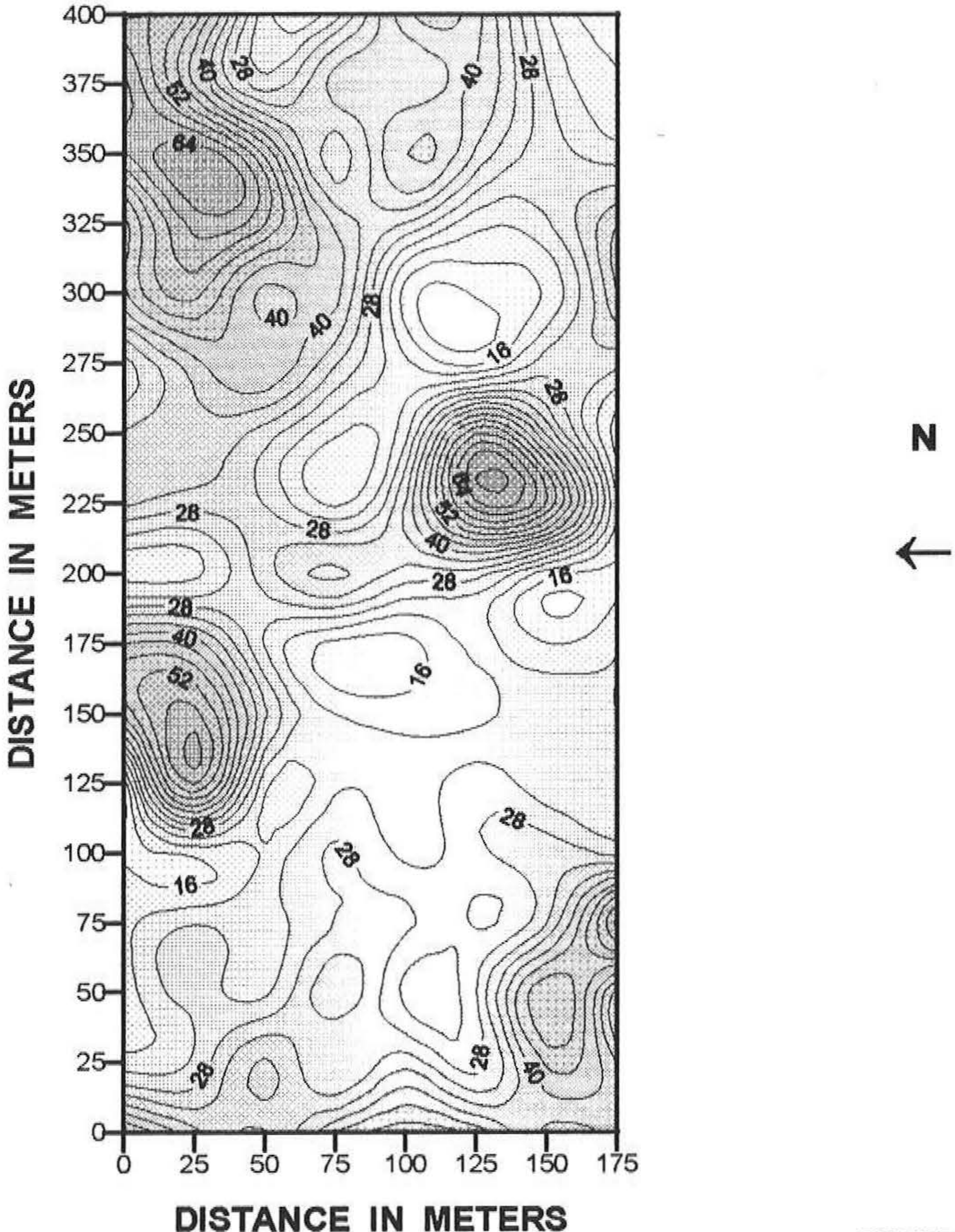


FIGURE 31

HARVEY COUNTY, KANSAS
SITE 8

EM38 METER
VERTICAL DIPOLE ORIENTATION

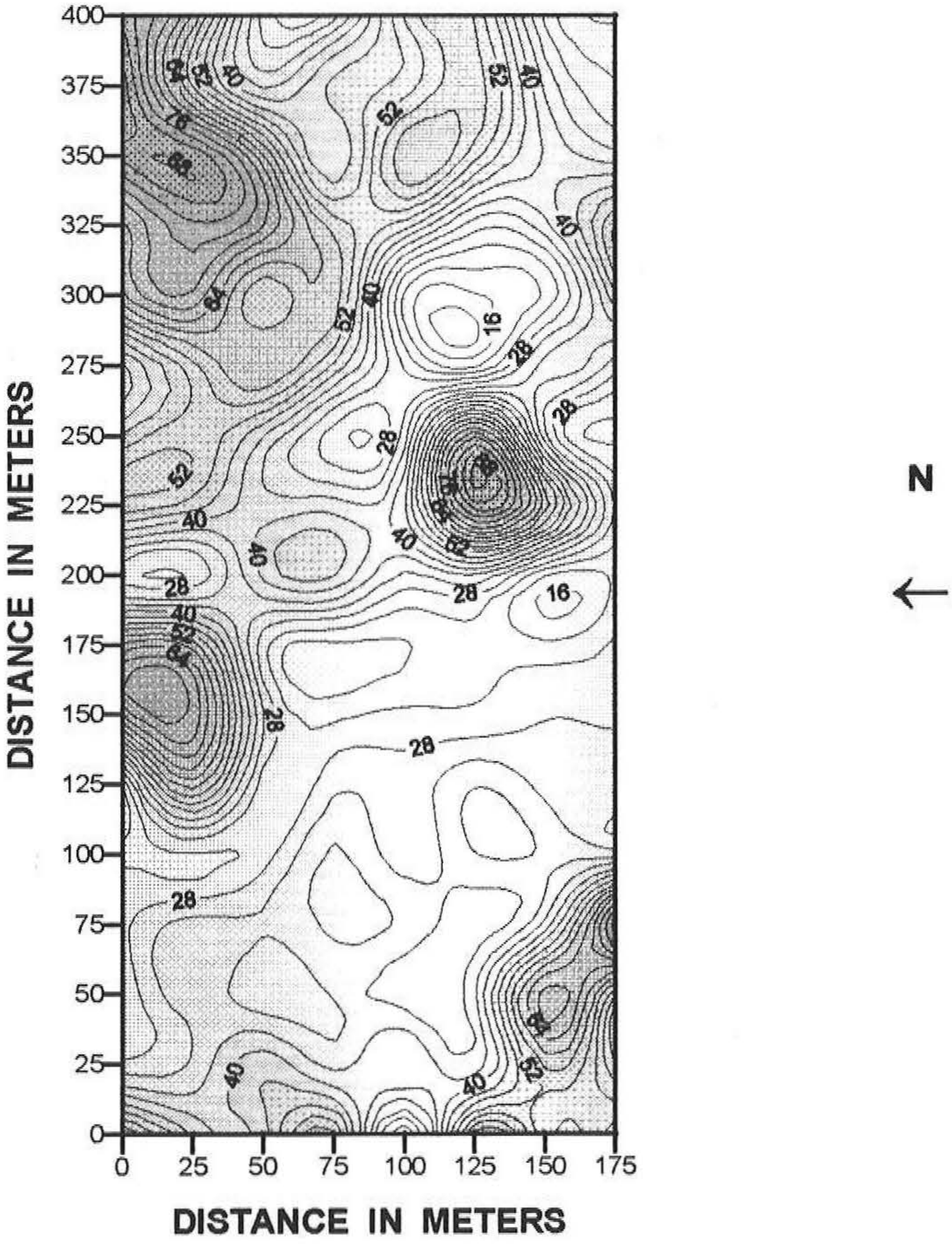


FIGURE 30

HARVEY COUNTY, KANSAS
SITE 10

RELATIVE TOPOGRAPHY
CONTOUR INTERVAL = 0.25 M

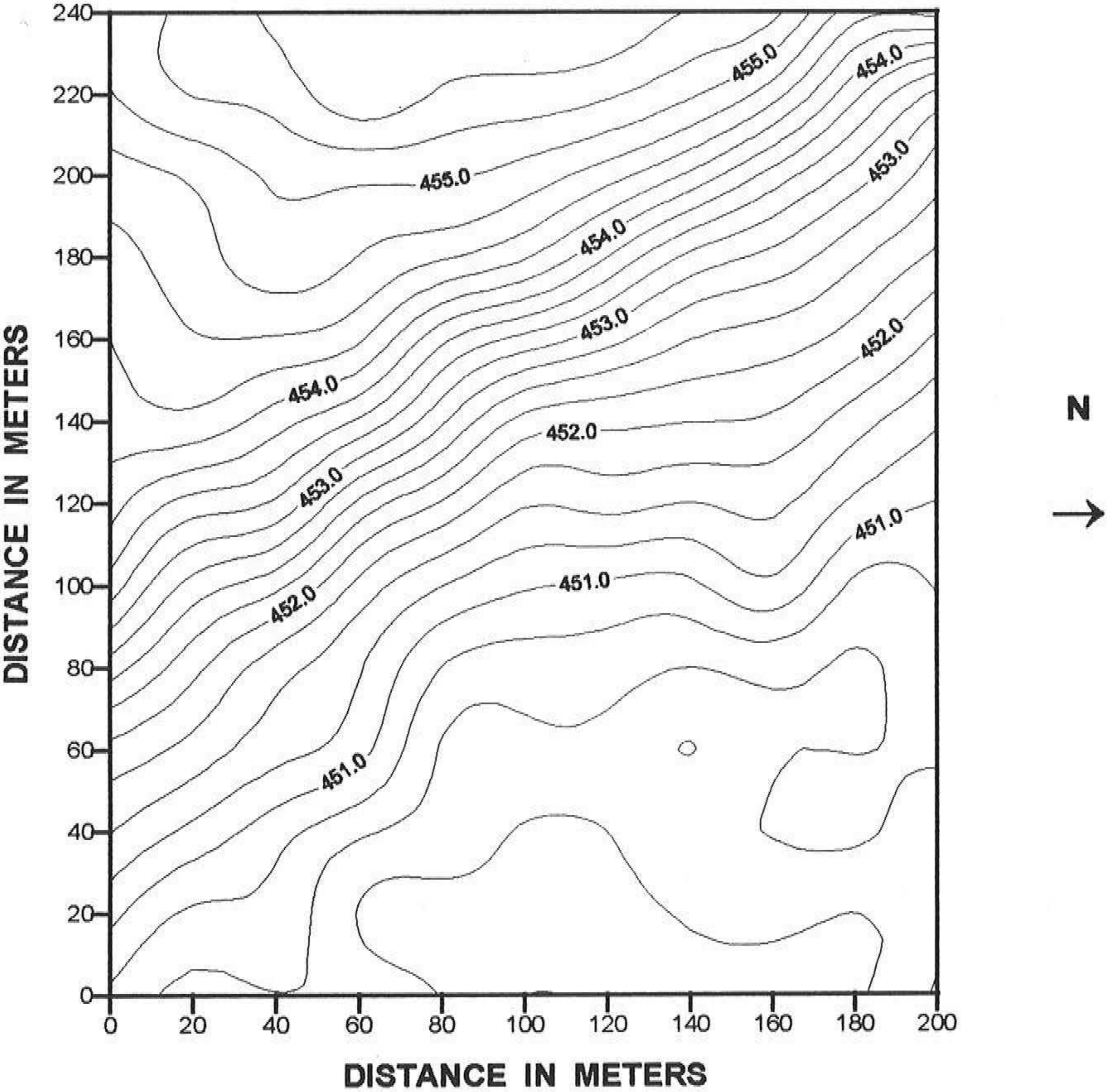


FIGURE 33

HARVEY COUNTY, KANSAS
SITE 10

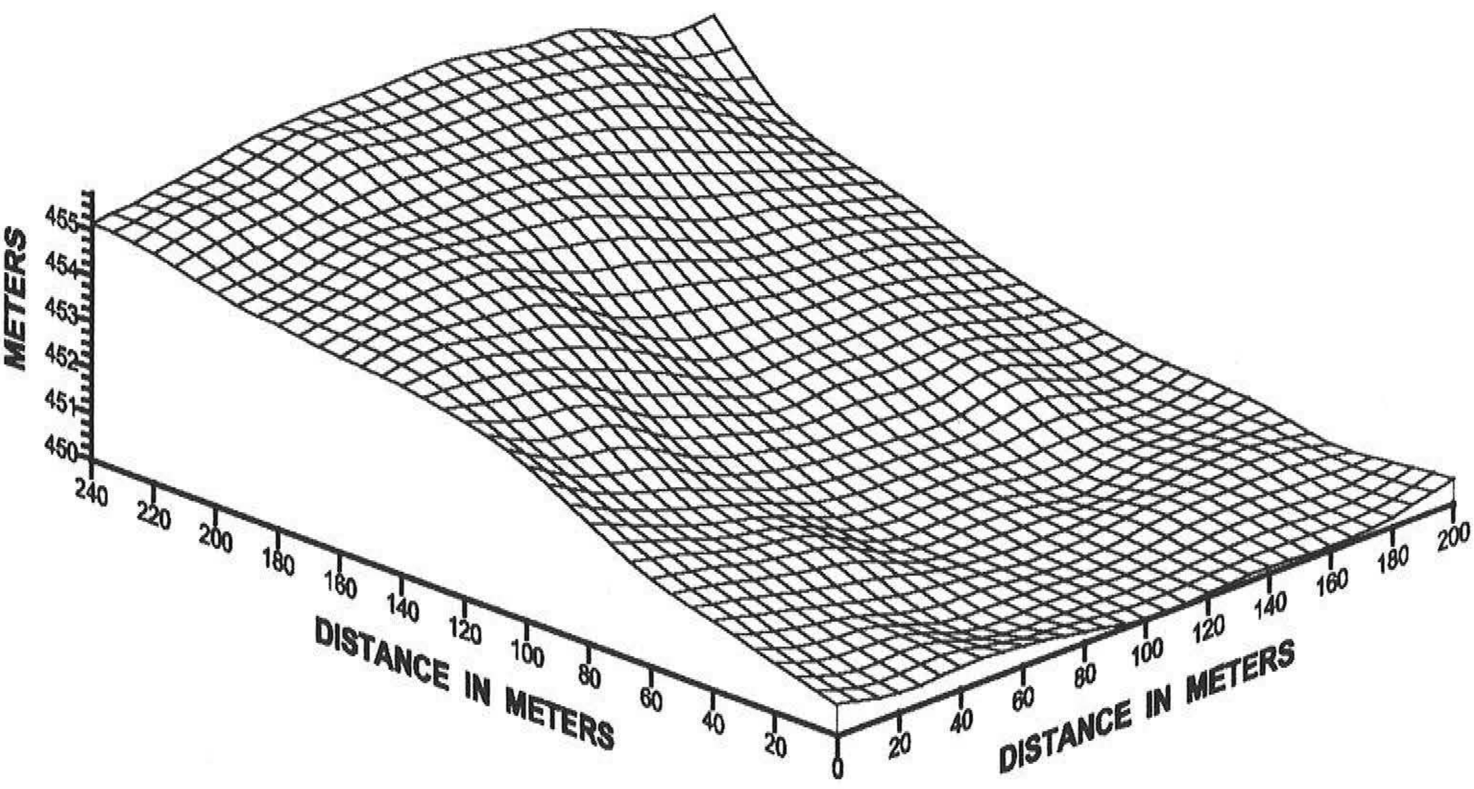


FIGURE 34

HARVEY COUNTY, KANSAS
SITE 10

EM38 METER
HORIZONTAL DIPOLE ORIENTATION

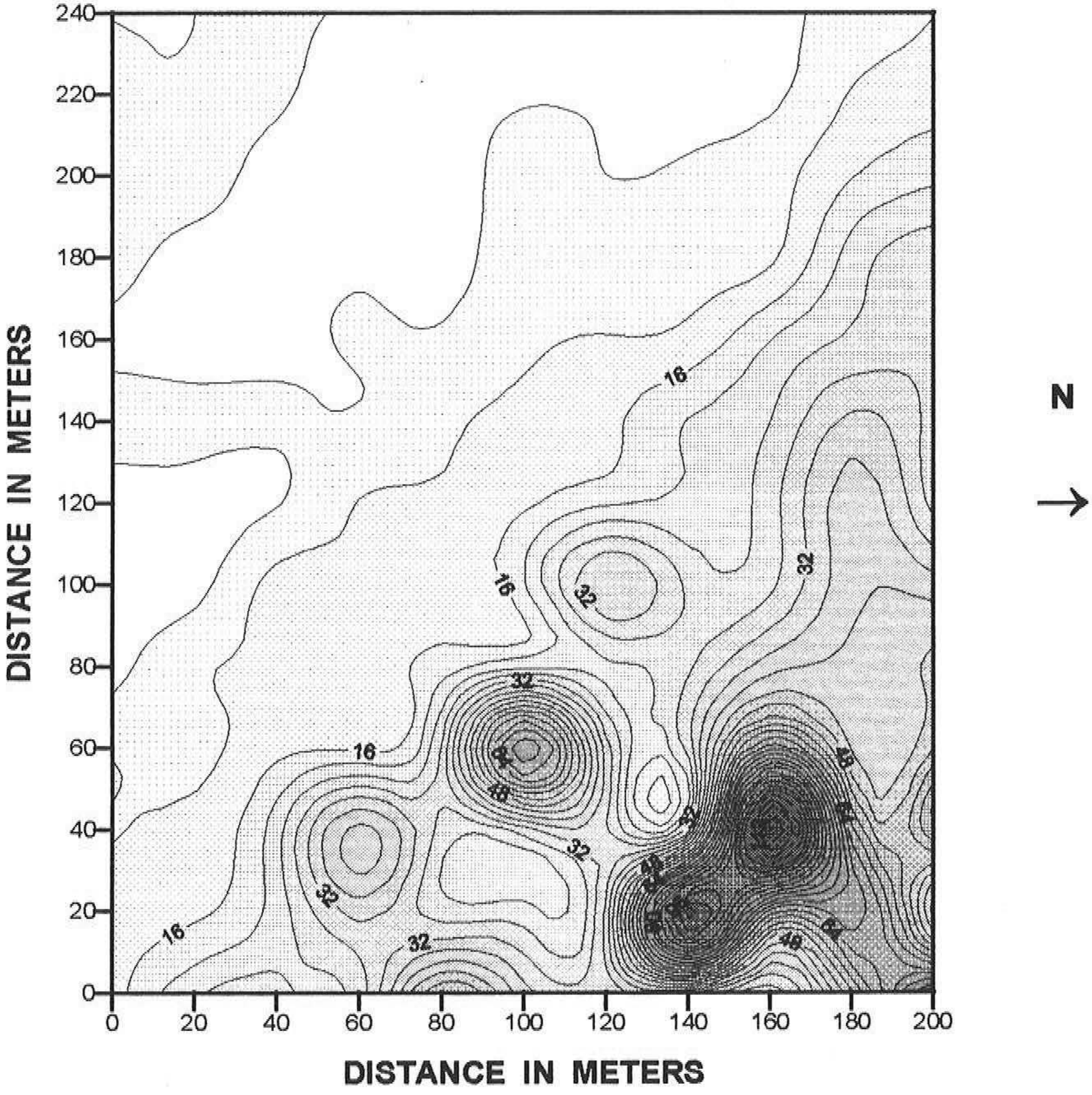


FIGURE 35

