United States Department of Agriculture **Chester, PA 19013**
Soil Conservation Service **610-490-6042**

Subject: Geophysical Investigations of Petrocalcic Horizons near Mills, Utah August 1 to 5, 1994 **Date:** 27 September 1994

To: Phillip J. Nelson
State Conservationist
USDA - Soil Conservation Service
P.O. Box 11350
Salt Lake City, Utah 84138-0350

Purpose:
Quantification and mapping of the depths to petrocalcic horizons are important components of soil surveys, site assessments, and research on water-quality and forage production. Collection of data with spades and augers is a tedious and labor intensive task, making it impractical to collect the large quantities of data necessary to implement comprehensive mapping studies over large areas. This study addressed the feasibility of using ground-penetrating radar (GPR) and electromagnetic induction (EM) techniques as mapping tools to assess variations in the depths to petrocalcic horizons within small sites and across large areas.

Participants:
Janis Boettinger, Ass't. Professor of Soils, Utah State U., Logan, UT
Edward Bork, Graduate Student, Utah State U., Logan, UT
Mike Domier, Soil Correlator, SCS, Salt Lake City, UT
Jim Doolittle, Soil Specialist, SCS, Chester, PA
Vick Parselow, Soil Survey Party Leader, SCS, Richfield, UT
Ron Veater, Civil Engineering Technician, SCS, Nephi, UT
Neil West, Professor of Range Science, Utah State U., Logan, UT

Activities:
Ground-penetrating radar and electromagnetic induction surveys were conducted at a site near Mills, Utah, on 8 to 12 August 1994. On 30 August 1994, following equipment repairs, a survey of Enclosure # 4 was completed with the EM38 meter.

Equipment:
The radar unit used in this study was the Subsurface Interface Radar (SIR) System-8 manufactured by Geophysical Survey Systems, Inc.* Principles of operation have been described in detail by Daniels and

---

* Trade names have been used to provide specific information. Their mention does not constitute endorsement.

others (1988). The radar unit was powered by a 12-volt vehicular battery. The models 3110 (120 mHz) and 3102 (500 mHz) antennas were used in this investigation. A model 705DA transceiver was used with the 120 mHz antenna. A model 38 video display unit (VDU) and a Sony digital audio tape-corder (TCD-D3) were used to record radar data for future playback and processing. Unfortunately, radar data were not acceptably recorded using these components and processing was not possible.

The electromagnetic induction meters used in this study were the EM31 and EM38 manufactured by Geonics Limited+. Principles of operation have been described in detail by McNeill (1980b, 1986). Depths of observation are dependent upon the intercoil spacing, transmission frequency, and coil orientation relative to the ground surface. The EM38 meter integrates values of apparent conductivity over the upper 0.75 m in the horizontal dipole orientation, and over the upper 1.5 m in the vertical dipole orientation. The EM31 meter integrates values of apparent conductivity over the upper 2.75 m in the horizontal dipole orientation, and over the upper 6.0 m in the vertical dipole orientation. With each meter, measurements were obtained in the quadrature phase and expressed in milliSiemens/meter (mS/m).

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

Study Area:
The study area was located on the eastern slopes of Canyon Mountains about 7.9 kilometers west of Mills, in central Utah (SW1/4 Sec. 30, T. 15 S., R. 2 W.).

A 11.5 hectare study site was selected on a north-east facing ballena. Relief was about 24.4 m. Figure 1 is a two-dimensional contour plot of the study site. This plot was prepared from data collected at 216, equally spaced (25-m grid interval), observation points. 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 recorded observation point was recorded as the 0.0 meter datum.

In Figure 1, the contour interval is 1.0 m. A narrow summit of the ballena can be seen extending across the plot in a northeasterly direction. The nearly level to gently sloping summit slopes towards the northeast and is bounded to the east and west by steeper shoulder and backslopes. These slopes have been dissected by several drainageways. In Figure 1, the locations and identifications of four enclosures have been shown. These enclosures are located along the summit. Each enclosure was more intensively (2-m grid interval)

+ Trade names have been used to provide specific information. Their mention does not constitute endorsement.

surveyed with GPR and EM techniques. Figure 2 is a three-dimensional surface net diagram of the study site. In this diagram, the vertical scale has been exaggerated by a factor of 10.

The study site was located in an area of Borvant cobbly loam, 2 to 8 percent slopes (Trickler and Hall, 1984). Borvant is a member of the loamy-skeletal, carbonatic, mesic, shallow Aridic Petrocalcic Palexerolls family. This shallow, somewhat excessively drained soil formed in medium-textured alluvium derived principally from limestone and sandstone. Borvant soils have a petrocalcic horizon between depths of 25 to 50 cm. The petrocalcic horizon is 35 to 60 percent rock fragments.

Included in mapping were areas of Donnardo (loamy-skeletal, mixed, mesic Aridic Calcixerolls), Jericho (loamy-skeletal, mixed, mesic, shallow Xerollic Durorthids), and Spangler (loamy-skeletal, carbonatic, mesic, shallow Xerollic Paleorthids) soils.

During the course of this study, a spade and soil auger were used to determine depths to the petrocalcic horizon. This information was used to help confirm GPR and EM interpretations. Within the study site, the depth to petrocalcic horizon was observed to range from less than 10 cm to more than 125 cm. The petrocalcic horizon was identified by its resistance to hand-excavations. The expression of the petrocalcic horizon was variable. It was observed as a conglomerate of gravels and cobbles coated with calcium carbonates, a laminated, weakly cemented layer, and an indurated layer. In most profiles, a calcic horizon occurred immediately above the petrocalcic horizon. The thickness of the calcic horizon ranged from 0 to 23 cm.

Ground-Penetrating Radar:

Introduction:

Since 1978, the Soil Conservation Service has used GPR to increase the efficiency of soil sampling and the frequency of observations, extend the depth of observation, estimate taxonomic composition of soil map units, and evaluate variations in soil properties. Ground-penetrating radar techniques have been used to estimate depths to soil horizons (Collins and Doolittle, 1987; Doolittle, 1987), hard pans (Olson and Doolittle, 1985), ortstein (Mokma et al., 1990a) dense till and bedrock (Collins et al., 1989); assess the concentration of lamellae in soils (Farrish et al., 1990; Mokma et al., 1990b); and evaluate the thickness of surface layers (Doolittle, 1987). In addition, GPR has been used to study changes in soil properties which affect forest productivity (Farrish et al., 1990) and stress in citrus trees (Shih et al., 1985). Interpretations have been used to update soil survey reports (Schellentrager and Doolittle, 1985; Collins et al., 1986; and Schellentrager et al., 1988).

Ground-penetrating radar is an impulse radar system designed for relatively shallow (<10 m) investigations. The maximum depth of observation is, to a large degree, determined by the electrical conductivity of earthen materials. Soils having high electrical conductivities rapidly dissipate the radar's energy and restrict observation depths. The principal factors influencing the electrical

conductivity of soils are: (i) volumetric water content, (ii) amount and type of salts in solution, and (iii) the amount and type of clay. The electrical conductivity of soils increases with volumetric water content, concentration of soluble salts, exchange capacity, and clay content.

Because of their relatively high electrical conductivity, many soils are essentially radar opaque (Cook, 1973). Conductive soils limit observation depths and diminish the likelihood of resolving subsurface features. Because it does not perform equally in all soils, ground-penetrating radar is an imperfect tool.

Calibration:
When assessing the appropriateness of using GPR, a major consideration is signal attenuation at the desired antenna operating frequency (Daniels et al., 1988). The maximum depth of observation decreases rapidly with increasing antenna frequency. High frequency antennas (>500 mHz) can provide well resolved images of shallow features in soils having low conductivity. However, excessive levels of signal attenuation often preclude the use of high frequency antennas in soil having moderate electrical conductivities (Daniels et al., 1988). In these soils, lower frequency (80, 120, and 300 mHz) antennas can be used to improve the depth of observation. However, as lower frequency antennas are used to increase the depth of observation, the resolution of subsurface features is reduced.

A preliminary assessment of the GPR was conducted across a small, representative area of Borvant soils with both the 500 and 120 mHz antennas. The purpose of this study was to evaluate the depth of observation and resolution of each antenna. A scanning time of 60 nanoseconds (ns) was established on the control unit. As part of the calibration trials, a metallic reflector was buried at a depth of 43 cm.

Borvant soils were highly attenuating to the pulses radiated from the 500 mHz antenna. With the 500 mHz antenna, the depth of observation was restricted to the surface layer. Little or no subsurface information was obtained below the air/ground interface. The buried metallic reflector could not be discerned with the 500 mHz antenna.

The metallic reflector as well as several subsurface interfaces were discerned with the 120 mHz antenna. Based on the scaled depth to the buried metallic reflector, the calculated dielectric constant of the relatively dry, soil was 7.7. The velocity of propagation was an estimated 0.039 m/ns (0.130 ft/ns). With a scanning time of 60 ns, the maximum observation depth of the 120 mHz antenna in areas of Borvant soils was about 1.9 m.