HARVEY COUNTY, KANSAS
SITE 10

EM38 METER
VERTICAL DIPOLE ORIENTATION

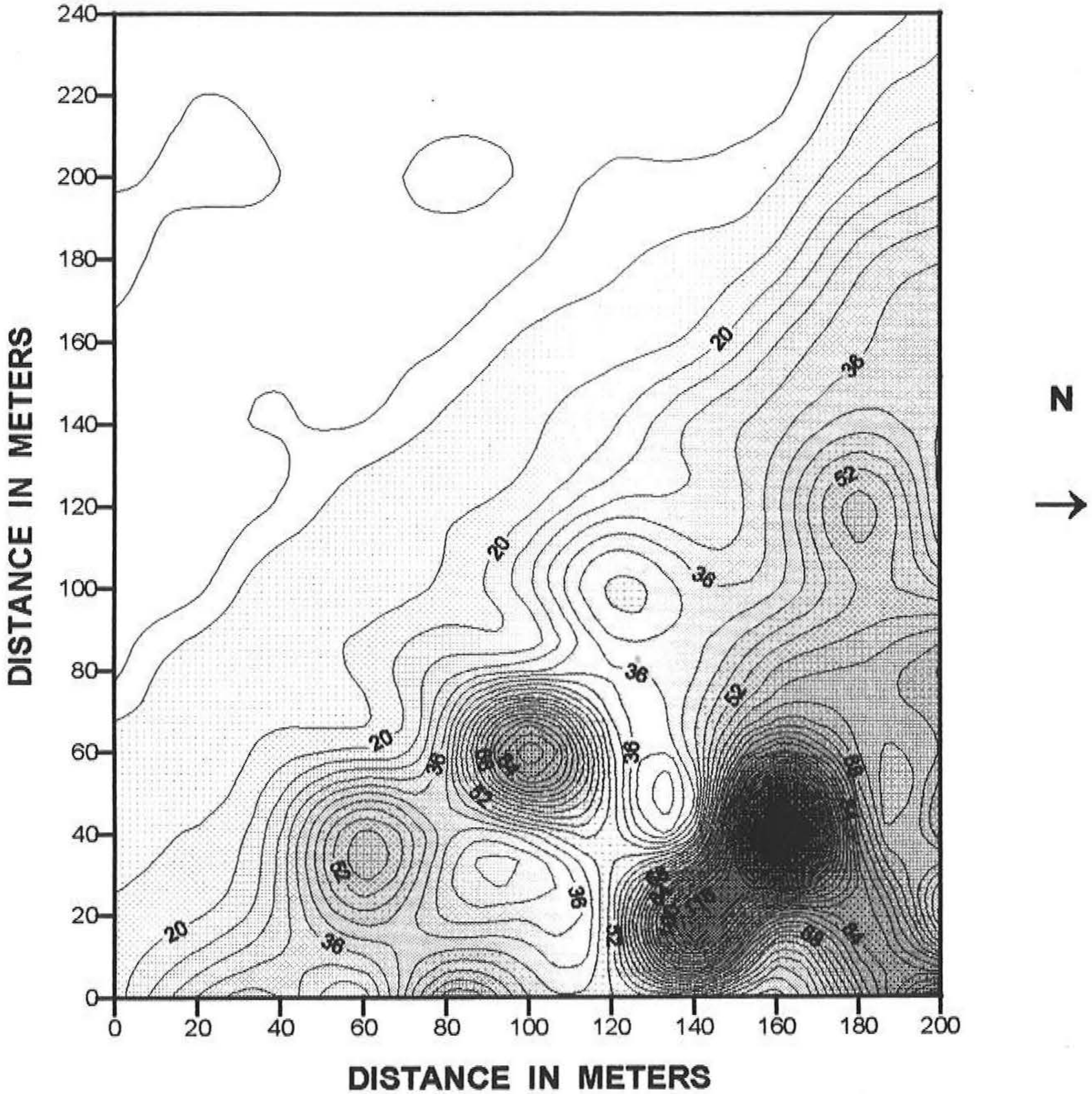


FIGURE 36

HARVEY COUNTY, KANSAS
SITE 10

EM31 METER
HORIZONTAL DIPOLE ORIENTATION

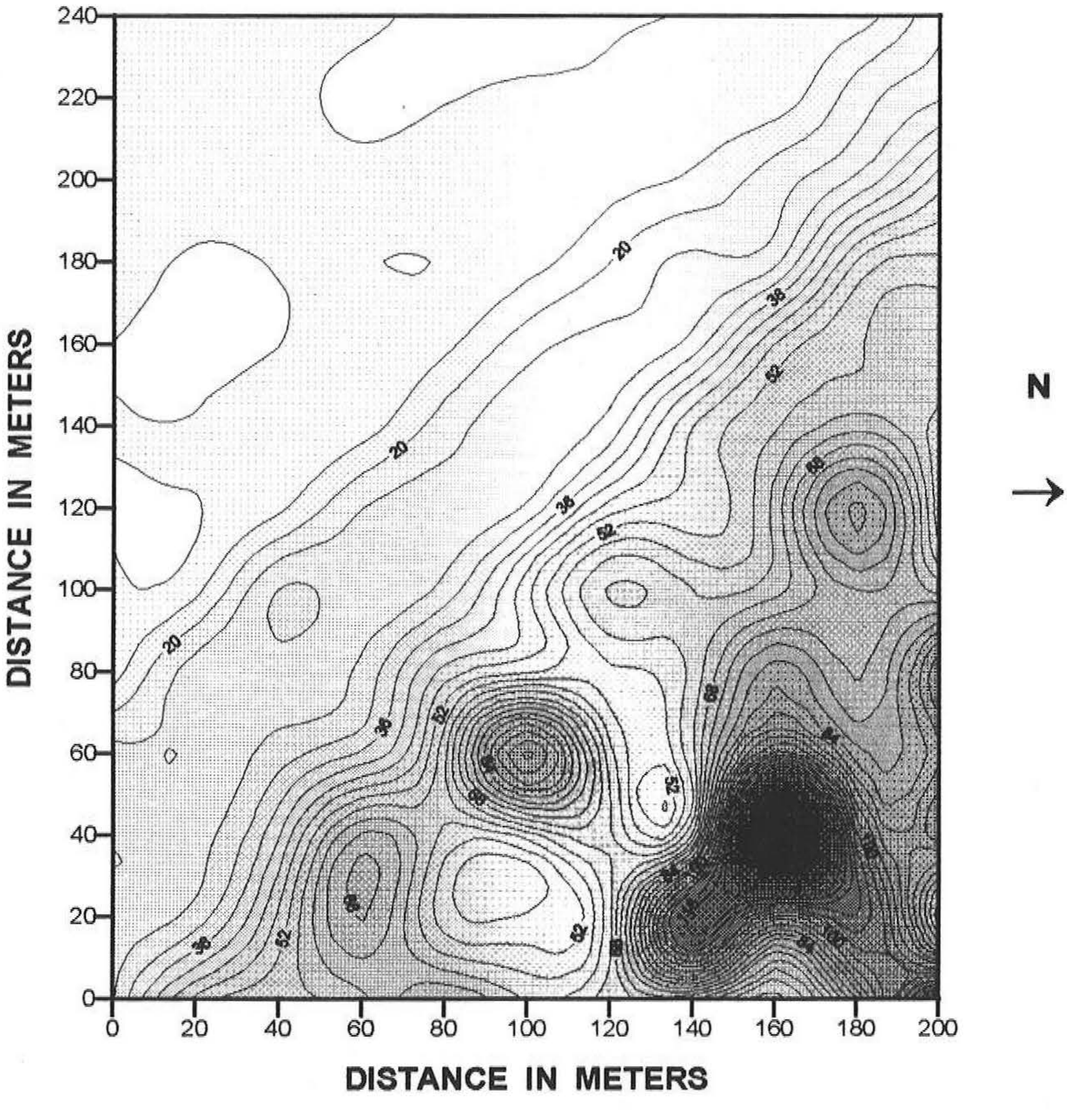


FIGURE 37

HARVEY COUNTY, KANSAS
SITE 10

EM31 METER
VERTICAL DIPOLE ORIENTATION

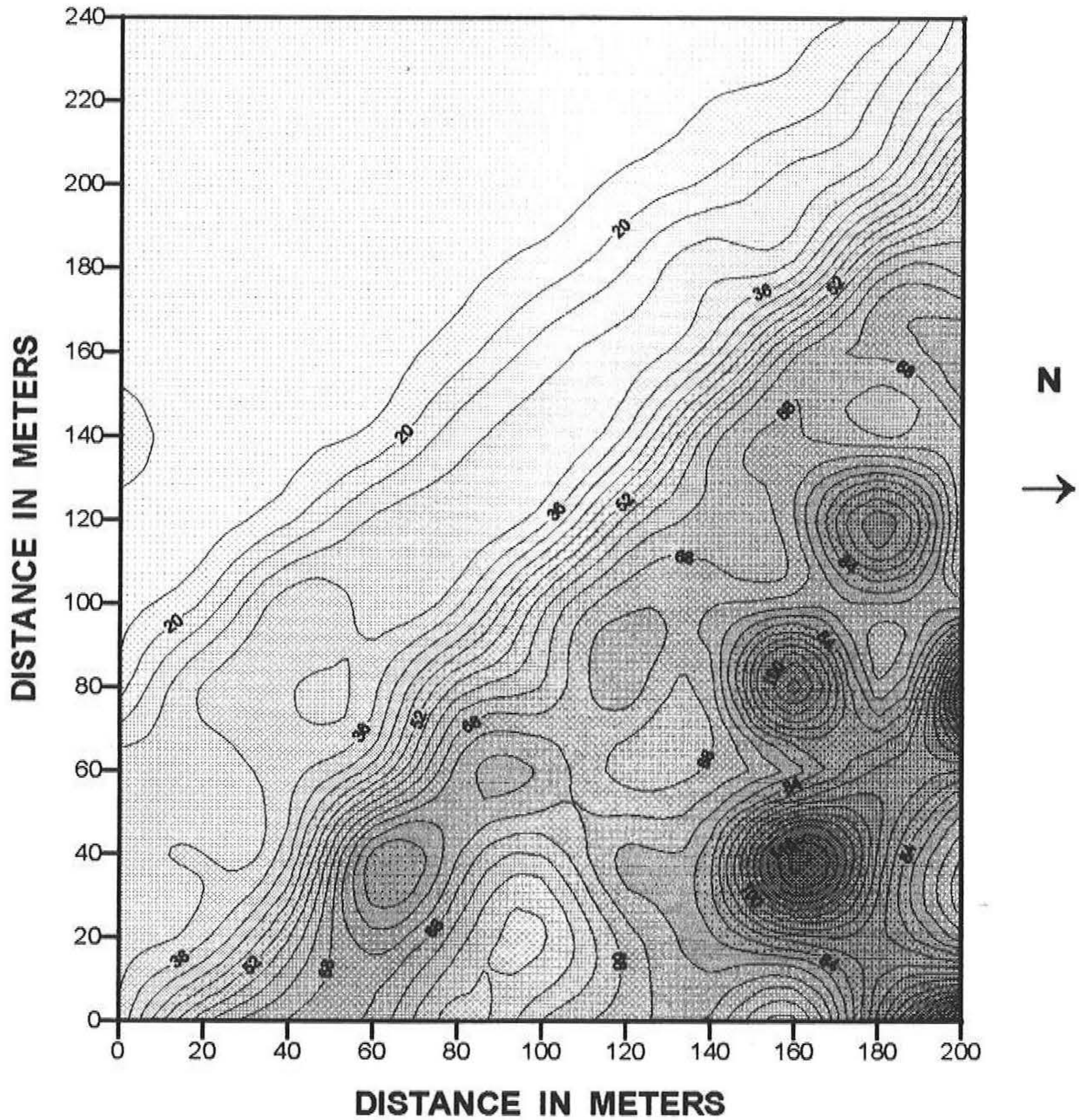


FIGURE 38

HARVEY COUNTY, KANSAS
SITE 12

RELATIVE TOPOGRAPHY
CONTOUR INTERVAL = 0.25 M

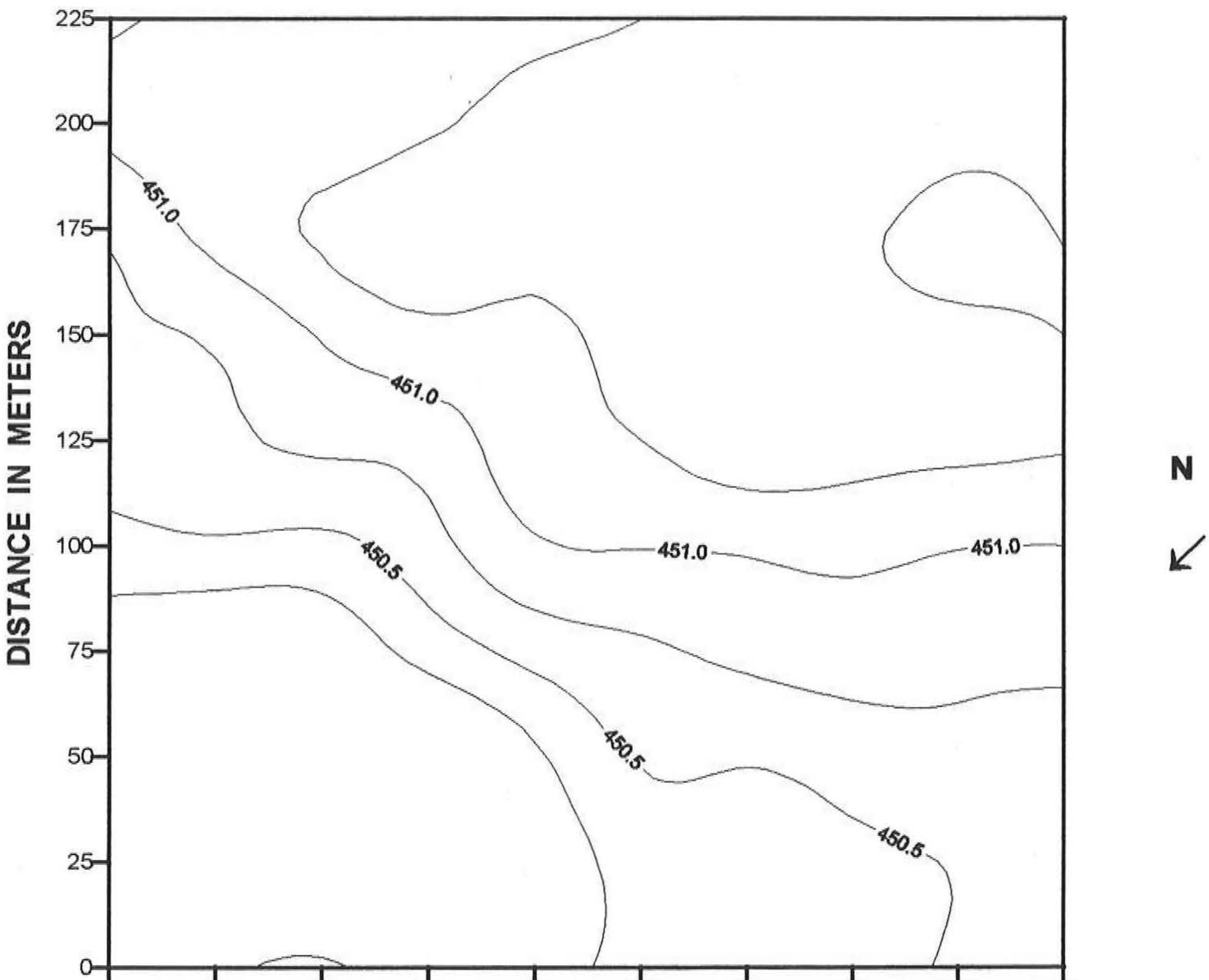


FIGURE 39

HARVEY COUNTY, KANSAS
SITE 12

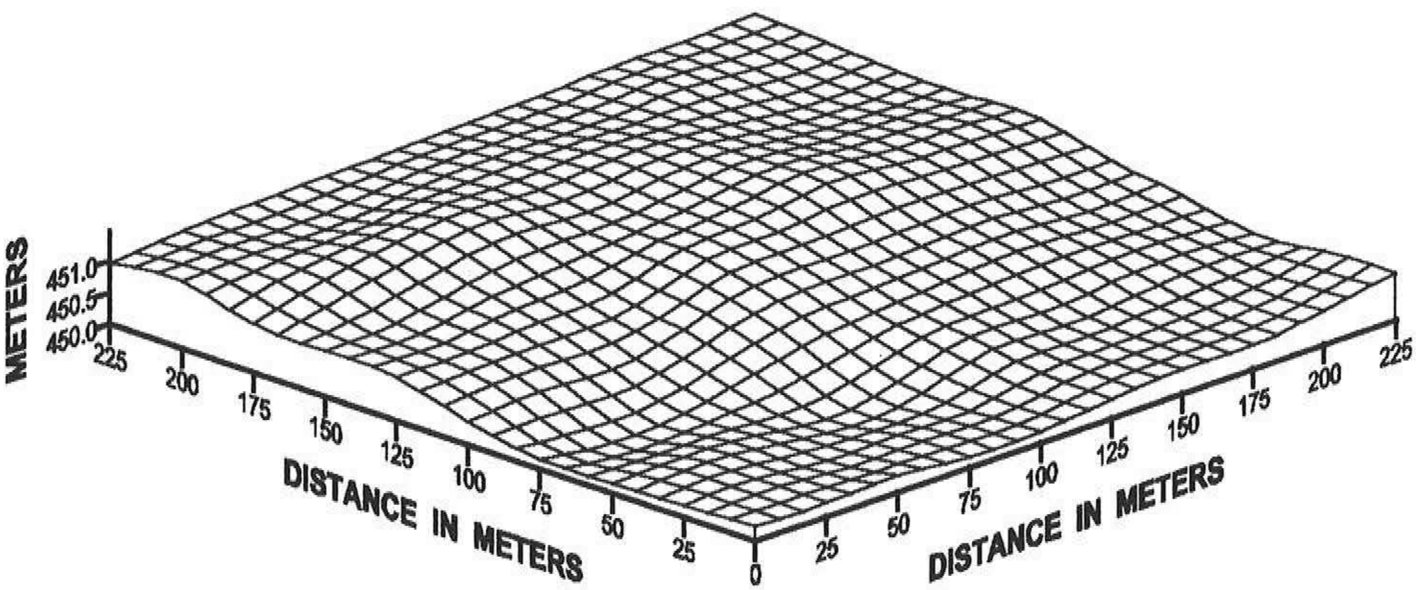


FIGURE 40

HARVEY COUNTY, KANSAS
SITE 12

EM38 METER
HORIZONTAL DIPOLE ORIENTATION

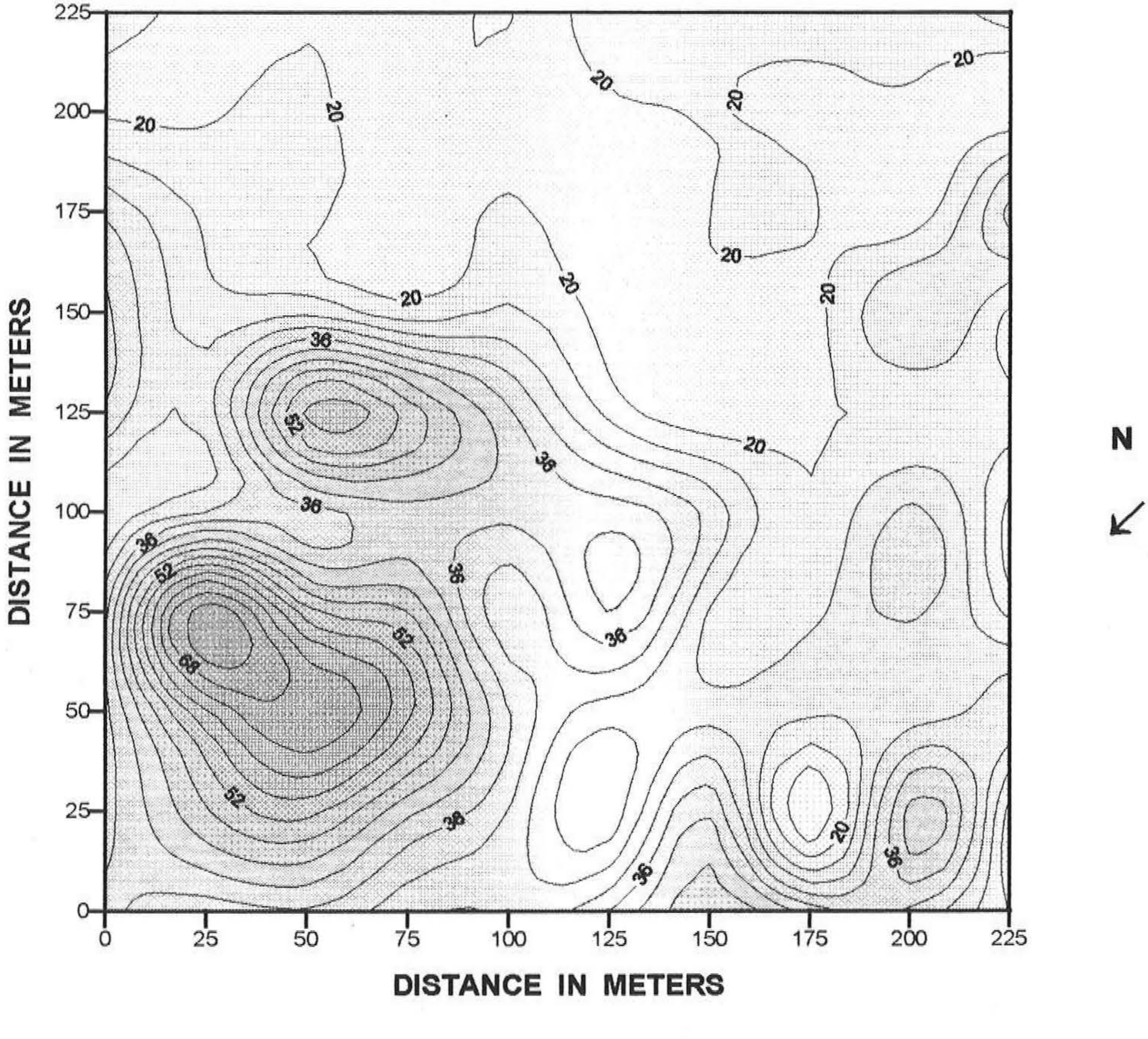


FIGURE 41

HARVEY COUNTY, KANSAS
SITE 12

EM38 METER
VERTICAL DIPOLE ORIENTATION

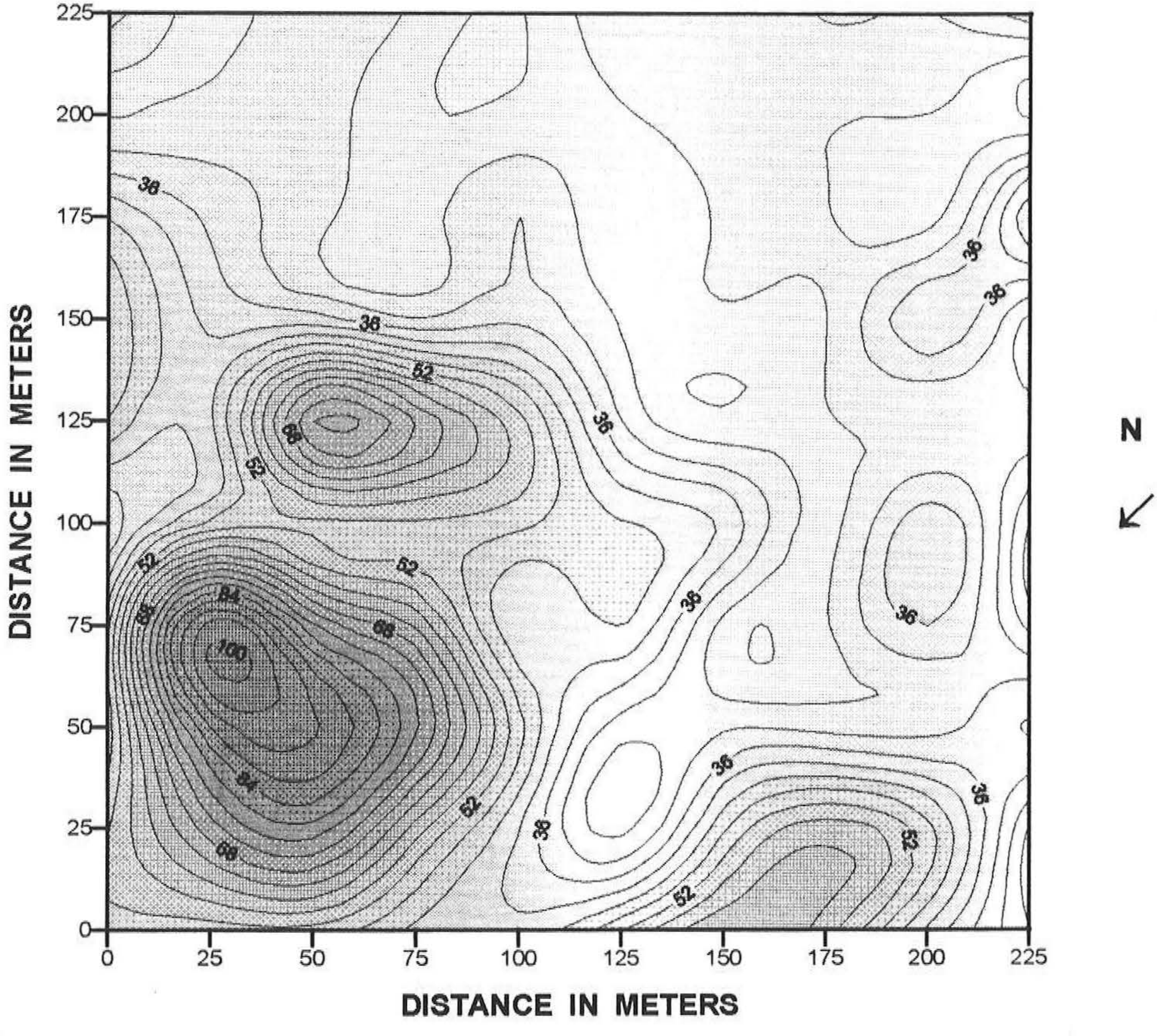


FIGURE 42

HARVEY COUNTY, KANSAS
SITE 12

EM31 METER
HORIZONTAL DIPOLE ORIENTATION

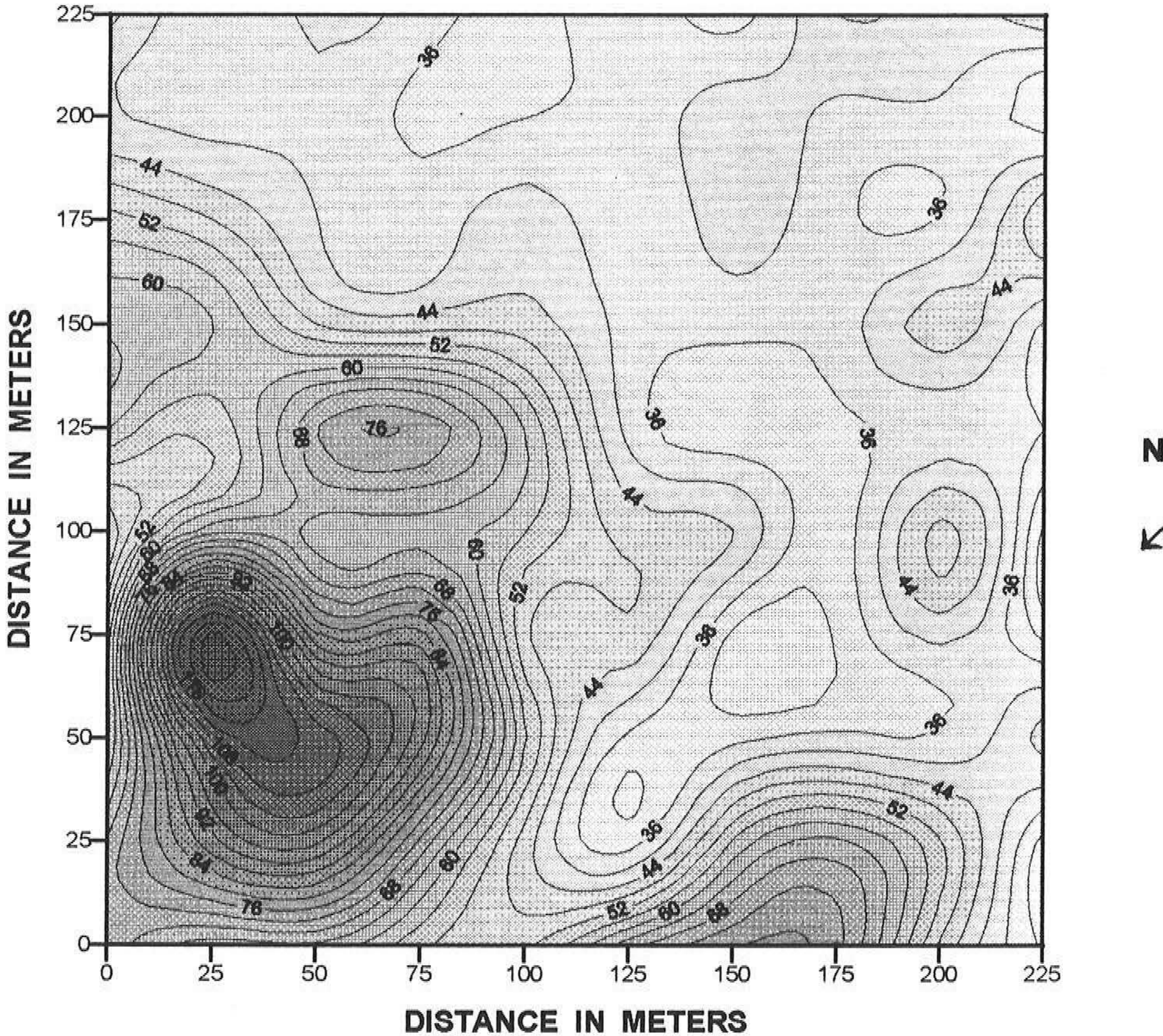


FIGURE 43

HARVEY COUNTY, KANSAS
SITE 12

EM31 METER
VERTICAL DIPOLE ORIENTATION

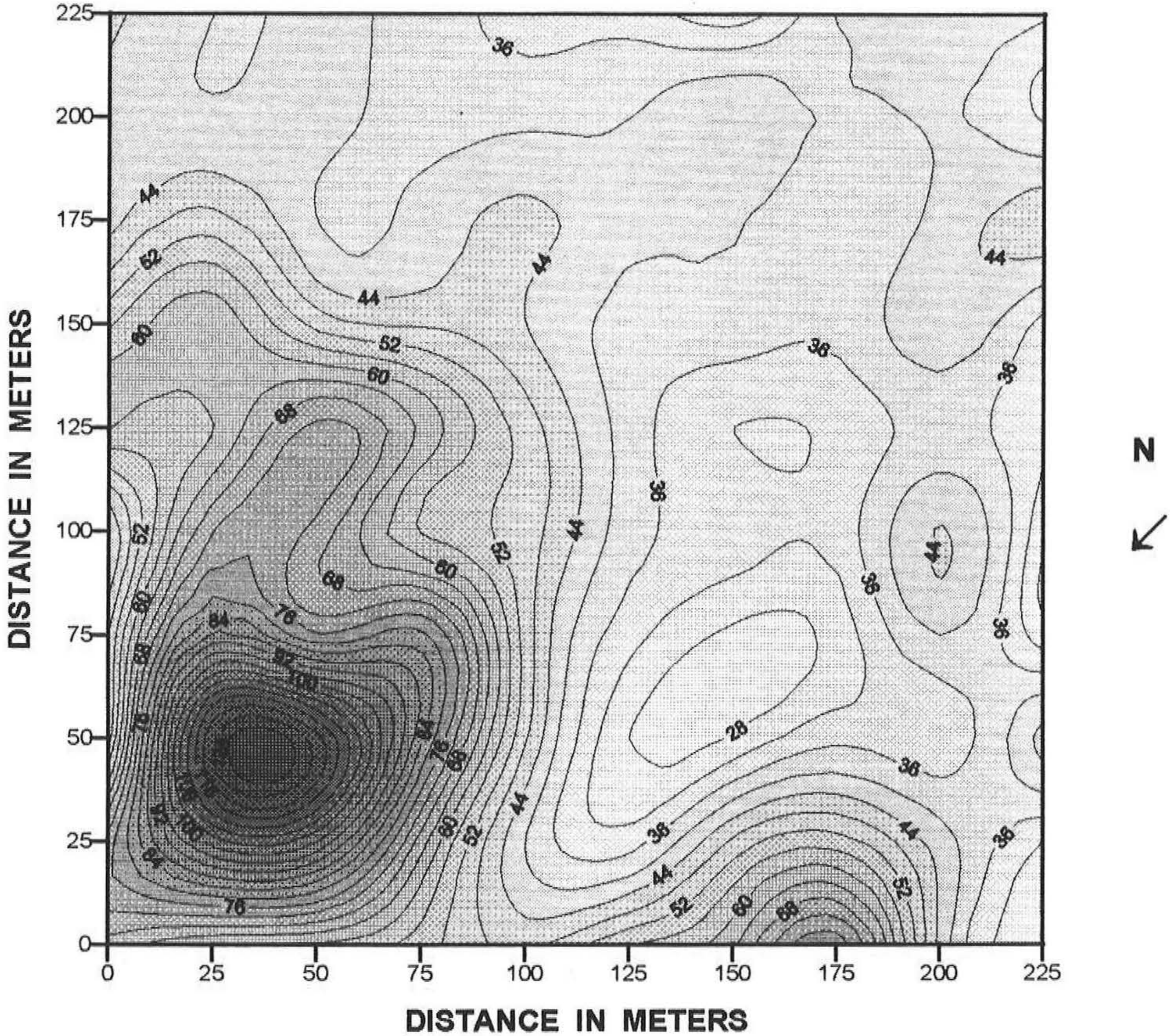