While the maximum observation depth of the 120 mHz antenna was appropriate for this investigation, the resolution of subsurface interfaces was found to be poor and limiting during subsequent data analysis. In most areas traversed with GPR, depths to the petrocalcic horizon were very shallow (0 to 25 cm) or shallow (0 to 50 cm). Because of excessive signal ringing (produced by antenna resonance) and strong signal reflections from the soil surface, objects within depths

of about 40 cm from the surface could not be distinguished on radar profiles. The petrocalcic horizon was not distinguishable on radar profiles collected with either the 500 or 120 mHz antenna.

Radar Interpretations:
Figure 3 is a representative radar profile from Enclosure 3. The horizontal and vertical scales measure distances along the transect line and depths, respectively. These scales are in meters. Along this traverse, at an interval of 2 m, the radar operator impressed a segmented line, or distance mark, on the radar profile. The segmented, vertical lines indicate the location of observation points.

Petrocalcic horizons were latter observed in shallow excavations made at each observation site along the radar traverse (see Figure 3). Depths to this horizon ranged from about 20.3 to 30.5 cm. This shallow horizon was not detected with the 120 mHz antenna. Features occurring within the upper 43 cm were obscured on radar profiles by signal reflections and ringing from the soil surface. Variations in the intensity (gray- scale) of the near-surface reflection (at a depth of about 25 cm) represents changes in soil materials and possibly the petrocalcic horizon.

In Figure 3, a major subsurface interface bends across the radar profile. This interface consists of three dark, sub-parallel bands. It ranges in depth from about 48 to 89 cm. Signal attenuation has obscured most images and limited signal penetration below this interface. Although the identity of this interface was not verified, it is most likely a layer of alluvial materials.

Figure 4 is a radar profile from a traverse conducted parallel with the summit's elongated axis. The interval between observation points is 25 m. The horizontal and vertical scales measure distances along the transect line and depths, respectively. These scales are in meters. In Figure 4, several inclined interfaces can be seen extending upwards (from left to right) towards the soil surface. These interfaces are believed to represent truncated layers of alluvium. A shallow (about 40 cm) interface which appears to vary in the expression and continuity could represent the petrocalcic horizon. However, this interface is poorly expressed and partially obscured by strong reflections from the soil surface.

Electromagnetic Induction:
Introduction:
Electromagnetic induction techniques use electromagnetic energy to measure the apparent or terrain conductivity of earthen materials. Apparent conductivity is a weighted average conductivity measurement for a column of earthen materials to a specified observation depth (Greenhouse and Slaine, 1983). The averages are weighted according to the depth response function of each meter (Slavich and Petterson, 1990).

Variations in electromagnetic response are produced by changes in the electrical conductivity of earthen materials. Electrical conductivity

is an indicator of the ease with which electrical currents can be made to flow through a material. The electrical conductivity of earthen materials is influenced by the (i) volumetric water content, (ii) type and concentration of ions in solution, (iii) temperature and phase of the soil water, and (iv) amount and type of clays in the soil matrix, (McNeill, 1980a). The apparent conductivity of soils increases with exchange capacity, moisture content, and clay content (Kachanoski et al., 1988; Rhoades et al., 1976).

Electromagnetic induction techniques have been used by geologists and geophysicists to map glacial deposits, bedrock surfaces (Zalasiewicz et al., 1985) and permafrost (Kawasaki and Osterkamp, 1988), estimate the thickness of clay deposits (Palacky, 1987), locate sand and gravel deposits (McNeill, 1986), predict soil-water content (Kachanoski et al., 1988), and for groundwater investigations (Cook et al., 1989, Cook et al., 1992, and Greenhouse and Slaine, 1983). This technology has been used in soil science principally to identify, map, and monitor soil salinity and groundwater contamination (Corwin and Rhoades, 1982; Corwin and Rhoades, 1990; De Jong et al., 1979; Rhoades and Corwin, 1981; Slavich and Petterson, 1990; and Williams and Baker, 1982). In addition, this technology has been used to identify sodium-affected soils (Ammons et al., 1989; Nettleton et al., 1994), to chart depths to claypans (Doolittle et al., 1994), and to assess edaphic properties important to forest site productivity (McBride et al., 1990). These studies have documented uses of EM techniques as a noninvasive tool for interpretations and site assessments over broad geographic areas and diverse soil types.

Electromagnetic induction techniques integrate the physical and chemical properties of soils into estimates of electrical conductivity. The accuracy of these estimates and clarity of interpretations vary with site or terrain conditions. Coincident and equivalent changes in more than one factor (clay, moisture, or salt content) complicate interpretative models, reduce the accuracy and increase the uncertainty of estimated values, and diminish the usefulness of EM techniques. Areas with heterogeneous soils, stratigraphic, and/or topographic conditions are often difficult to characterize with EM techniques. In these area, changes in one factor can be obscured or eclipsed by variations in other factors.

Generally, the use of EM techniques has been most successful in areas where subsurface properties are reasonably homogeneous, the effects of one factor (clay, moisture, or salt content) dominates over the other factors, and variations in EM response can be related to changes in the dominant factor (Cook et al., 1992). In such areas, information is gathered on the dominant factor, and assumptions are made concerning the behavior of the other factors (Cook et al., 1989).

In this study, depth to petrocalcic horizons was assumed to be the dominant factor. Variations in the thickness of the solum and the presumed, marked contrasts in electrical properties between overlying solum and the more resistive petrocalcic horizon were considered the dominant factors likely to influence the response of the EM38 meter. Because of the effects of weathering, soils and unconsolidated alluvial sediments were assumed to have higher electrical conductivities than

the consolidated materials from which they formed. Borvant soils formed in medium-textured alluvium derived principally from limestone and sandstone bedrock. In most areas, unless affected by saline groundwater, sandstone and limestone bedrock have very low electrical conductivities (Palacky, 1987). It was assumed that the electromagnetic response of a petrocalcic horizon would be similar to the response of limestone bedrock. In addition, strongly cemented or indurated horizons (i.e. petrocalcic horizons) were assumed to have lower conductivities than noncemented soil horizons (i.e. calcic horizon). Based on these assumptions, it was hypothesized that values of apparent conductivity would be lower in areas of Borvant soils where either the petrocalcic horizon was nearer the soil surface or where rock fragments were more concentrated in the soil profile.

Field Methods:

A 200 by 575 meter grid (11.5 ha) was established across the study site. The grid interval was 25 meters. Survey flags were inserted in the ground at each grid intersection. This provided 216 observation points. At each grid intersection, measurements were taken with an EM38 and an EM31 meter placed on the ground surface in both the horizontal and vertical dipole orientations.

The study site contained four enclosures (see Figure 1). Each enclosure had dimensions of about 50 by 22 m (0.1 ha). Survey grids were established within each enclosure. Grid lines were referenced and measured into the larger grid which had been previously established across the study site. The grid interval within each enclosure was 2.0 m. Survey flags were inserted in the ground at each grid intersection. This provided 172, 166, 143, and 162 observation points for enclosures 1, 2, 3, and 4, respectively. Within each enclosure, to limit interference, grid lines and observation points were kept at least 2 meters away from the encircling barbed-wire fence. At each grid intersection, measurements were taken with the EM38 meter placed on the ground surface in both the horizontal and vertical dipole orientations.

The EM38 meter became inoperable during the later stages of the field work. The meter was returned to its manufacturer for repairs. After the meter had been repaired and returned, field work was completed on 30 August. Only the detailed survey of Enclosure 4 had been delayed by equipment repairs. To confirm the repeatability of EM measurements, seventy-one observation points within Enclosures 1, 2, and 3 were resurveyed. For each observation points, measurements taken with the EM38 meter on 30 August were higher than measurements taken during the first week of August. In both orientations, measurements averaged 2 mS/m higher on 30 August than during the first week of August. Differences were attributed to the effects of equipment repairs and recalibration, meter misplacement, observation errors, and/or temporal differences in electrical conductivity caused by variations in soil temperature and/or moisture content.

While the absolute difference between measurements taken during the first and last weeks of August was considered slight, because of the low electrical conductivities of Borvant soils, the relative difference was considered great. The results from measurements taken during the two periods are not comparable. However, in an attempt to reduce the

observed inaccuracy, 2 mS/m was subtracted from all EM38 measurements collected on 30 August. Had time permitted, all enclosures should have been resurveyed with the EM38 meter. The reader should bear in mind the differences that occurred and the changes that have been made to the data set.

Results and Discussion:

EM Surveys of the 11.5 Hectare Study Site

Electromagnetic responses recorded with each meter and coil orientation were relatively low across the 11.5 hectare study site. At most observation points, apparent conductivity increased with increasing observation depths. This relationship was believed to be associated with increasing calcium carbonate, clay and/or moisture contents with increasing depth. Similar spatial patterns were obtained with each meter and coil orientation across the ballena. Values of apparent conductivity were generally higher on summit and lower backslope positions and lower on shoulder and upper backslope positions.

Based on 216 observations, the apparent conductivity measured with the EM38 meter in the horizontal dipole orientation averaged 5.3 mS/m and ranged from 1 mS/m to 19 mS/m. One-half of the observations collected in the horizontal dipole orientation had apparent conductivity values between 3 and 7 mS/m. In the vertical dipole orientation, apparent conductivity averaged 8.8 mS/m, with a range of 3 to 28 mS/m. One-half of the observations collected in the vertical dipole orientation had apparent conductivity values between 5 and 11 mS/m.

At each observation point, measurements taken with the EM38 meter in the vertical dipole orientation were higher than measurements taken in the horizontal dipole orientation. This relationship was believed to be associated with increasing calcium carbonate, clay and/or moisture contents with increasing depth.

In general, values of apparent conductivity obtained with the EM38 meter were lower on shoulder and upper backslope positions and higher on summit and lower-lying side slope positions. This pattern is presumed to reflect shallower depths to the petrocalcic horizon, greater concentrations of rock fragments, and/or coarser-textured soil materials on shoulder and upper backslope positions. On shoulder and upper backslope positions of the ballena, erosion has been most severe, surface layers removed, gravels concentrated, and in some areas, the petrocalcic horizon exposed. Values of apparent conductivity increased on lower backslope positions. Soils on these positions were presumed to be deeper over petrocalcic horizons and to have slightly higher clay and moisture contents.

With the deeper-sensing EM31 meter, the apparent conductivity averaged 15.4 mS/m in the horizontal dipole orientation across the ballena. In the horizontal dipole orientation, values of apparent conductivity ranged from 6 mS/m to 43 mS/m. One-half of the observations (216) collected in the horizontal dipole orientation had apparent conductivity values between 10 and 20 mS/m. In the vertical mode, the averaged apparent conductivity was 22.1 mS/m, with a range of 9 to 49

mS/m. One-half of the observations collected in the vertical dipole orientation had apparent conductivity values between 14 and 29 mS/m.

At most (96 percent) observation points, measurements taken with the EM31 meter in the vertical dipole orientation were higher than measurements taken in the horizontal dipole orientation. This relationship suggests the presence of more resistive materials (i.e. coarser-textured soil materials, rock fragments, petrocalcic horizons) near the surface and more conductive materials (i.e. clays, soluble salts, and/or water) at greater soil depths. This relationship also suggests the presence of unconsolidated alluvial materials and the absence of either sandstone or limestone bedrock (unless affected by saline groundwater) within depths of 6 m. The bedrock was presumed to have lower conductivities than the weathered, unconsolidated alluvial materials. If present within the observation depth of the EM31 meter, limestone or sandstone bedrock should cause values of apparent conductivity to decrease with increasing soil depths.

Two-dimensional plots of apparent conductivity values have been simulated from data collected with the EM38 meter (see figure 5 to 8) and with the EM31 meter (see figures 9 to 12). These plots simulate data collected with each meter and coil orientation. In these plots, the isarithmic intervals are either 2, 4, or 8 mS/m. Intervals were selected based on the range of data, range in observation or equipment errors (2 to 4 mS/m), and to illustrate spatial patterns.

EM Survey of the 0.1 Hectare Enclosures

Each enclosure was surveyed with the EM38 meter. The general spatial patterns revealed in simulations of the data collected over the large grid site (figures 5 to 12) compares acceptably with data collected in each enclosure (figures 13 to 18). However, a more intense sampling scheme (2 m versus 25 m interval) has produced more intricate and concise plots of the spatial distribution of apparent conductivity values within each enclosure.

Enclosure 1

Based on 172 observations, the apparent conductivity measured with the EM38 meter in the horizontal dipole orientation averaged 5.9 mS/m and ranged from 2 mS/m to 11 mS/m. One-half of the observations collected in the horizontal dipole orientation had apparent conductivity values between 4 and 7 mS/m. In the vertical mode, the apparent conductivity averaged 11.0 mS/m, with a range of 6 to 16 mS/m. One-half of the observations collected in the vertical dipole orientation had apparent conductivity values between 9 and 13 mS/m.

The spatial distributions of apparent conductivity values within Enclosure 1 have been simulated in Figures 13 and 14. In each figure, the isarithmic intervals is 2 mS/m. At each observation point, measurements taken with the EM38 meter in the vertical dipole orientation were higher than measurements taken in the horizontal dipole orientation. This relationship is believed to be associated with increasing calcium carbonate or more soluble salts, clay and/or moisture contents with increasing soil depth.

In the data sets collected with the EM38 meter, values were higher in the east and the south portions of the enclosure. These areas are suspected of having slightly deeper depths to the petrocalcic horizon. In addition, the rate and magnitude of change appears greatest in the southwestern and central portions of the enclosure. It was assumed that the depth to the petrocalcic horizon would be more variable in these portions of the enclosure.

Enclosure 2

Based on 166 observations, the apparent conductivity measured with the EM38 meter in the horizontal dipole orientation averaged 4.5 mS/m and ranged from 2 mS/m to 10 mS/m. One-half of the observations collected in the horizontal dipole orientation had apparent conductivity values between 3 and 6 mS/m. In the vertical mode, the apparent conductivity averaged 6.6 mS/m, with a range of 4 to 13 mS/m. One-half of the observations collected in the vertical dipole orientation had apparent conductivity values between 5 and 8 mS/m.

The spatial distributions of apparent conductivity values within Enclosure 2 have been simulated in Figures 15 and 16. In each figure, the isarithmic intervals is 2 mS/m. At each observation point, measurements taken with the EM38 meter in the vertical dipole orientation were higher than measurements taken in the horizontal dipole orientation. This relationship is believed to associated with increasing calcium carbonate or more soluble salts, clay, and/or moisture contents with increasing depth.

In both orientations, with the exception of the northwest portion of the enclosure, values of apparent conductivity were relatively low and invariable. The higher measurements in the northwest portion are associated with slightly deeper depths to petrocalcic horizons.

Enclosure 3

Based on 143 observations, the apparent conductivity measured with the EM38 meter in the horizontal dipole orientation averaged 4.0 mS/m and ranged from 2 mS/m to 8 mS/m. One-half of the observations collected in the horizontal dipole orientation had apparent conductivity values between 3 and 5 mS/m. In the vertical mode, the apparent conductivity averaged 6.8 mS/m, with a range of 4 to 11 mS/m. One-half of the observations collected in the vertical dipole orientation had apparent conductivity values between 6 and 8 mS/m.

The spatial distributions of apparent conductivity values within Enclosure 3 have been simulated in Figures 17 and 18. In each figure, the isarithmic intervals is 2 mS/m. At all but one observation point, measurements taken with the EM38 meter in the vertical dipole orientation were higher than measurements taken in the horizontal dipole orientation.

In both orientations, values of apparent conductivity were slightly higher along the western border and in the northeast portion of the enclosure. The higher measurements in these areas are associated with slightly deeper depths to the petrocalcic horizons.

Enclosure 4

Based on 162 observations, the apparent conductivity measured with the EM38 meter in the horizontal dipole orientation averaged 4.8 mS/m and ranged from 1 mS/m to 12 mS/m. One-half of the observations collected in the horizontal dipole orientation had apparent conductivity values between 3 and 6 mS/m. In the vertical mode, the apparent conductivity averaged 10.6 mS/m, with a range of 5 to 21 mS/m. One-half of the observations collected in the vertical dipole orientation had apparent conductivity values between 9 and 12 mS/m.

The spatial distributions of apparent conductivity values within Enclosure 4 have been simulated in Figures 19 and 20. In each figure, the isarithmic intervals is 2 mS/m. At all but one observation point, measurements taken with the EM38 meter in the vertical dipole orientation were higher than measurements taken in the horizontal dipole orientation.

In both orientations, values of apparent conductivity were noticeably higher and more variable in the northwest corner of the enclosure. The higher measurements in the northwest portion of the enclosure are associated with deeper depths to the petrocalcic horizons.

Estimating the Depths to Petrocalcic Horizon

Based on a small sample (nineteen observations), depths to petrocalcic horizon and apparent conductivity values are related (figures 21 and 22). The coefficient of determination, r^2, between the depth to petrocalcic horizon and values of apparent conductivity was 0.7674 in the horizontal dipole orientation (see Figure 21) and 0.6871 in the vertical dipole orientation (see Figure 22). Considering the diverse topographic setting, the potential variability of the alluvial materials, and the large volume of soil measured with the EM38 meter compared with the relatively small volume of soil sampled with the probe, the correlation was considered favorable.