FIGURE 44

HARVEY COUNTY, KANSAS
SITE 13

RELATIVE TOPOGRAPHY
CONTOUR INTERVAL = 0.25 M

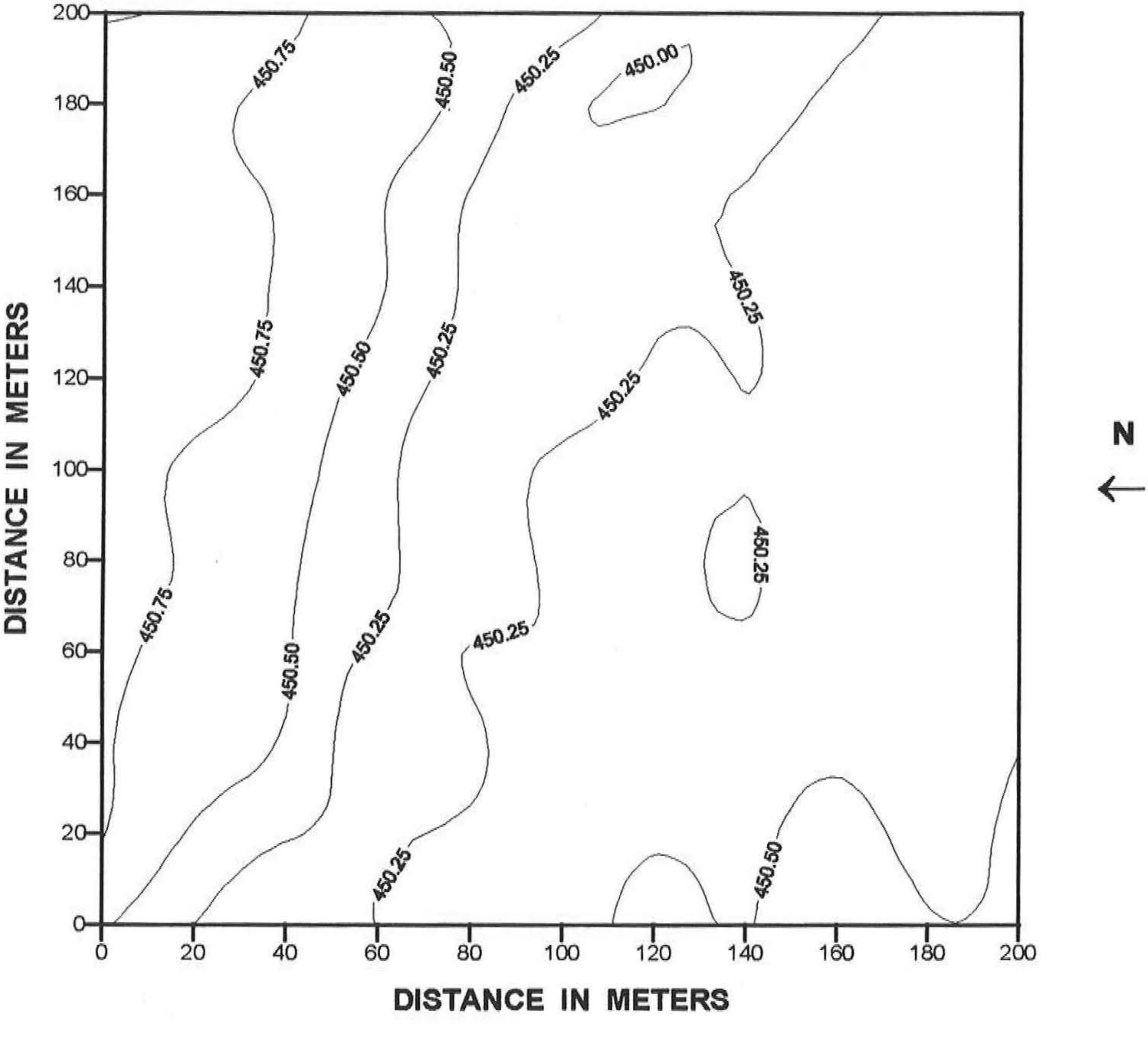


FIGURE 45

HARVEY COUNTY, KANSAS
SITE 13

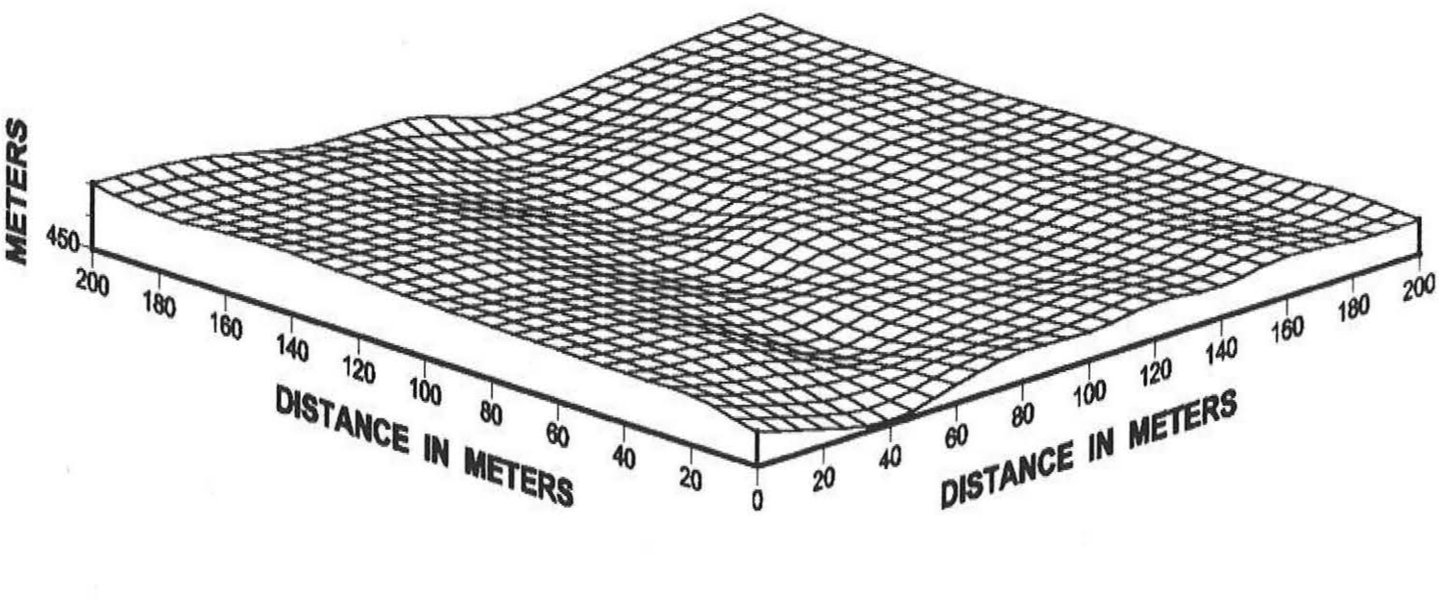


FIGURE 46

HARVEY COUNTY, KANSAS
SITE 13

EM38 METER
HORIZONTAL DIPOLE ORIENTATION

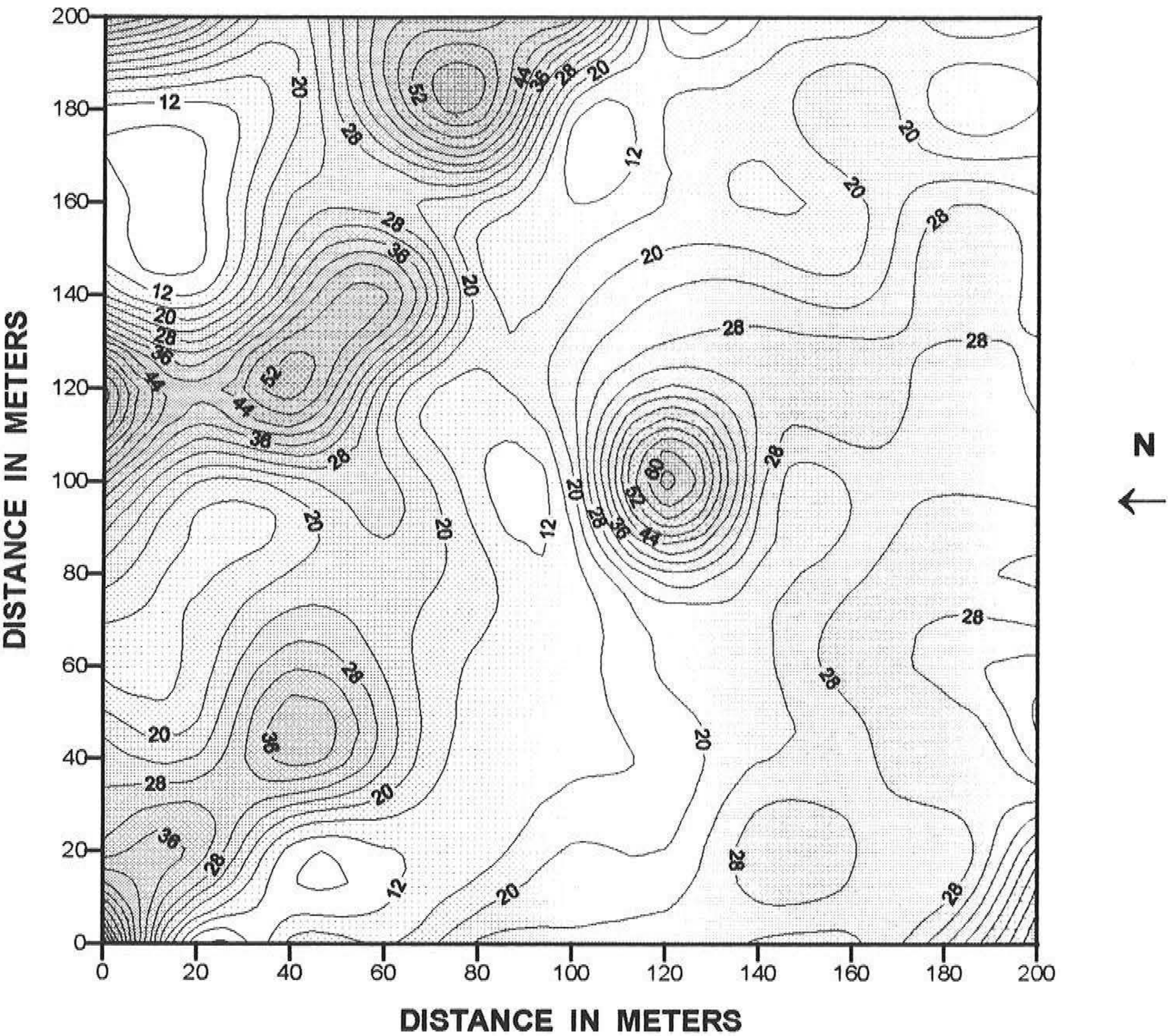


FIGURE 47

HARVEY COUNTY, KANSAS
SITE 13

EM38 METER
VERTICAL DIPOLE ORIENTATION

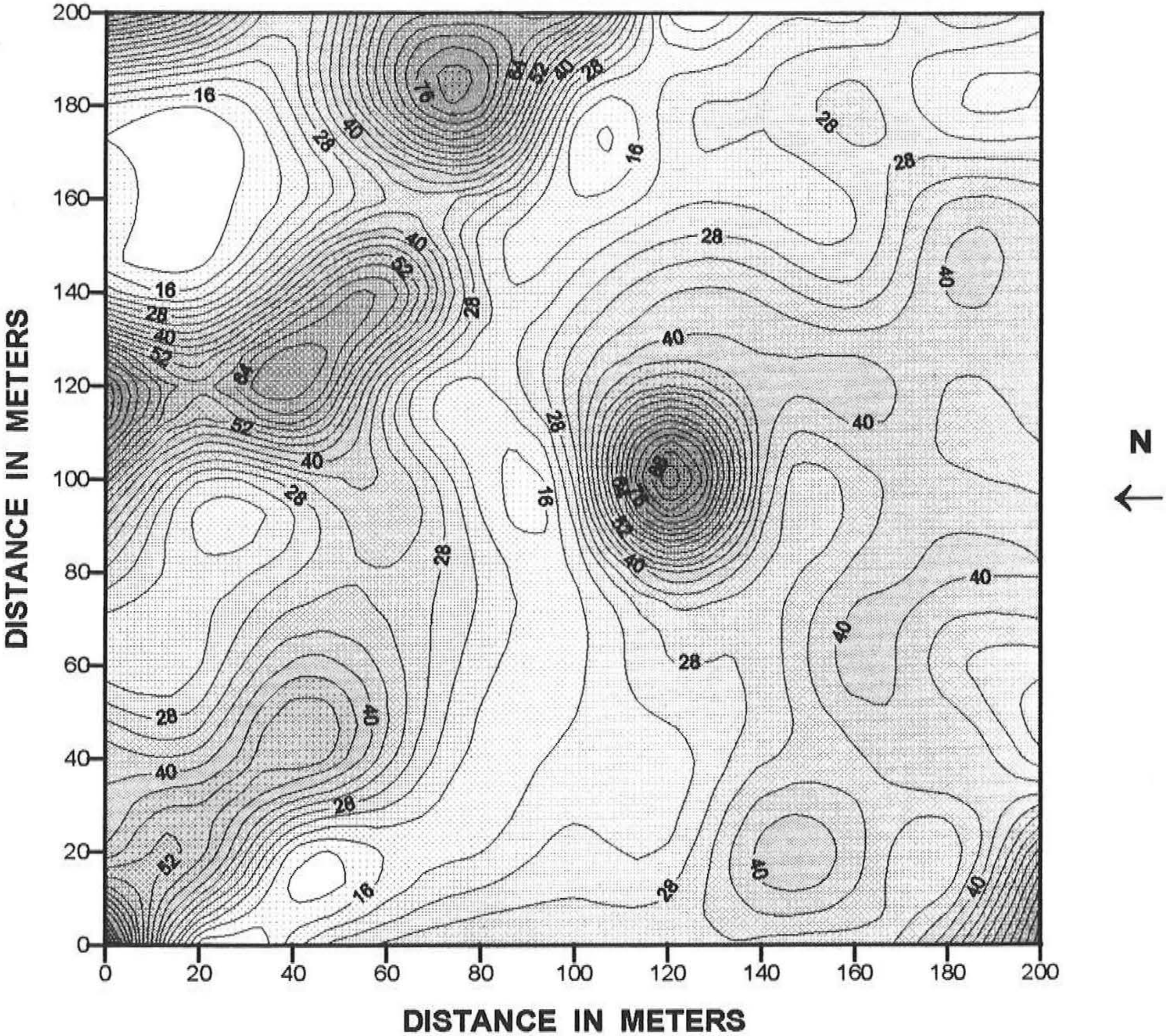


FIGURE 48

HARVEY COUNTY, KANSAS
SITE 13

EM31 METER
HORIZONTAL DIPOLE ORIENTATION

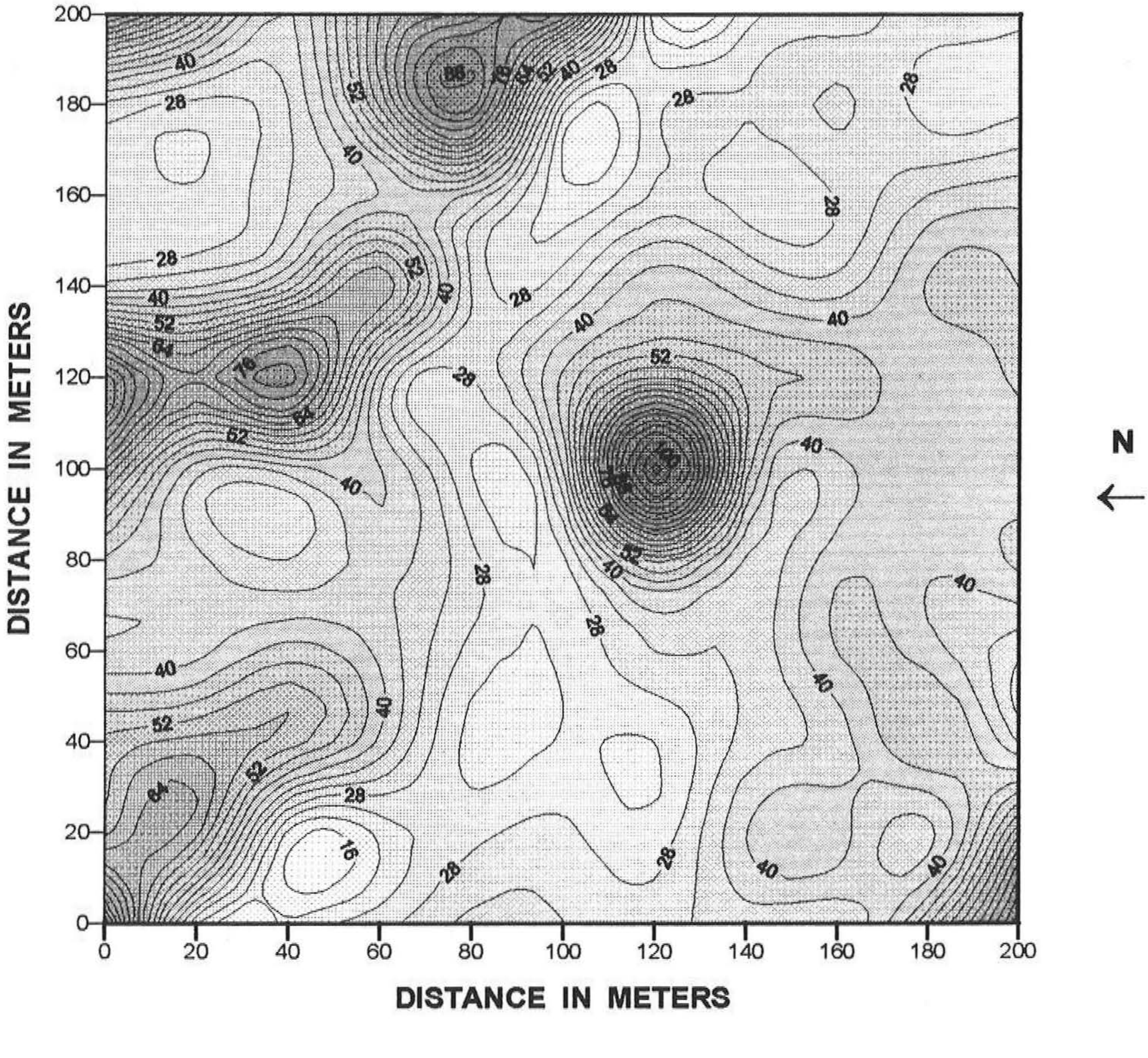


FIGURE 49

HARVEY COUNTY, KANSAS
SITE 13

EM31 METER
VERTICAL DIPOLE ORIENTATION

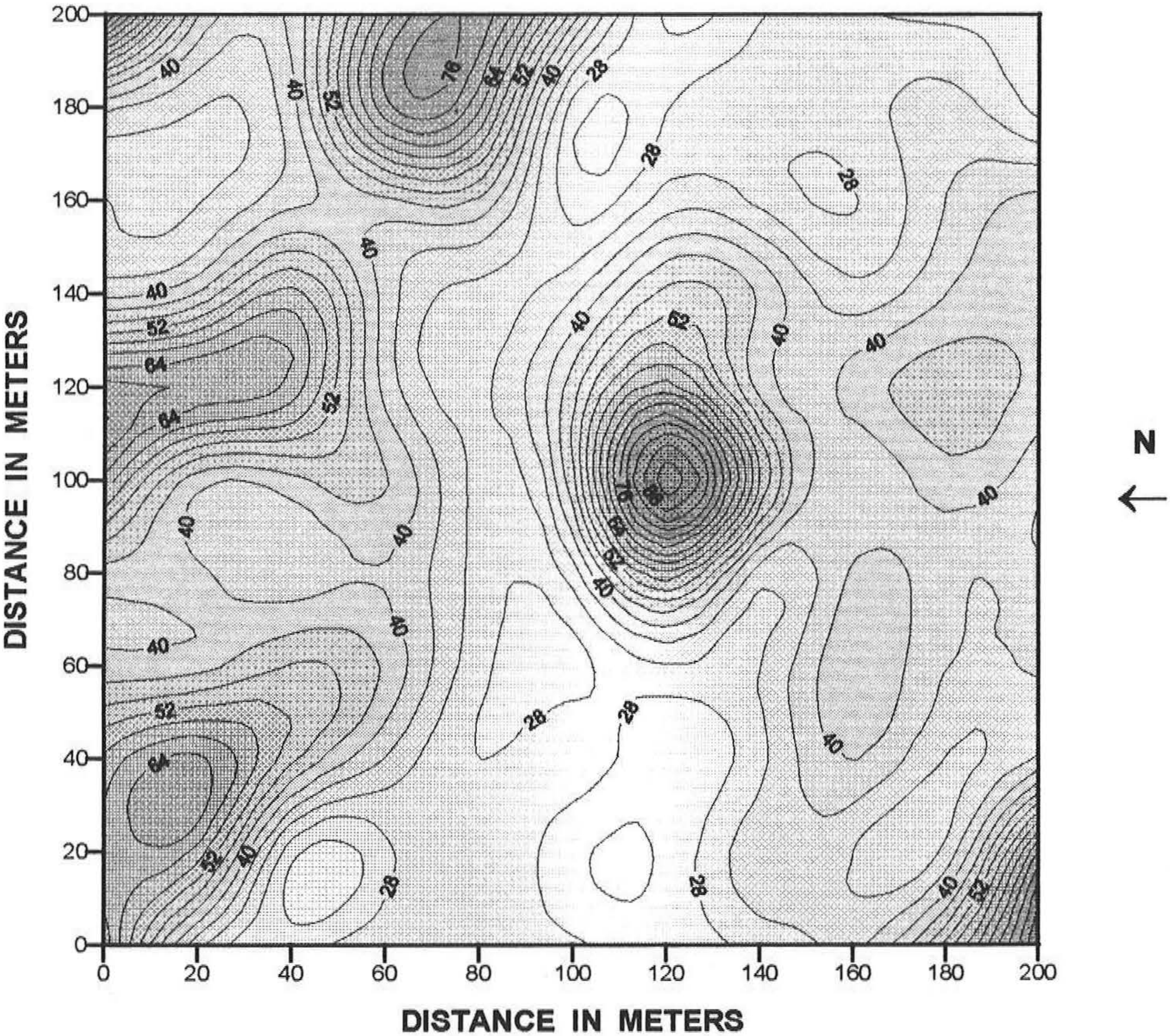


FIGURE 50

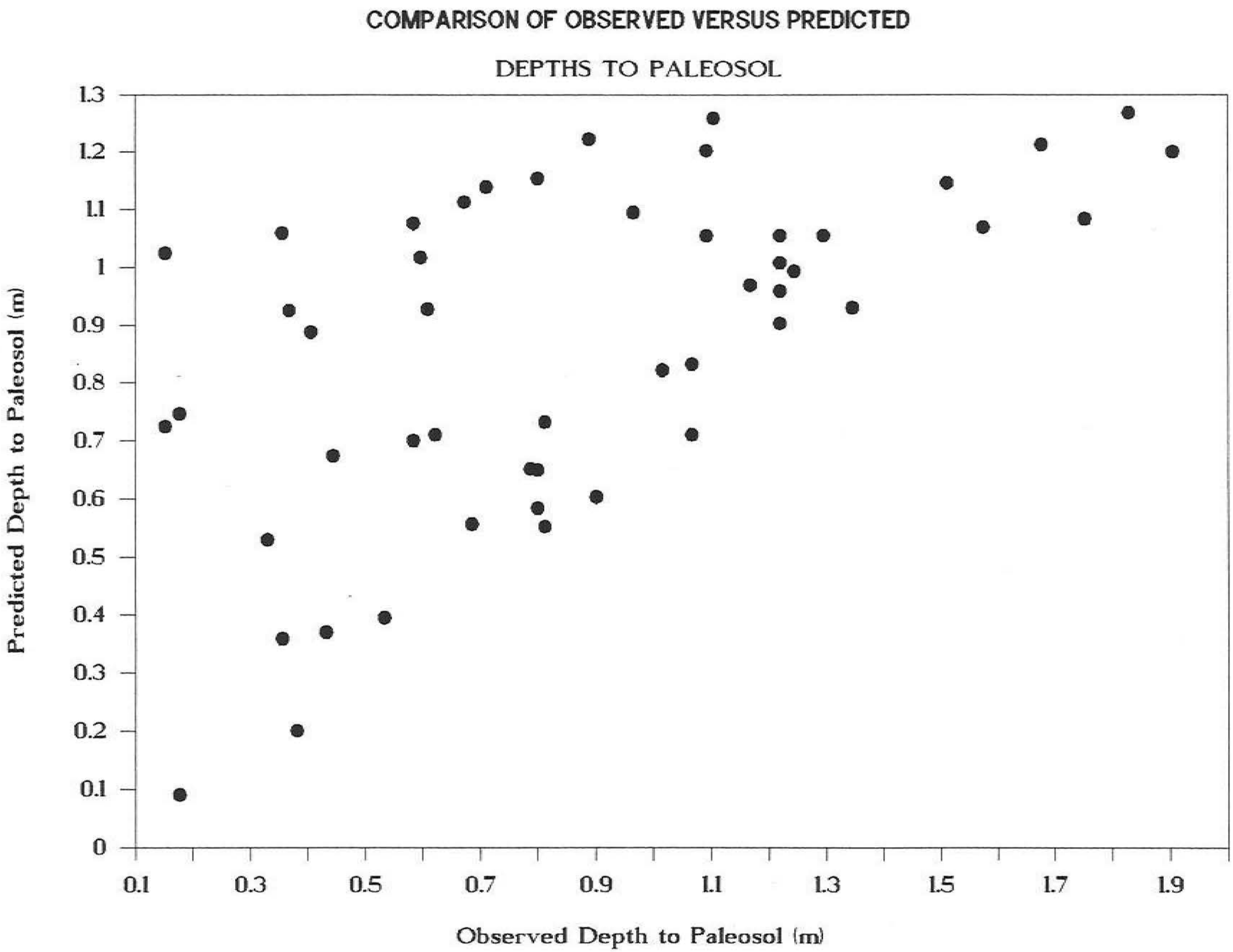
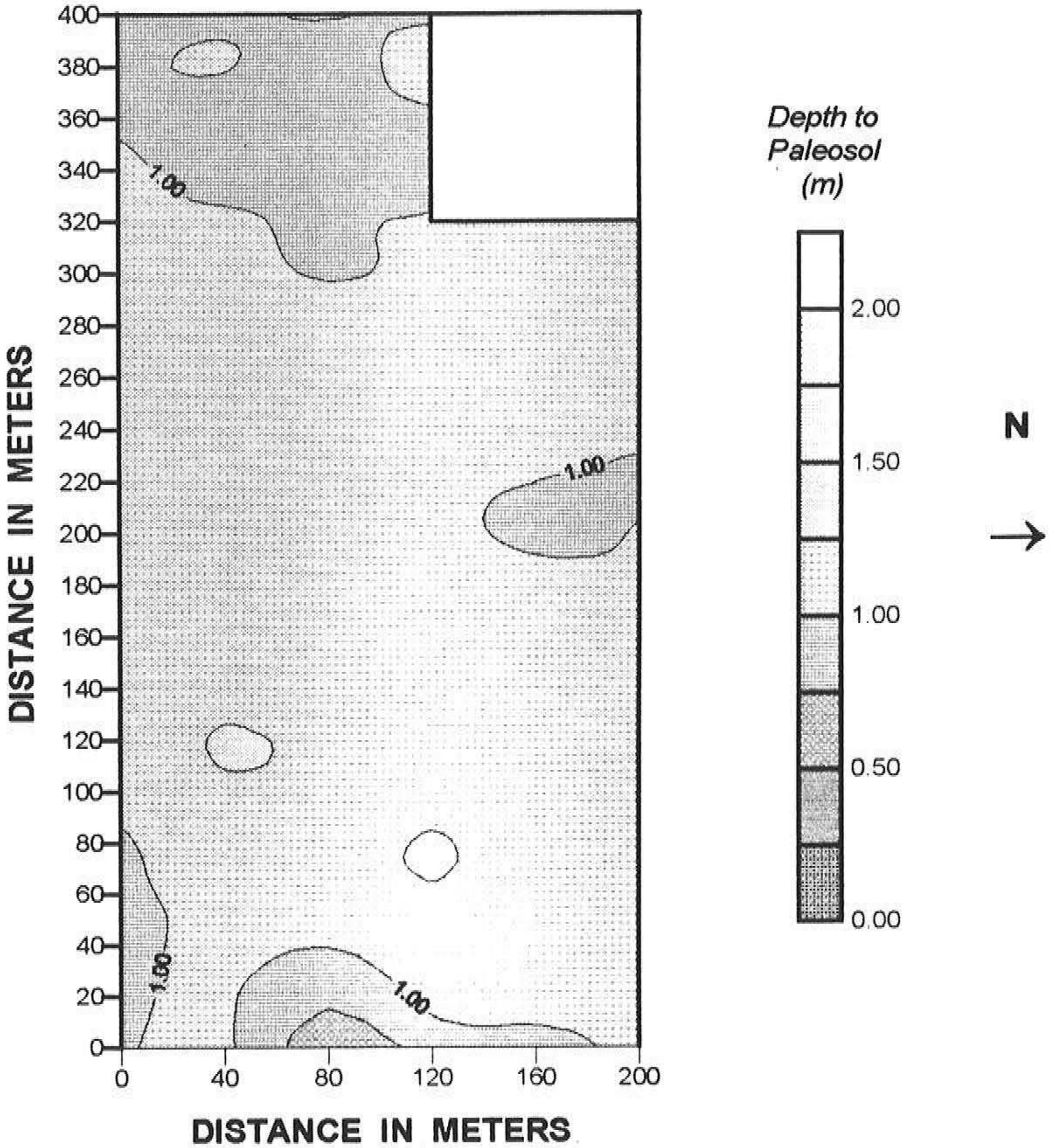

COMPARISON OF OBSERVED VERSUS PREDICTED
DEPTHS TO PALEOSOL
Predicted Depth to Paleosol (m)
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0.3
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
Observed Depth to Paleosol (m)