Values of apparent conductivity obtained with the different coil orientations were strongly inter-dependent ($r^2 = 0.9588$). Since a stronger relationship existed between the apparent conductivity values obtained with the EM38 meter in the horizontal dipole orientation and the depth to petrocalcic horizon, these values were used to develop a regression equation to predict the depths to the petrocalcic horizon from values of apparent conductivity. The following equation was developed for this area of Borvant soils:

Linear regression ($r^2 = 0.767$):

$$D = -2.06970 + (7.015341 * X) \qquad [1]$$

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

Depths to the petrocalcic horizon can be estimated using measurements taken with the EM38 meter in the horizontal dipole orientation and the regression equation [1]. This data can be statistical analyzed. Analysis may indicate the suitability of sites for range plants. Computer simulations can be developed to help summarize variations in the depths to the petrocalcic horizon, assess the suitability of sites for various uses, and facilitate the selection of sampling sites. However, the accuracy of these simulations depends on knowledge of terrain conditions and the adequacy of the data used to construct the regression equations.

Based on EM measurements taken at the 216 observation points and the regression equation [1], the average depth to the petrocalcic horizon within the 11.5 hectare study site was 35.1 cm with a range of 4.95 to 131.22 cm. One-half of the observations had estimated depths to the petrocalcic horizon between 18.98 and 47.04 cm.

Within the 11.5 hectare area of Borvant soils, depths to the petrocalcic horizon were estimated to be very shallow (0 to 25 cm) at 29 percent, shallow (0 to 50 cm) at 79 percent, moderately-deep (50 to 100 cm) at 19 percent, and deep (100 to 150 cm) at 2 percent of the observation points. Figure 23 is a two-dimensional contour plot of the estimated depths to the petrocalcic horizon within the study site. The contour interval is 25 cm.

Based on EM measurements taken at 172 observation points within Enclosure 1 and the regression equation [1], the average depth to the petrocalcic horizon was 39.7 cm with a range of 11.96 to 75.10 cm. One-half of the observations had estimated depths to the petrocalcic horizon between 25.99 and 47.04 cm.

Depths to the petrocalcic horizon were estimated to be very shallow (0 to 25 cm) at 11 percent, shallow (0 to 50 cm) at 76 percent, and moderately-deep (50 to 100 cm) at 24 percent of the observation points. Figure 24 is a two-dimensional contour plot of the estimated depths to the petrocalcic horizon within Enclosure 1. The contour interval is 25 cm.

Based on EM measurements taken at 166 observation points within Enclosure 2 and the equation [1], the average depth to the petrocalcic horizon was 29.2 cm with a range of 11.96 to 68.08 cm. One-half of the observations had estimated depths to the petrocalcic horizon between 18.98 and 40.02 cm.

Depths to the petrocalcic horizon were estimated to be very shallow (0 to 25 cm) at 43 percent, shallow (0 to 50 cm) at 92 percent, and moderately-deep (50 to 100 cm) at 8 percent of the observation points. Figure 25 is a two-dimensional contour plot of the estimated depths to the petrocalcic horizon within Enclosure 2. The contour interval is 25 cm.

Based on EM measurements taken at 143 observation points within Enclosure 3 and the equation [1], the average depth to the petrocalcic horizon was 25.8 cm with a range of 11.96 to 54.05 cm. One-half of the

observations had estimated depths to the petrocalcic horizon between 18.98 and 33.03 cm.

Depths to the petrocalcic horizon were estimated to be very shallow (0 to 25 cm) at 40 percent, shallow (0 to 50 cm) at 99 percent, and moderately-deep (50 to 100 cm) at 1 percent of the observation points. Figure 26 is a two-dimensional contour plot of the estimated depths to the petrocalcic horizon within Enclosure 3. The contour interval is 25 cm.

Based on EM measurements taken at 162 observation points within Enclosure 4 and the equation [1], the average depth to the petrocalcic horizon was 31.5 cm with a range of 1.00 to 82.11 cm. One-half of the observations had estimated depths to the petrocalcic horizon between 18.98 and 40.02 cm.

Depths to the petrocalcic horizon were estimated to be very shallow (0 to 25 cm) at 25 percent, shallow (0 to 50 cm) at 89 percent, and moderately-deep (50 to 100 cm) at 11 percent of the observation points. Figure 27 is a two-dimensional contour plot of the estimated depths to the petrocalcic horizon within Enclosure 4. The contour interval is 25 cm.

If depth to the petrocalcic horizon is the dominant limiting factor to range production in areas of Borvant soils, very shallow and shallow depths are the most restricting soil depths. Petrocalcic horizons were shallowest within Enclosure 3 (99 percent shallow) and deepest within Enclosure 1 (76 percent). In terms of the averaged depth to petrocalcic horizon the enclosures would be arranged (in order from the deepest to the shallowest averaged depths) as Enclosure 1 (39.7 cm), Enclosure 4 (31.50 cm), Enclosure 2 (29.2 cm), and Enclosure 3 (25.8 cm).

CONCLUSIONS

1. Within the investigated area of Borvant soils, the use of GPR techniques is appropriate for the investigation of petrocalcic horizons. However, poor knowledge of GPR performance in these soils and incorrect antenna selection were responsible, in part, for the radar's poor performance. In addition, the failure of the model 38 VDU unit and digital audio tape-corder to capture the radar data, prevented any attempts at signal processing. The acquisition of the newly developed SIR System-2 radar system and the use of a 300 mHz antenna would help to overcome these deficiencies and should permit improved detection and resolution of the petrocalcic horizon in areas of Borvant soils. The SIR System-2 is a portable, digital radar system with a wide variety of data processing, transfer and display functions.

This study has helped to emphasize our rudimentary knowledge of the radar performance and applications in "western" soils. Prior to this study, SCS had used GPR techniques only once (1986) in areas west of the Rocky Mountains. In this region, increased experience can only

help to facilitate the greater and more appropriate applications of GPR techniques.

2. Electromagnetic induction techniques appears to be useful for estimating depths to the petrocalcic horizons within selected sites. A high correlation was found between EM response and the depth to petrocalcic horizon in an area of Borvant soils. More investigations in other areas of Borvant soil are needed to verify and to establish the general form of this relationship.

In order to assess the effects of temporal differences in soil moisture and temperature on EM measurements, investigations needs to include more extensive data sets collected at multiple sites and at different times of the year. It does appears feasible, at least in some areas, to use EM methods and computer graphics techniques for mapping the depth to contrasting soil horizons and lithologic layers, thus enhancing our understanding of these subsurface features.

Large quantities of data are needed to support soil information and modeling systems. Lateral and vertical variations in some soils properties can be inferred using the techniques discussed in this report. A large number of measurements can be collected with EM techniques in a very short period of time. Empirical relationships between the depth to petrocalcic horizon and EM response can be developed from a limited number of observation points. Regression equations can be used to predict the depth to petrocalcic horizon over large areas. Data can be processed and displayed on two-dimensional plots.

3. Drs. Boettinger and West of Utah State University will evaluate the results of this survey and determine whether a correlation exist between EM data and forage productions within the enclosures.

4. An EM38 meter (serial number 9319007) has been loaned to the soil staff in Utah for the period of 15 August to 1 November 1994.

It was my pleasure to work in Utah and with members of your fine staff and the staff of Utah State University. If I can be of any further assistance, please do not hesitate to ask.

With kind regards

Jim Doolittle

James A. Doolittle
Soil Specialist

cc:
Janis Boettinger, Utah State University, Logan, Utah
James Culver, Assistant Director, NSSC, MNTC, SCS, Lincoln, NE
William Dollarhide, State Soil Scientist, SCS, 5301 Longley Lane, Reno, NV 89511
Mike Domier, Soil Correlator, SCS, Salt Lake City, UT
Steve Holzhey, Assistant Director, NSSC, MNTC, SCS, Lincoln, NE
Cameron Loerch, Team Leader LRR 5, NSSC, MNTC, SCS, Lincoln, NE

REFERENCES

Ammons, J. T., M. E. Timpson, and D. L. Newton. 1989. Application of an aboveground electromagnetic conductivity meter to separate Natraqualfs and Ochraqualfs in Gibson County, Tennessee. Soil Survey Horizons 30(3):66-70.

Collins, M. E., and J. A. Doolittle. 1987. Using ground-penetrating radar to study soil microvariability. Soil Sci Soc. Am. J. 51:491-493.

Collins, M. E., J. A. Doolittle, and R. V. Rourke. 1989. Mapping depth to bedrock on a glaciated landscape with ground-penetrating radar. Soil Sci. Soc. Am. J. 53:1806-1812.

Collins, M. E., G. W. Schellentrager, J. A. Doolittle, and S. F. Shih. 1986. Using ground-penetrating radar to study changes in soil map unit composition in selected Histosols. Soil Sci. Soc. Am. J. 50:408-412.