Figure 51

HARVEY COUNTY, KANSAS
SITE 1

ESTIMATED DEPTHS TO PALEOSOL
CONTOUR INTERVAL = 0.25 M



HARVEY COUNTY, KANSAS
SITE 2

ESTIMATED DEPTHS TO PALEOSOL
CONTOUR INTERVAL = 0.25 M

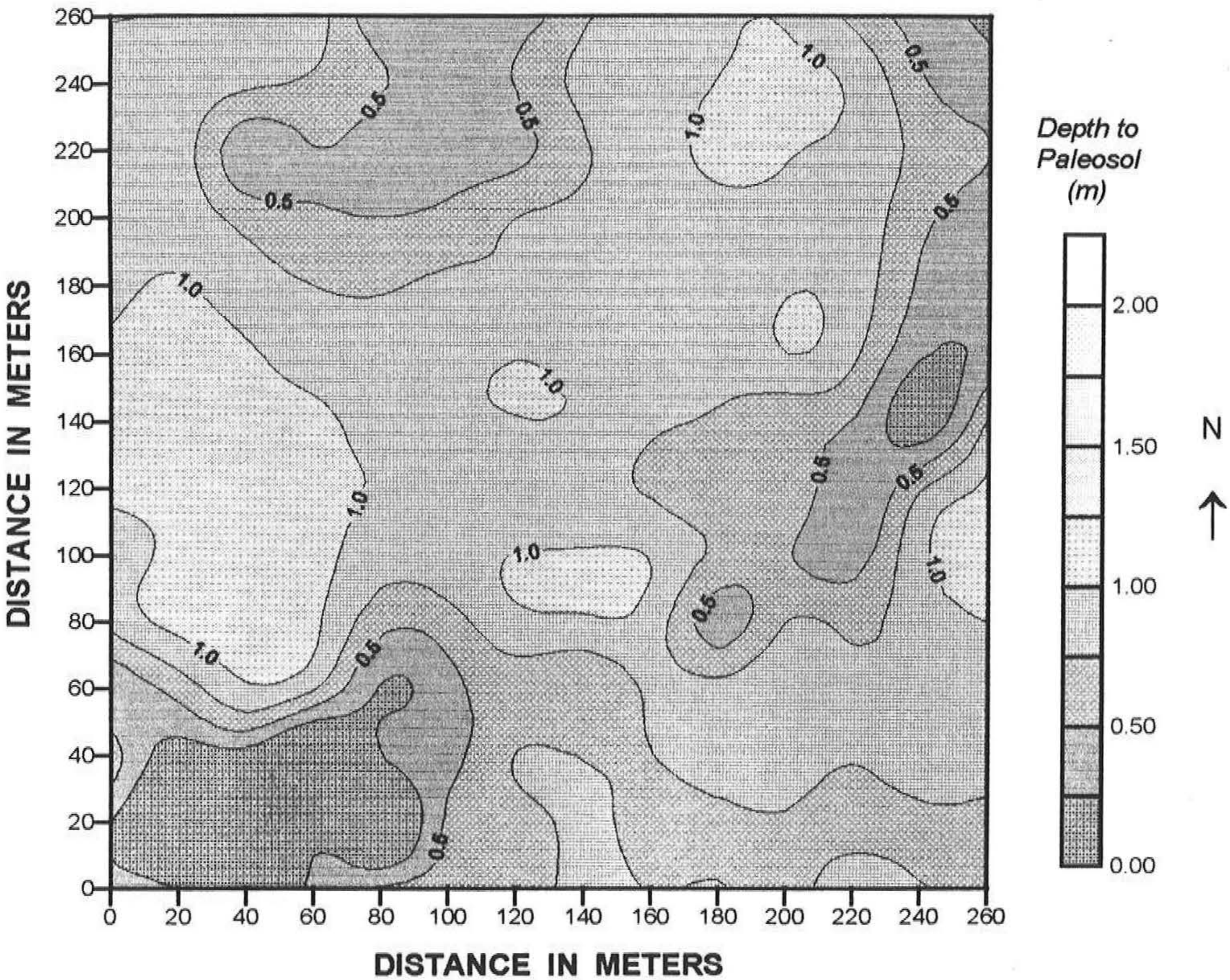


FIGURE 53

HARVEY COUNTY, KANSAS
SITE 5

ESTIMATED DEPTHS TO PALEOSOL
CONTOUR INTERVAL = 0.50 M

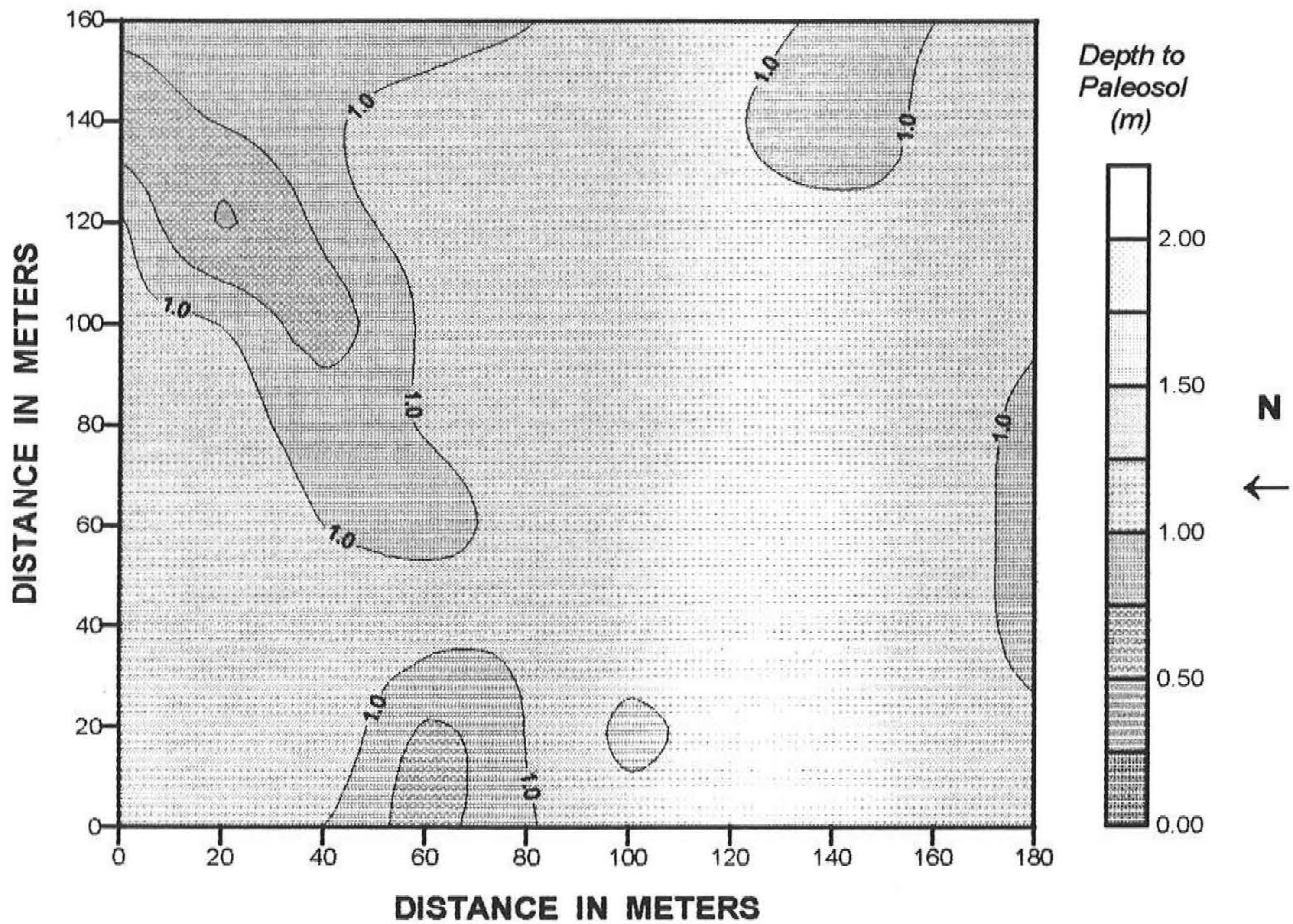


FIGURE 54

HARVEY COUNTY, KANSAS
SITE 7

ESTIMATED DEPTHS TO PALEOSOL
CONTOUR INTERVAL = 0.25 M

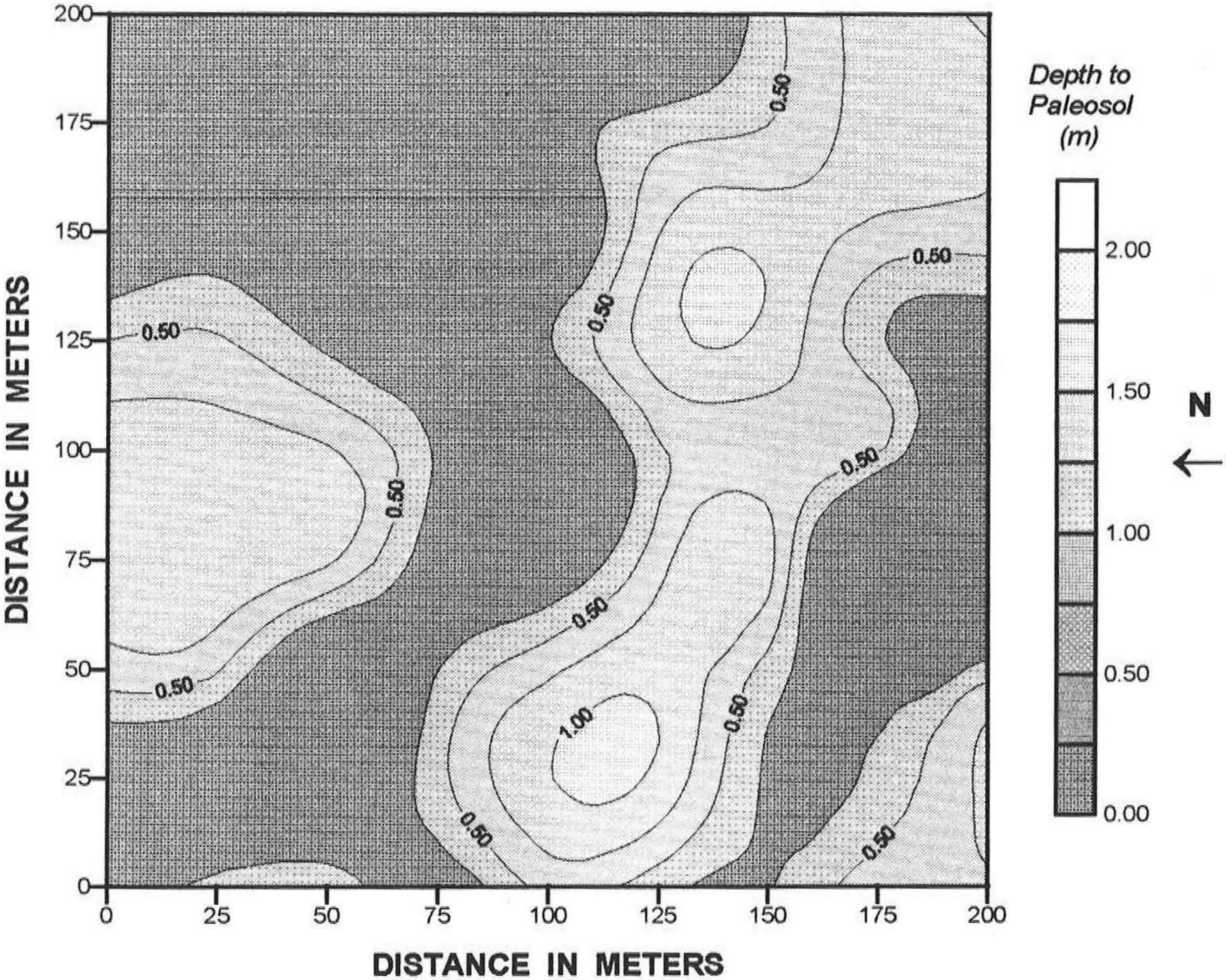


FIGURE 55

HARVEY COUNTY, KANSAS
SITE 8

ESTIMATED DEPTHS TO PALEOSOL
CONTOUR INTERVAL = 0.50 M

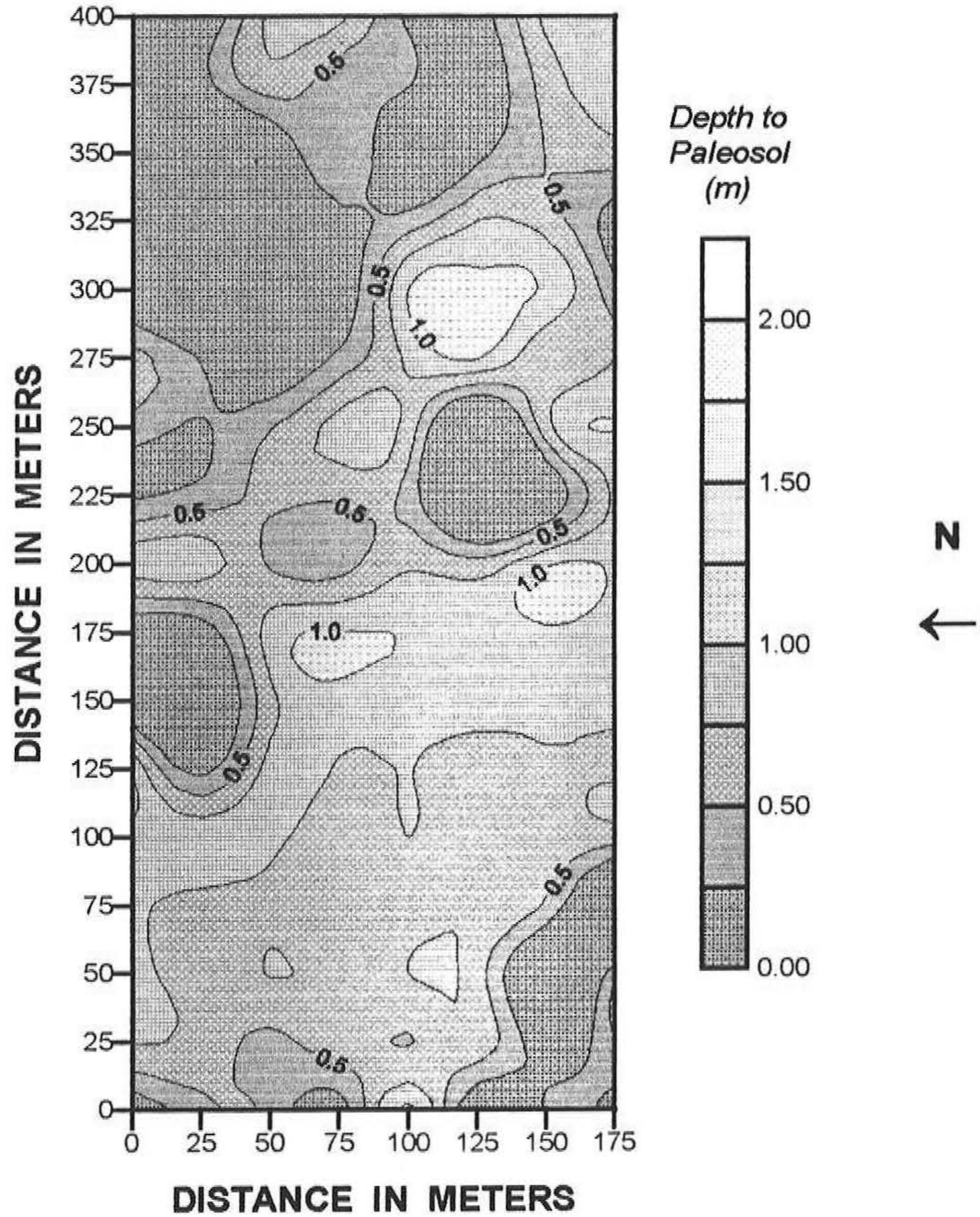


FIGURE 56