Cook, J. C. 1973. Radar exploration through rock in advance of mining. Trans. Society of Mining Engineers, AIME 254:140-146.

Cook, P. G., M. W. Hughes, G. R. Walker, and G. B. Allison. 1989. The calibration of frequency-domain electromagnetic induction meters and their possible use in recharge studies. Journal of Hydrology 107:251-265.

Cook, P. G., G. R. Walker, G. Buselli, I. Potts, and A. R. Dodds. 1992. The application of electromagnetic techniques to groundwater recharge investigations. Journal of Hydrology 130:201-229.

Corwin, D. L., and J. D. Rhoades. 1982. An improved technique for determining soil electrical conductivity-depth relations from above-ground electromagnetic measurements. Soil Sci. Soc. Am. J. 46:517-520.

Corwin, D. L., and J. D. Rhoades. 1990. Establishing soil electrical conductivity - depth relations from electromagnetic induction measurements. Communications in Soil Sci. Plant Anal. 21(11&12):861-901.

Daniels, D. J., D. J. Gunton, and H. F. Scott. 1988. Introduction to subsurface radar. IEE Proceedings 135:(F4) 278-320.

De Jong, E., A. K. Ballantyne, D. R. Cameron, and D. W. L. Read. 1979. Measurement of apparent electrical conductivity of soils by an electromagnetic induction probe to aid salinity surveys. Soil Sci. Soc. Am. J. 43:810-812.

Doolittle, J. A. 1987. Using ground-penetrating radar to increase the quality and efficiency of soil surveys. IN Soil Survey Techniques, Soil Science Society of America Special Publ. No 20. pp. 11-32.

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

Farrish, K. W., J. A. Doolittle, and E. E. Gamble., 1990. Loamy substrata and forest productivity of sandy glacial drift soils in Michigan. Canadian J. of Soil Sci. 70:181-187.

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

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

Kawasaki, K. and T. E. Osterkamp. 1988. Mapping shallow permafrost by electromagnetic induction - practical considerations. Cold Region Science and Technology 15: 279-288.

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

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

McNeill, J. D. 1980b. Electromagnetic terrain conductivity measurements at low induction numbers. Technical Note TN-6. Geonics Ltd., Mississauga, Ontario. p. 15.

McNeill, J. D. 1986. Geonics EM38 ground conductivity meter operating instructions and survey interpretation techniques. Technical Note TN-21. Geonics Ltd., Mississauga, Ontario. p. 16.

Mokma, D. L., R. J. Schaetzl, J. A. Doolittle, and E. P. Johnson. 1990a. Ground-penetrating radar study of ortstein continuity in some Michigan Haplaquods. Soil Sci. Soc. Am. J. 54:936-938.

Mokma, D. L., R. J. Schaetzl, E. P. Johnson, and J. A. Doolittle. 1990b. Assessing Bt horizon character in sandy soils using ground-penetrating radar: Implications for soil surveys. Soil Survey Horizons. 30(2):1-8.

Nettleton, W. D., L. Bushue, J. A. Doolittle, T. J. Endres, and S. J. Indorante. 1994. Sodium-affected soil identification in south-central Illinois by electromagnetic induction. Soil Sci. Soc. Am. J. 58:1190-1193.

Olson, C. G. and J. A. Doolittle. 1985. Geophysical techniques for reconnaissance investigations of soils and surficial deposits in mountainous terrain. Soil Sci. Soc. Am. J. 49: 1490-1498.

Palacky, G. J. 1987. Clay mapping using electromagnetic methods. First Break 5(8):295-306.

Rhoades, J. D. and D. L. Corwin. 1981. Determining soil electrical conductivity-depth relations using an inductive electromagnetic soil conductivity meter. Soil Sci. Soc. Am. J. 45:255-260.

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

Schellentrager G. W. and J. A. Doolittle. 1985. Evaluating subsidence of Histosols in the Everglade Agricultural Area using ground-penetrating radar. Final Report. USDA-Soil Conservation Service, Gainesville, Florida. pp. 40.

Schellentrager, G. W., J. A. Doolittle, T. E. Calhoun, and C. A. Wettstein. 1988. Using ground-penetrating radar to update soil survey information. Soil Sci. Soc. Am. J. 52:746-752.

Shih, S. F., D. L. Myhre, G. W. Schellentrager, V. W. Carlisle, and J. A. Doolittle. 1985. Using radar to assess the soil characteristics related to citrus stress. Soil and Crop Science of Florida, Proc. 45:54-59.

Slavich, P. G. and G. H. Petterson. 1990. Estimating average rootzone salinity from electromagnetic induction (EM-38) measurements. Australian J. Soil Res. 28:453-463.

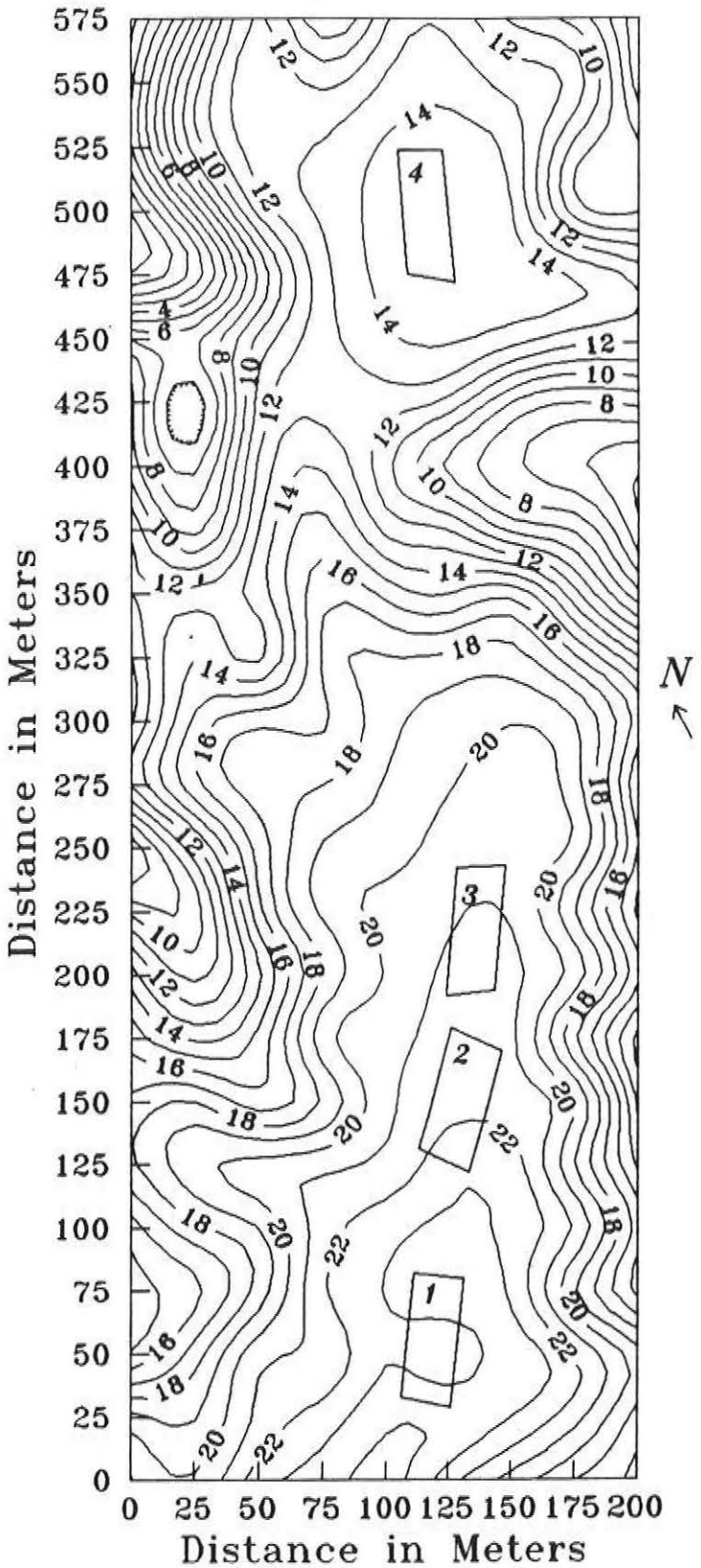
Trickler, D. L. and D. T. Hall. 1984. Soil Survey of Fairfield-Nephi Area, Utah; Parts of Juab, Sanpete, and Utah Counties. USDA Soil Conservation Service. U.S. Government Printing Office, Washington, D.C. p. 361.

Williams, B. G. and G. C. Baker. 1982. An electromagnetic induction technique for reconnaissance surveys of soil salinity hazards. Australian J. Soil Res. 20:107-118.

Zalasiewicz, J. A., S. J. Mathers, and J. D. Cornwell. 1985. The application of ground conductivity measurements to geological mapping. Q. J. English Geol. London 18:139-148.

RELATIVE TOPOGRAPHY OF MILLS SITE

Contour Interval = 1.0 M



TOPOGRAPHY AT THE MILLS SITE

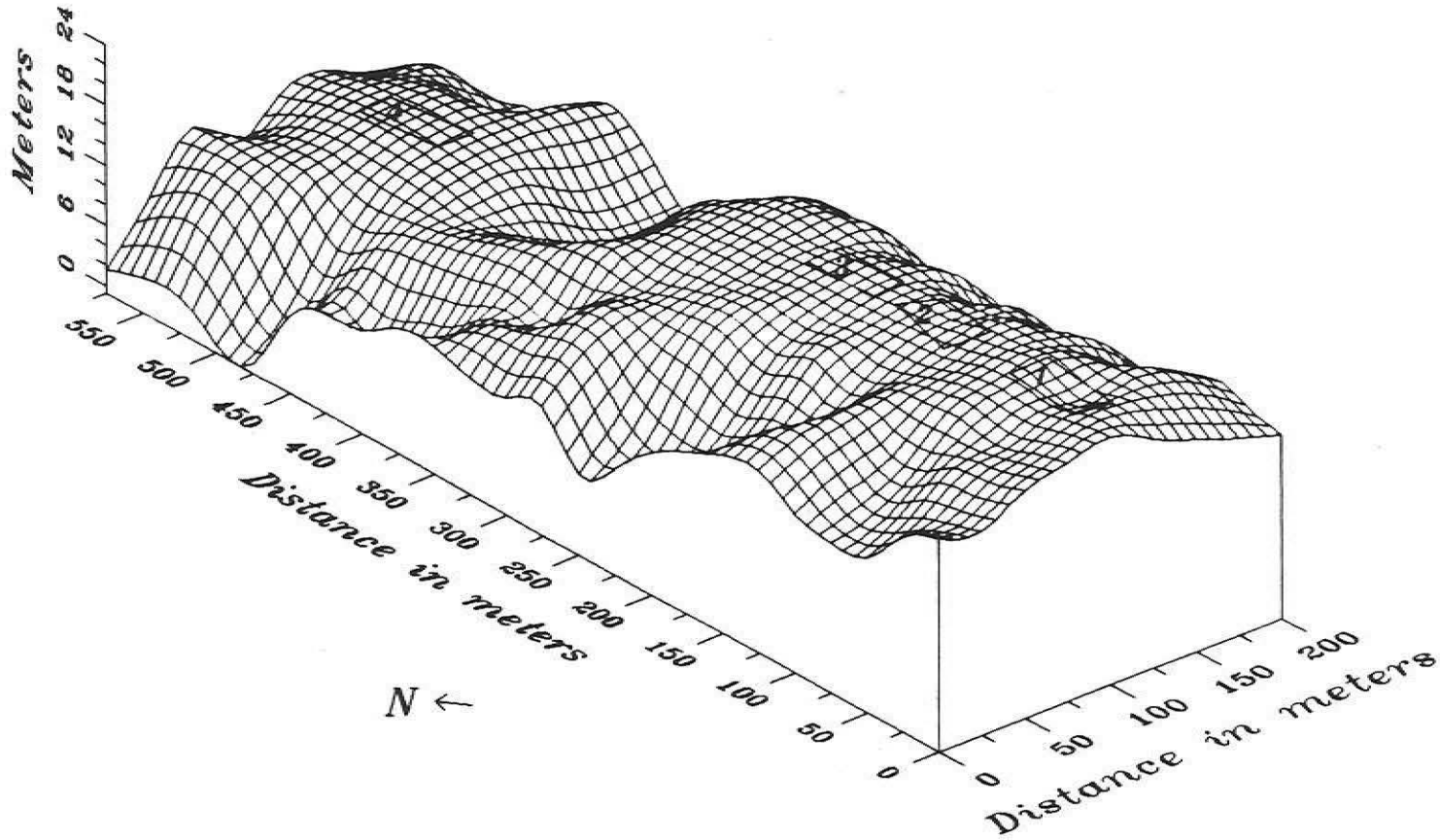