HARVEY COUNTY, KANSAS
SITE 10

ESTIMATED DEPTHS TO PALEOSOL
CONTOUR INTERVAL = 0.25 M

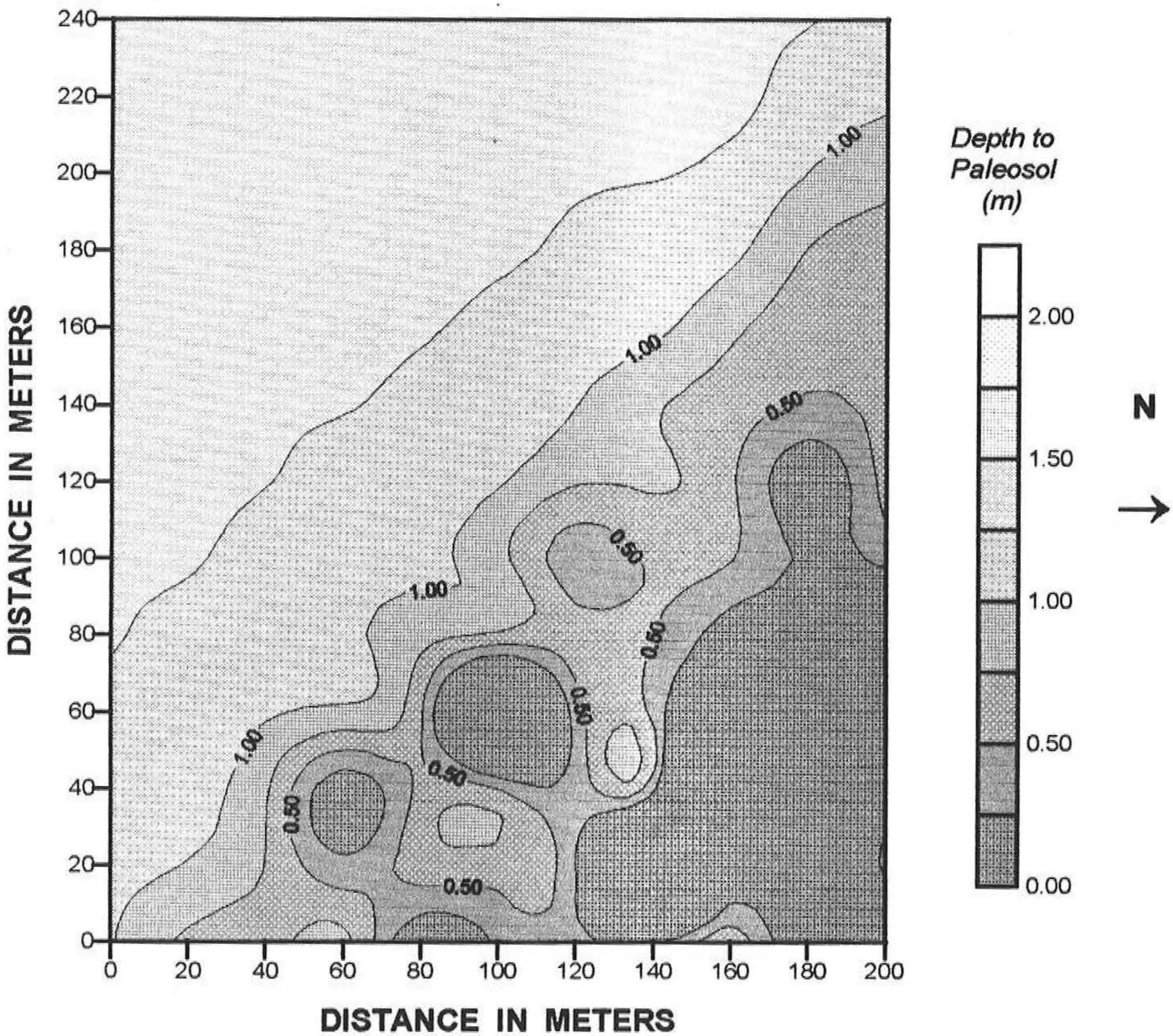


FIGURE 57

HARVEY COUNTY, KANSAS
SITE 12

ESTIMATED DEPTHS TO PALEOSOL
CONTOUR INTERVAL = 0.25 M

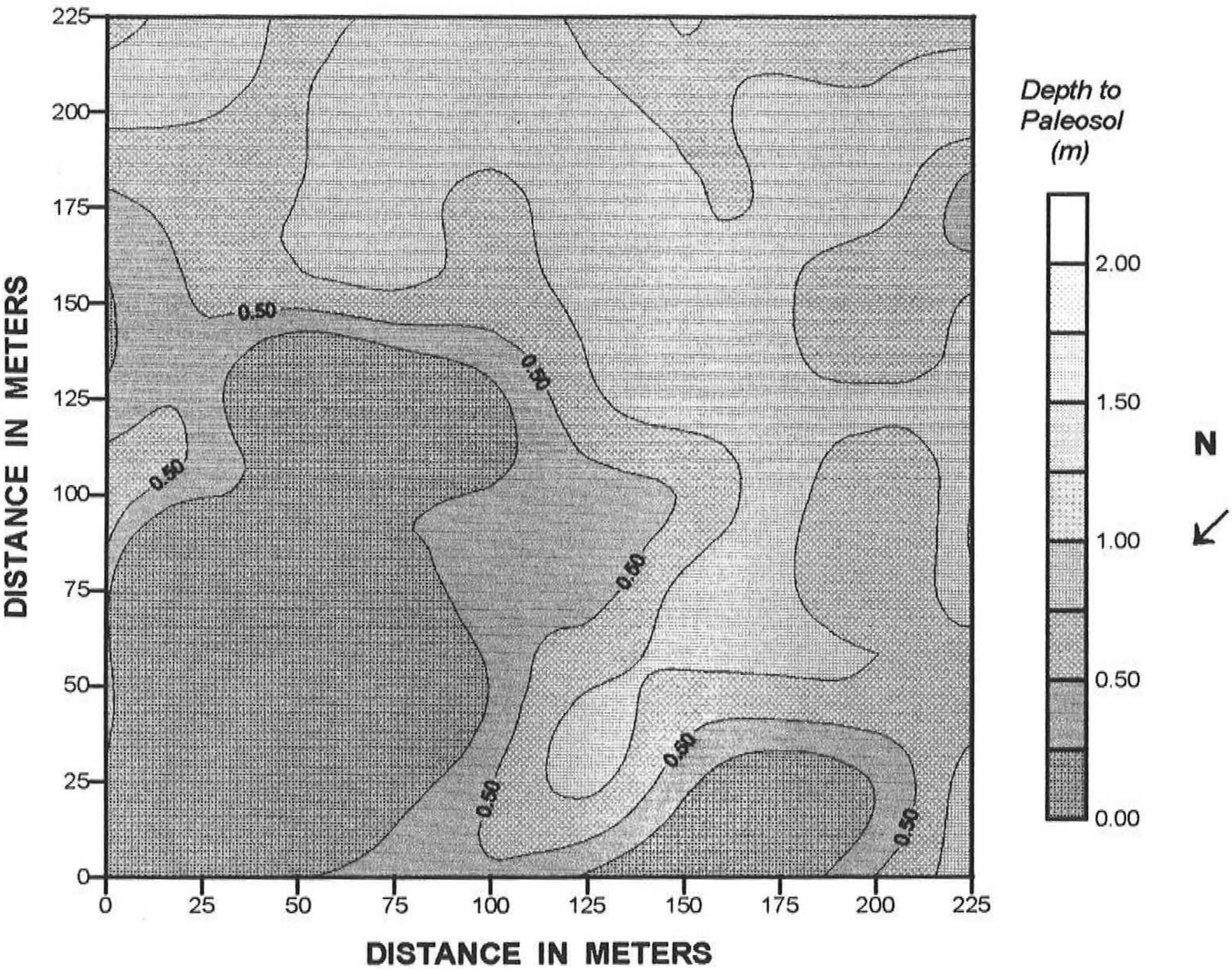


FIGURE 58

HARVEY COUNTY, KANSAS
SITE 13

ESTIMATED DEPTH TO PALEOSOL
CONTOUR INTERVAL = 0.25 M

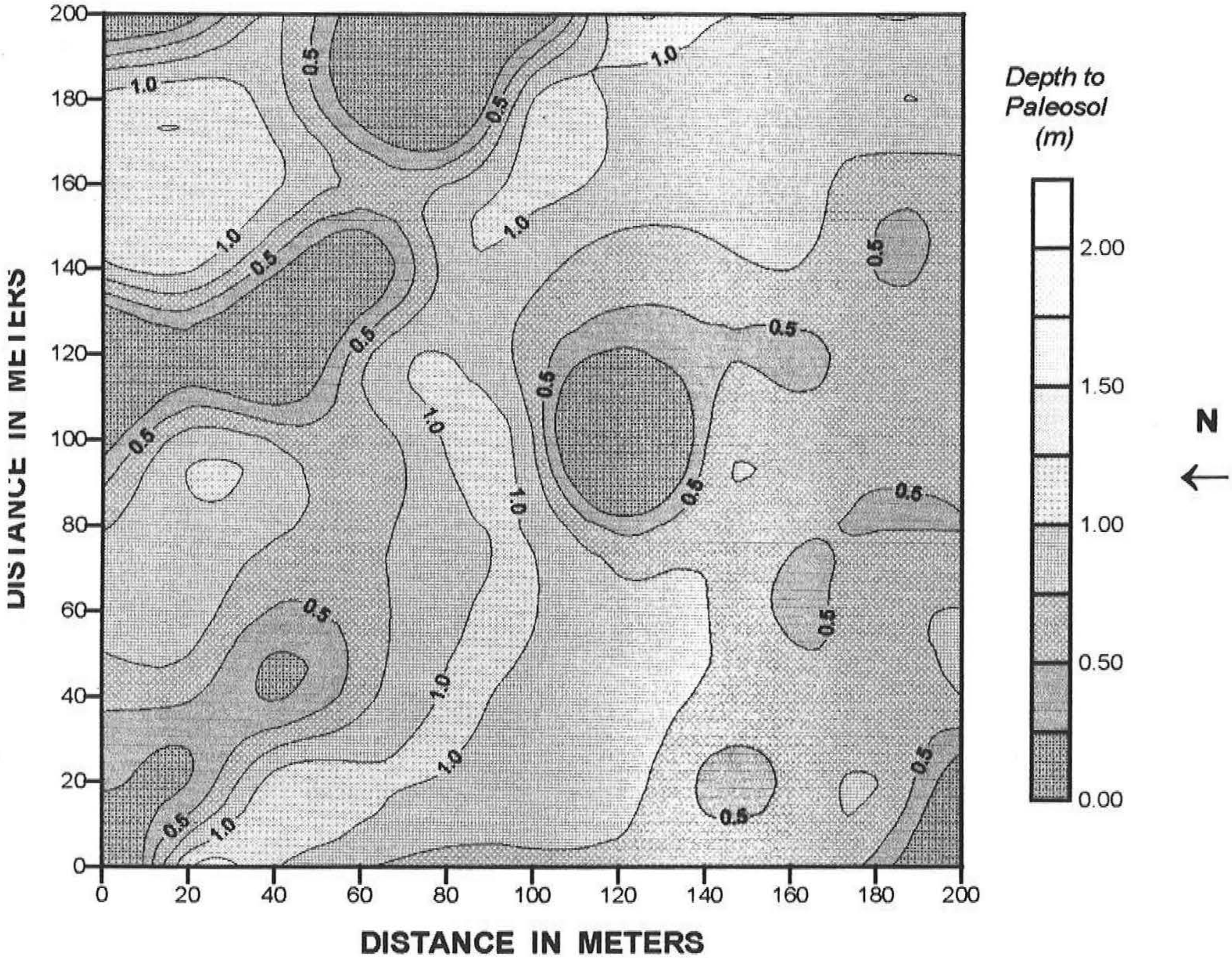


FIGURE 59

HARVEY COUNTY, KANSAS
SITE 1

ESTIMATED DEPTHS TO PALEOSOL

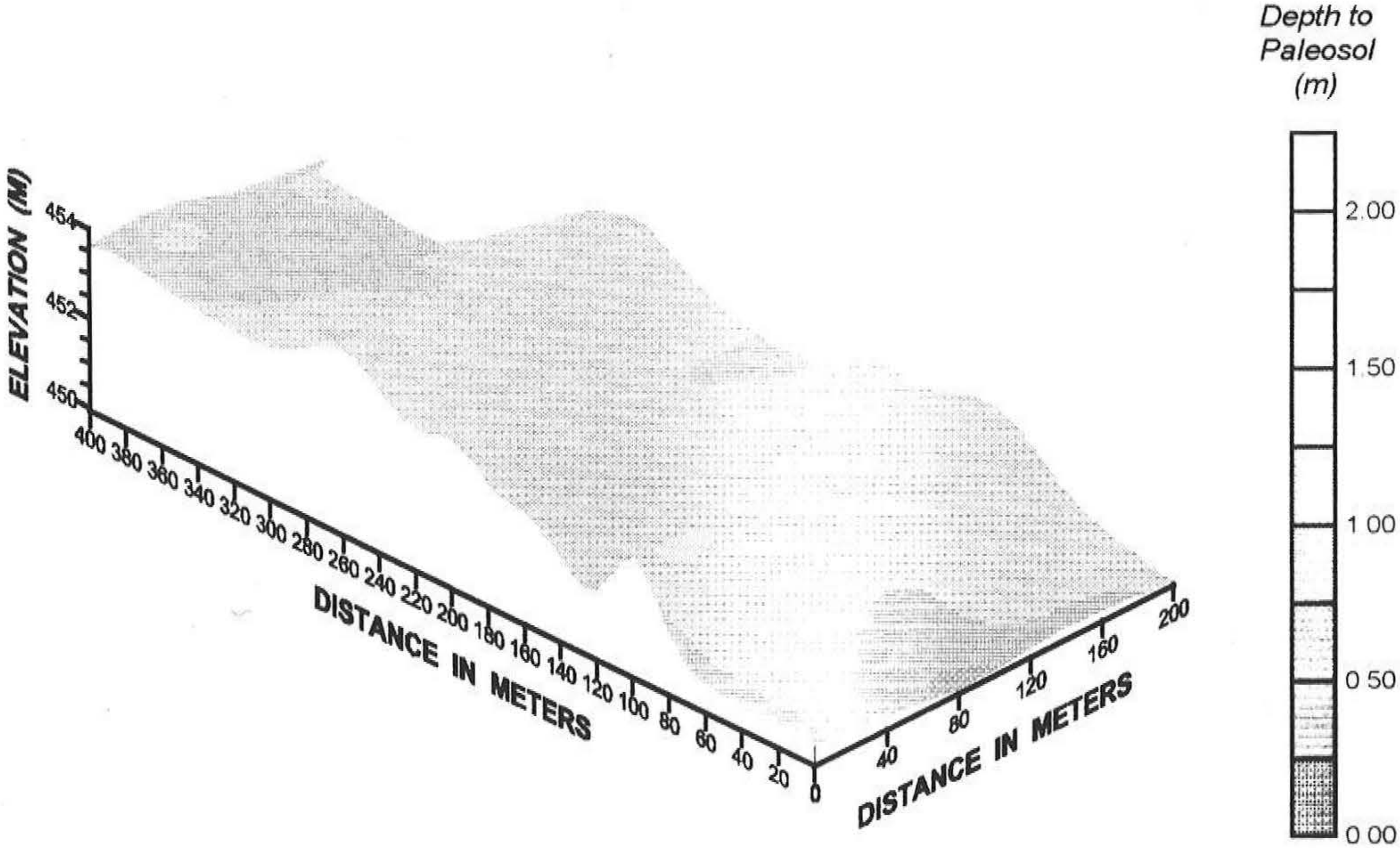


FIGURE 60

HARVEY COUNTY, KANSAS
SITE 2

ESTIMATED DEPTHS TO PALEOSOL

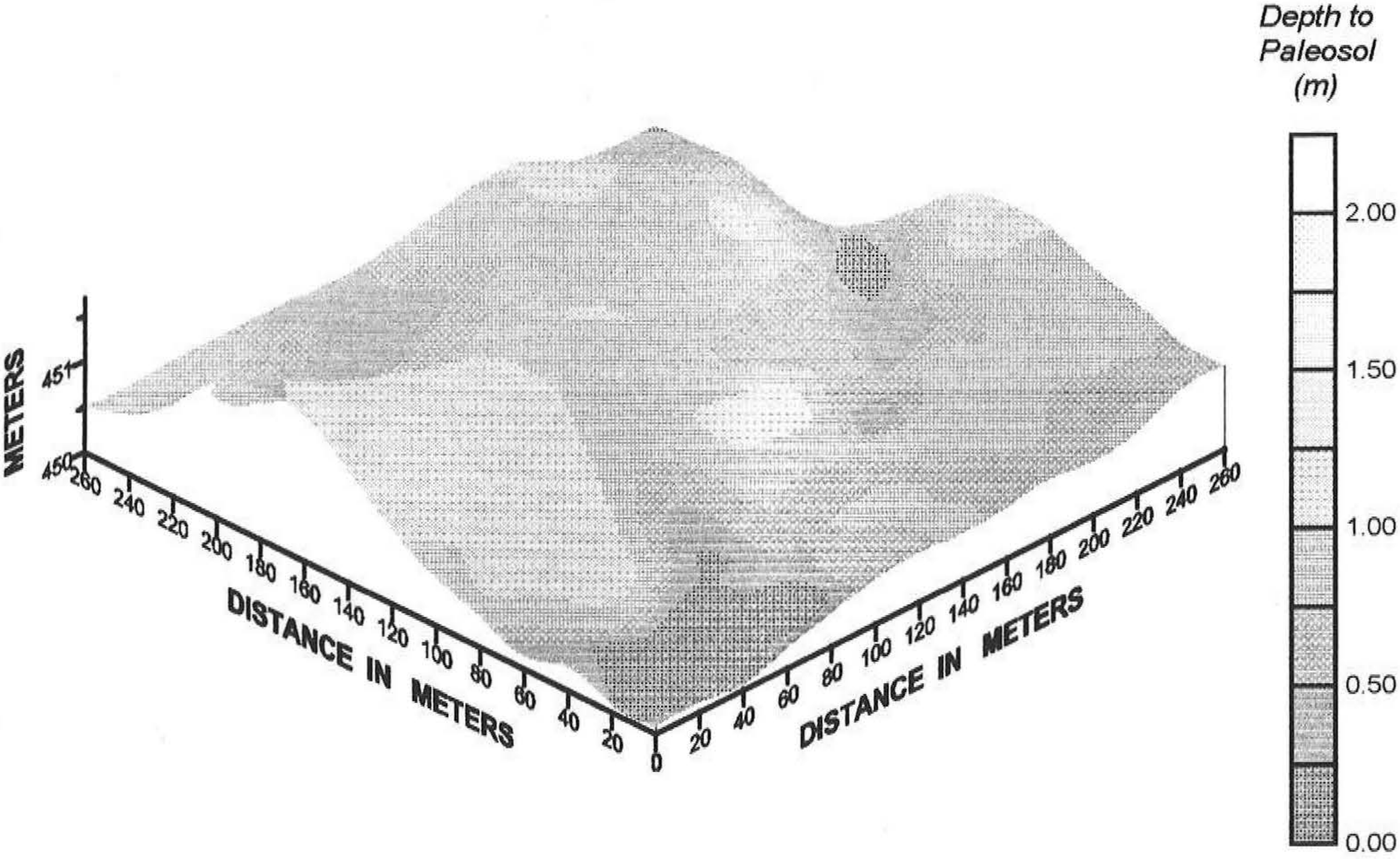


FIGURE 61

HARVEY COUNTY, KANSAS