Figure 2

Figure 3

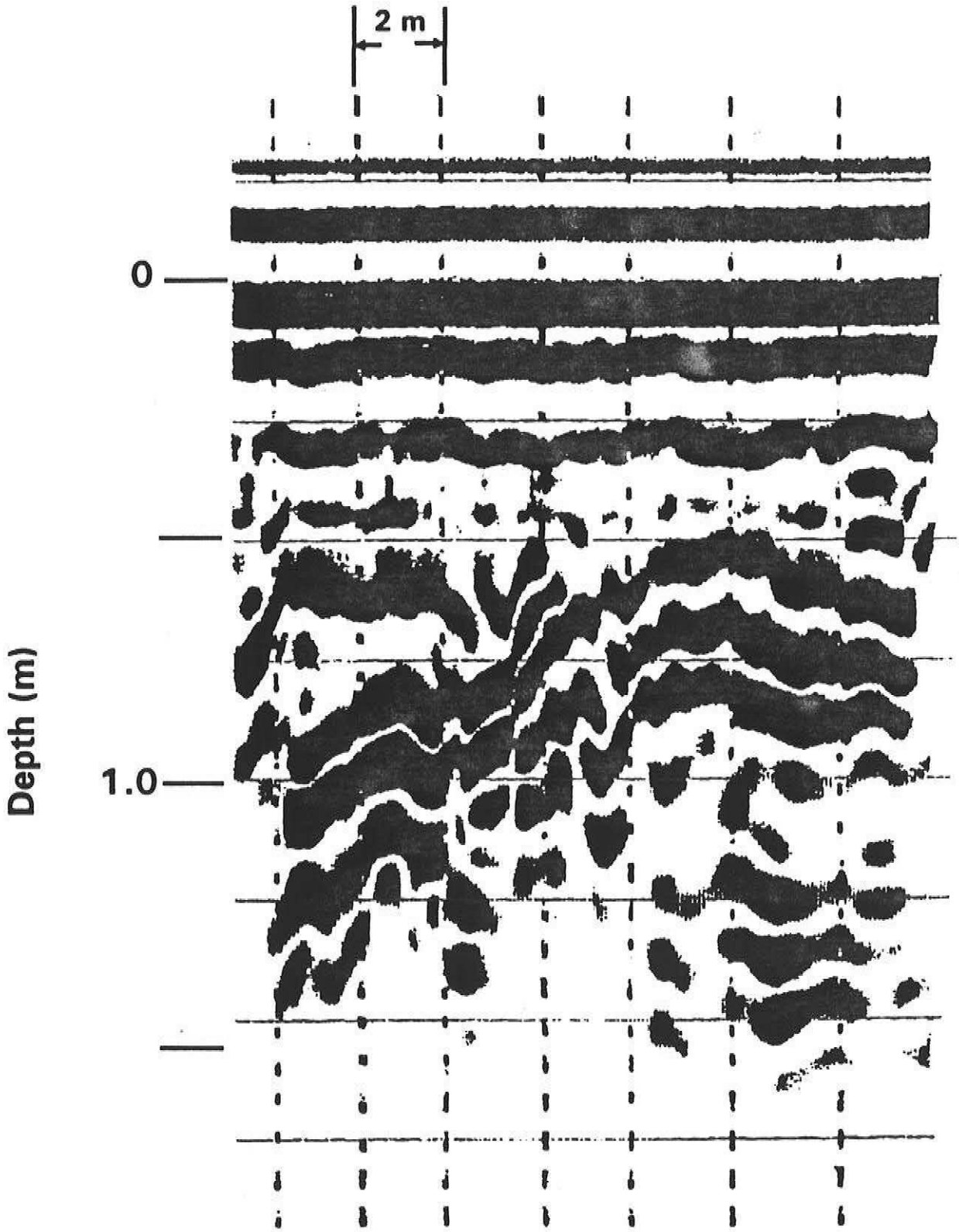
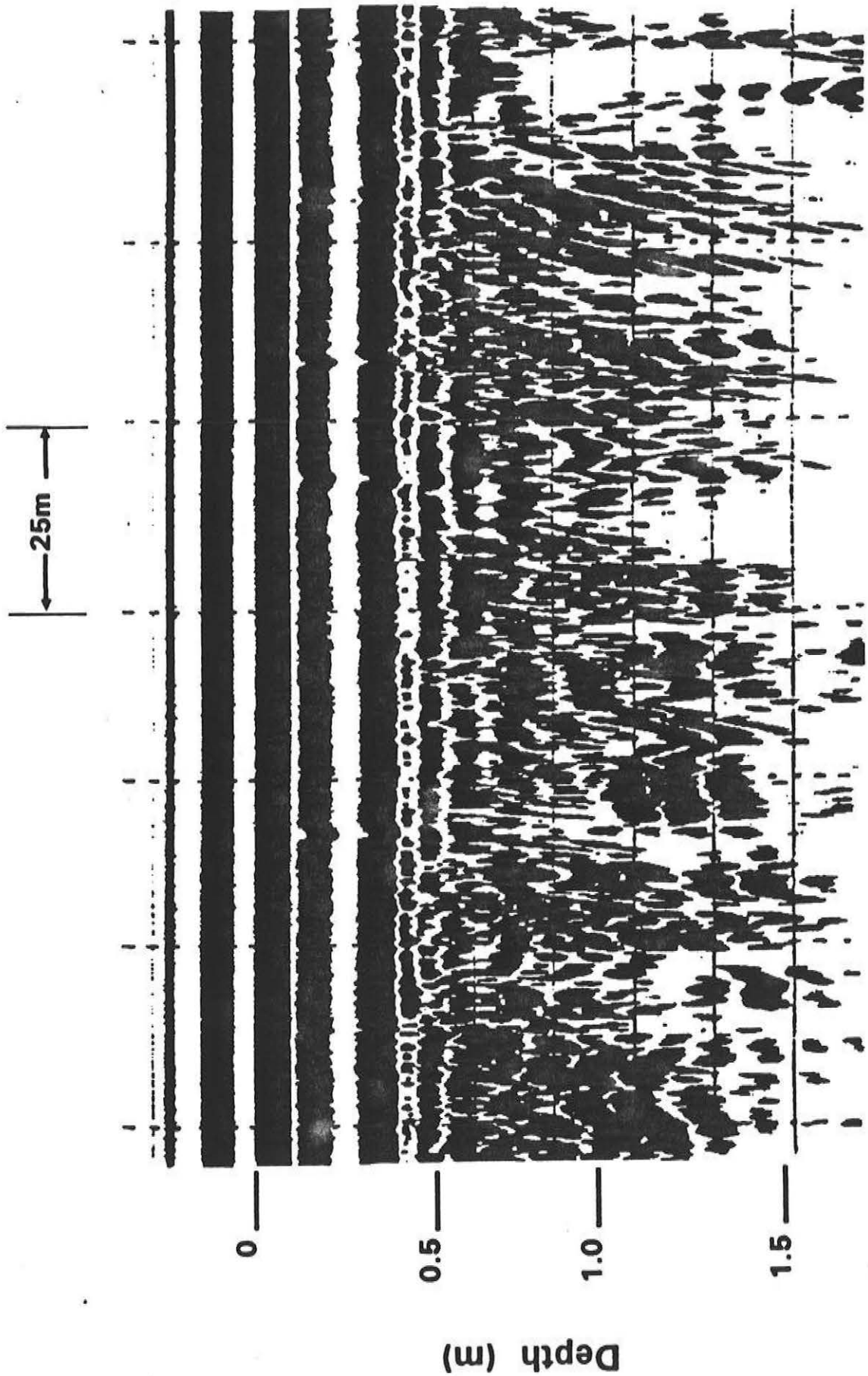
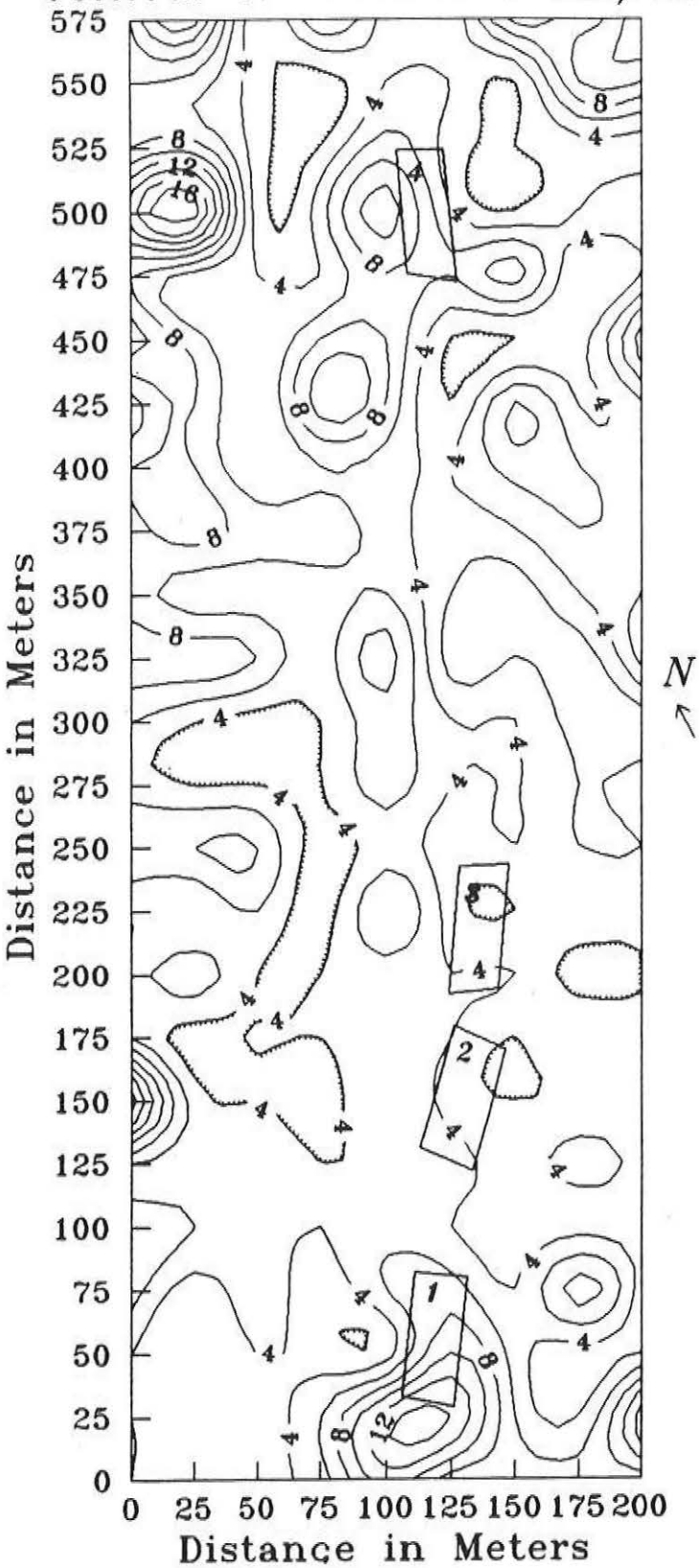