SITE 5

ESTIMATED DEPTHS TO PALEOSOL

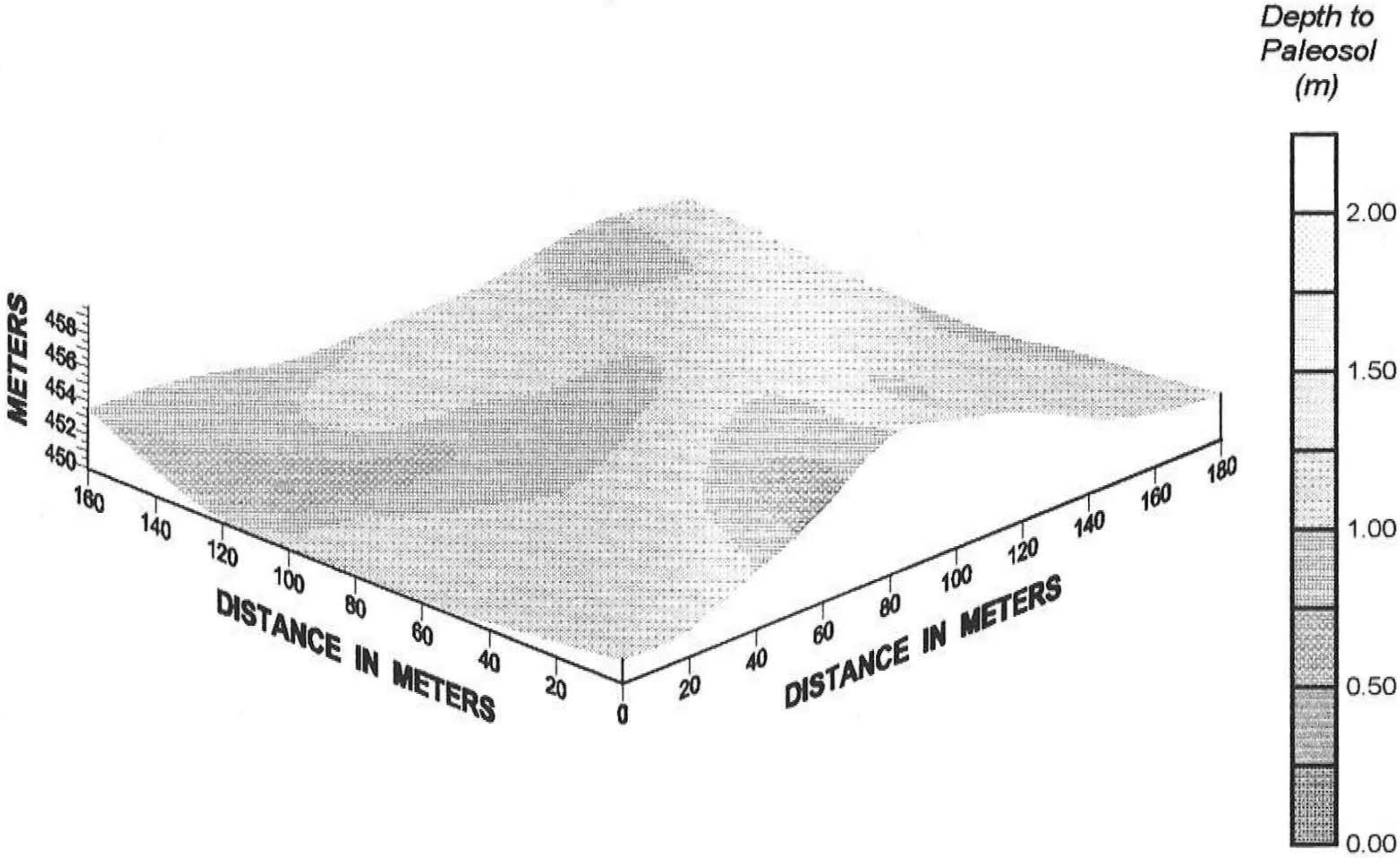


FIGURE 62

HARVEY COUNTY, KANSAS
SITE 7

ESTIMATED DEPTHS TO PALEOSOL

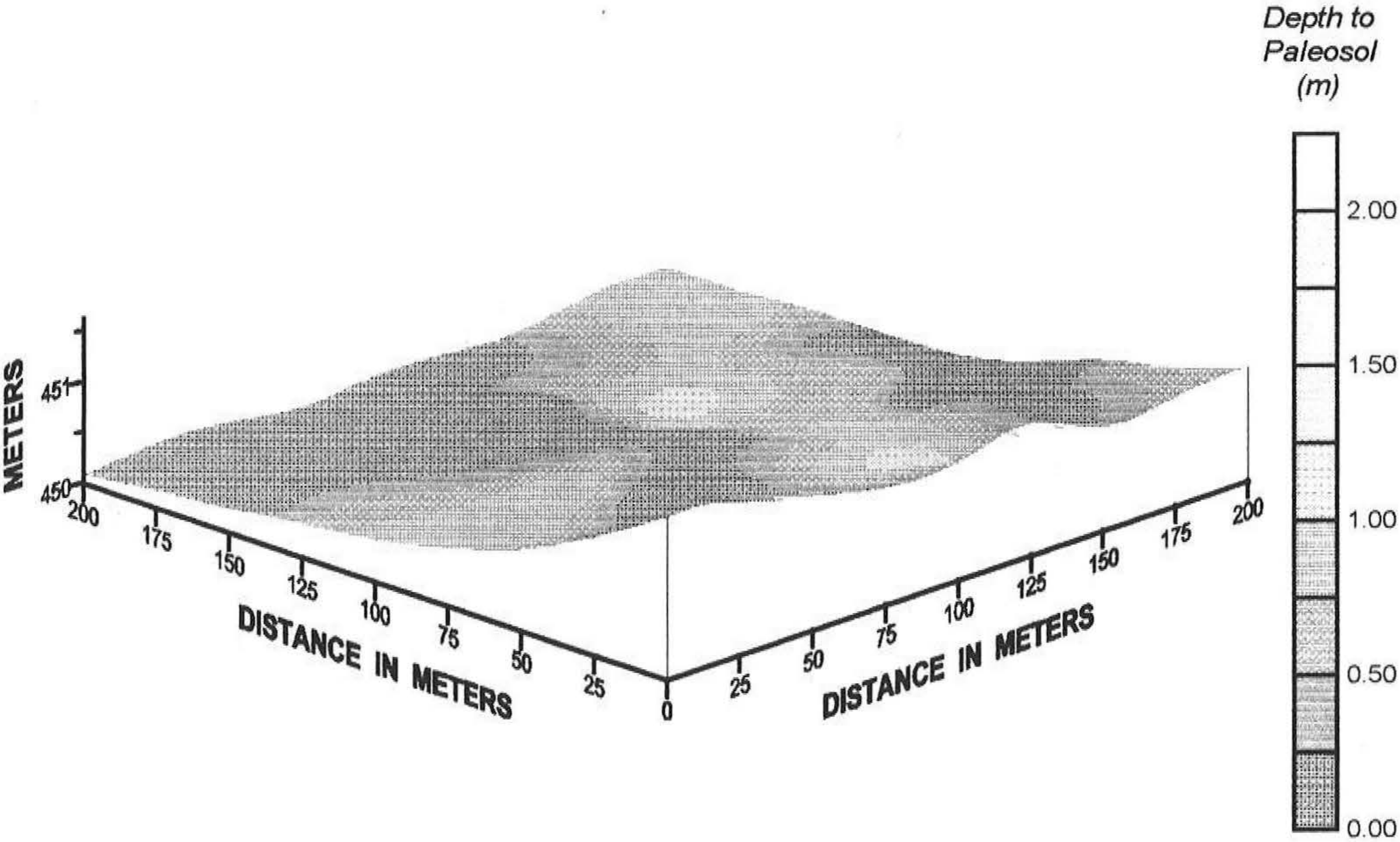


FIGURE 63

HARVEY COUNTY, KANSAS
SITE 8

ESTIMATED DEPTHS TO PALEOSOL

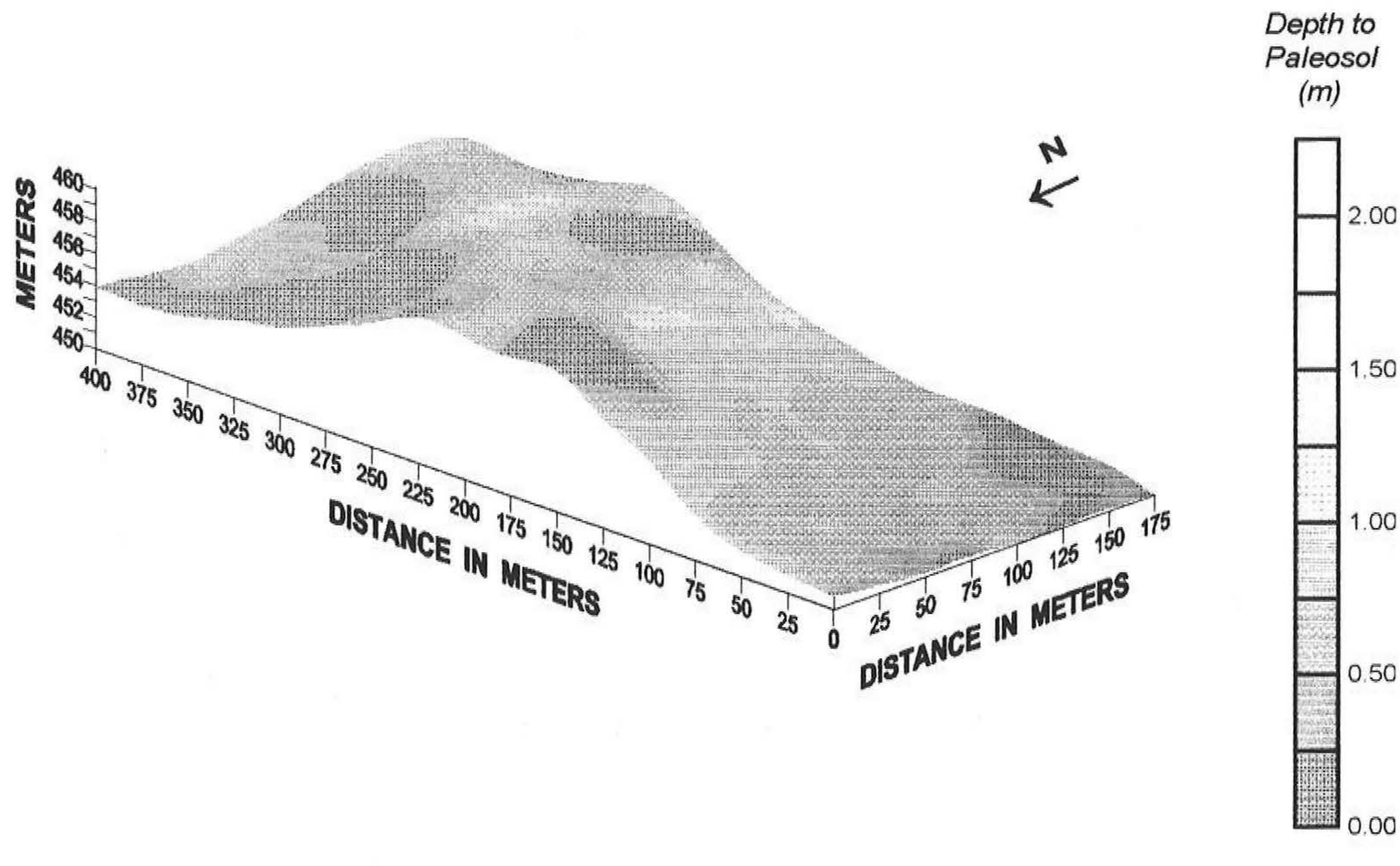


FIGURE 64

HARVEY COUNTY, KANSAS
SITE 10

ESTIMATED DEPTHS TO PALEOSOL

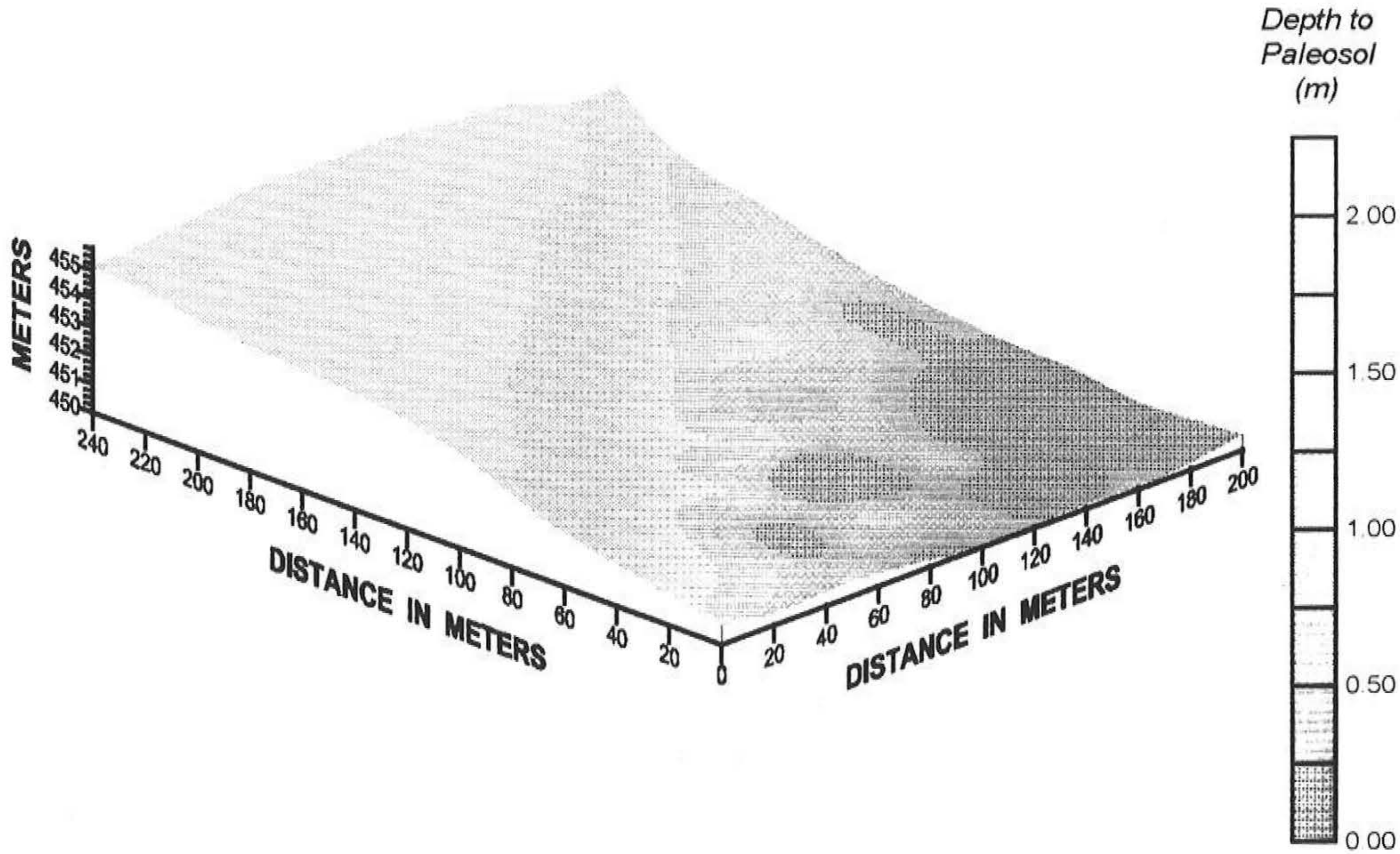


FIGURE 65

HARVEY COUNTY, KANSAS
SITE 12

ESTIMATED DEPTHS TO PALEOSOL

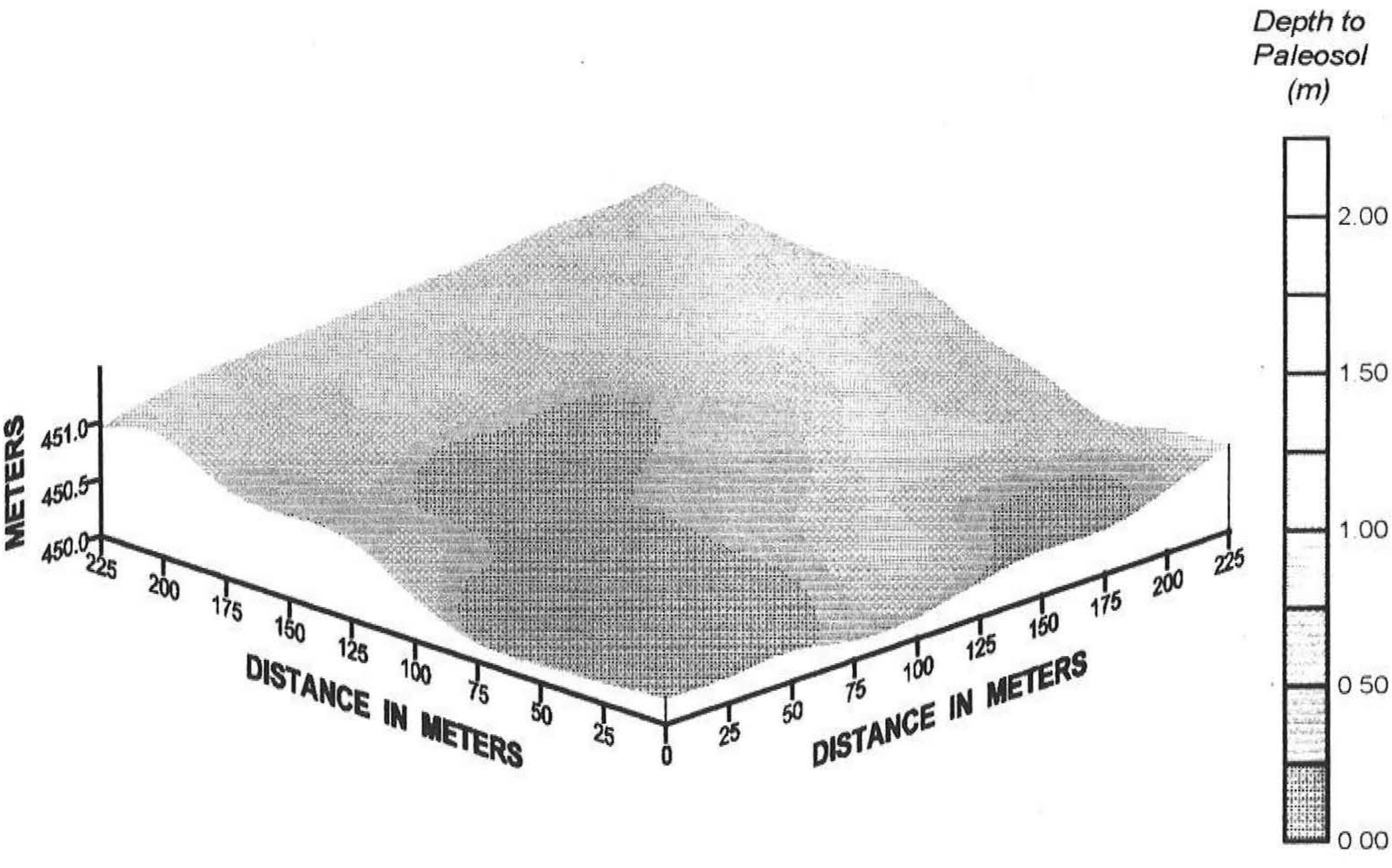


FIGURE 66

HARVEY COUNTY, KANSAS
SITE 13

ESTIMATED DEPTHS TO PALEOSOL

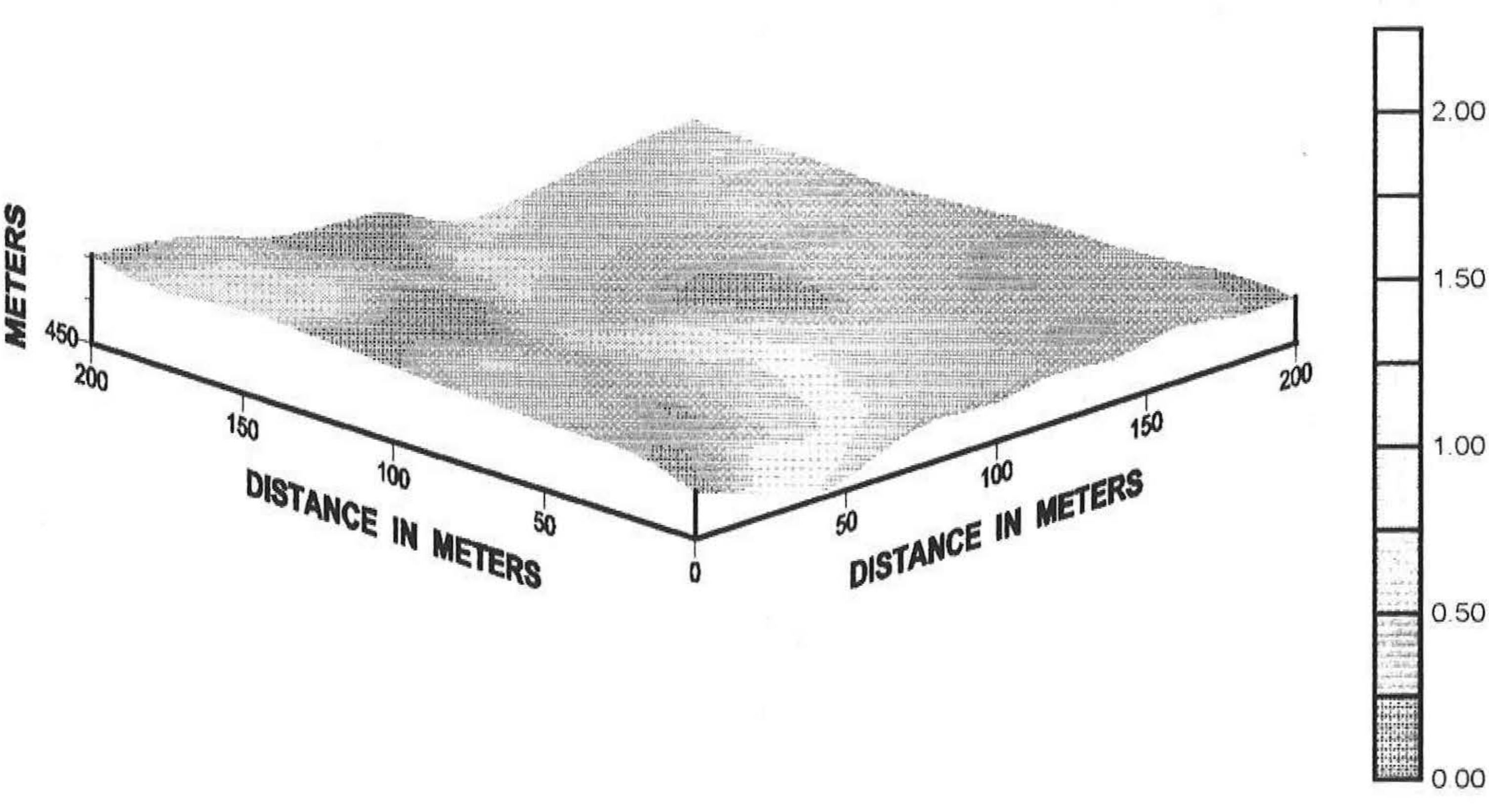


FIGURE 67