Figure 4



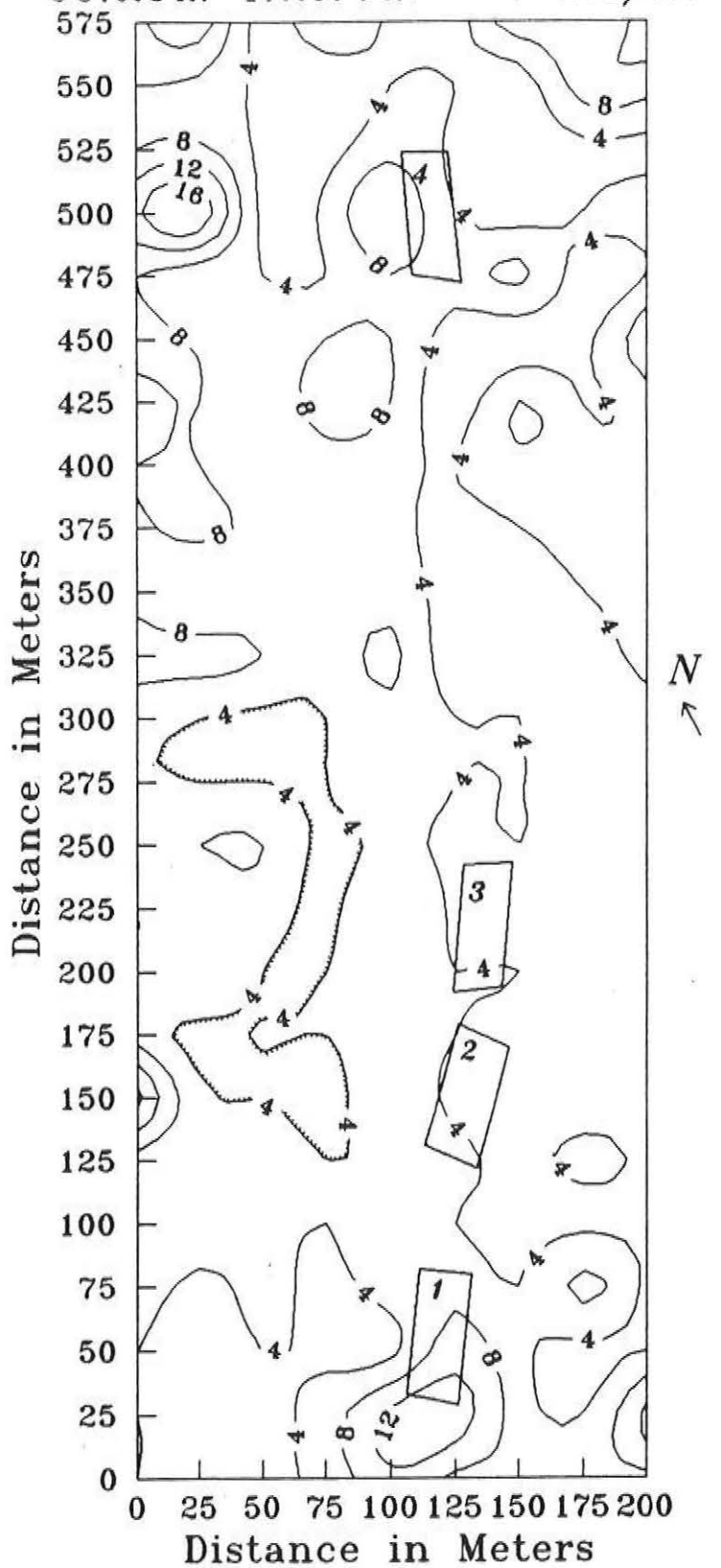
EM SURVEY OF MILLS SITE

EM38 Meter
Horizontal Dipole Orientation
Contour Interval = 2 mS/m



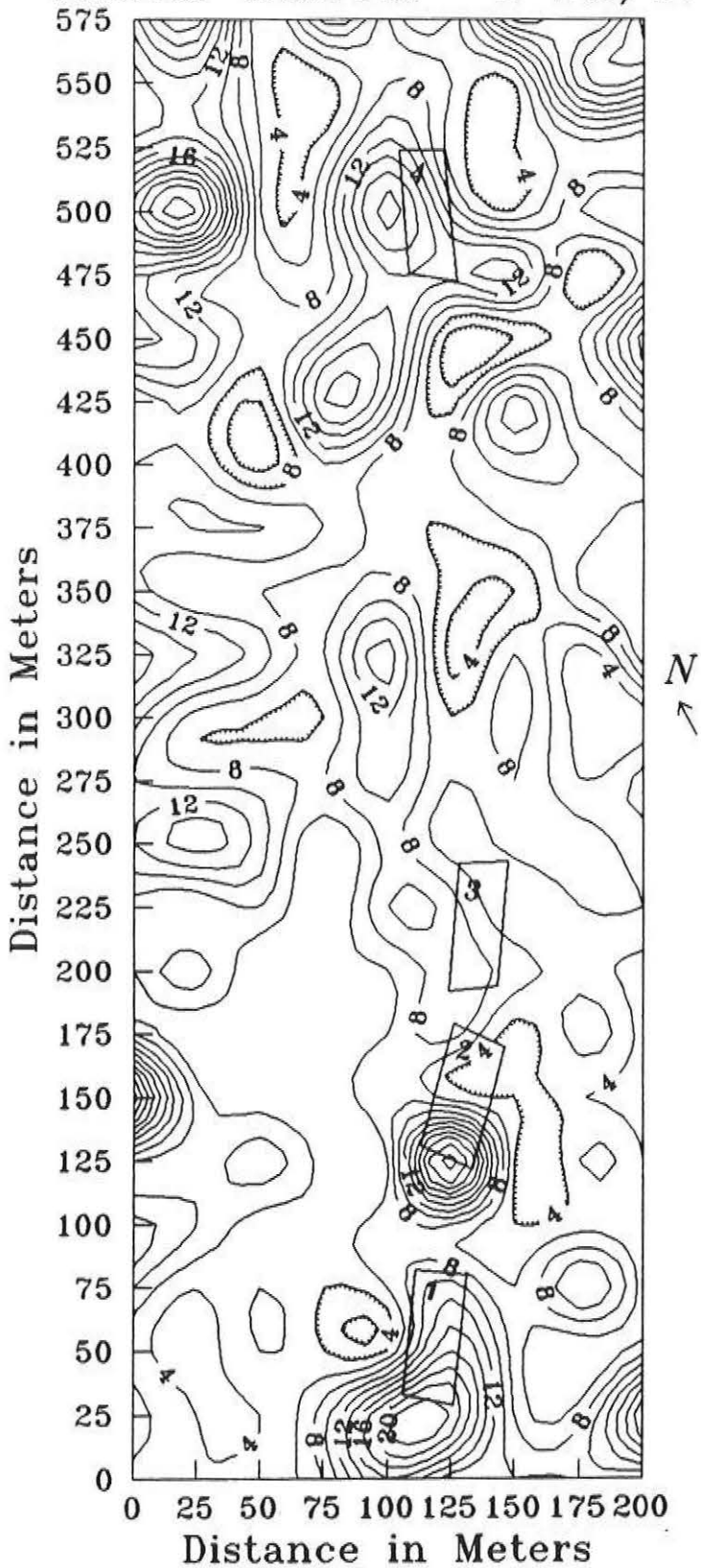
EM SURVEY OF MILLS SITE

EM38 Meter
Horizontal Dipole Orientation
Contour Interval = 4 mS/m



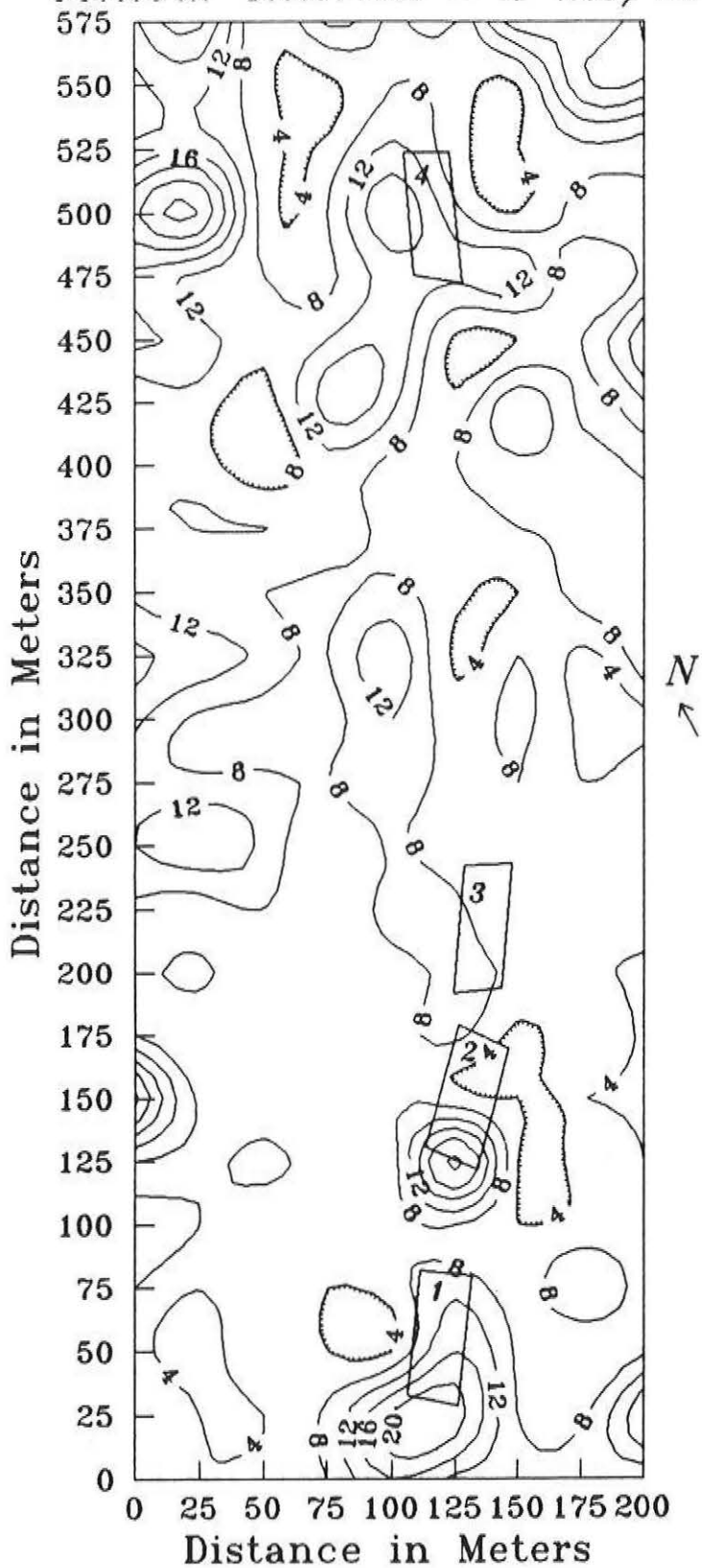
EM SURVEY OF MILLS SITE

EM38 Meter
Vertical Dipole Orientation
Contour Interval = 2 mS/m



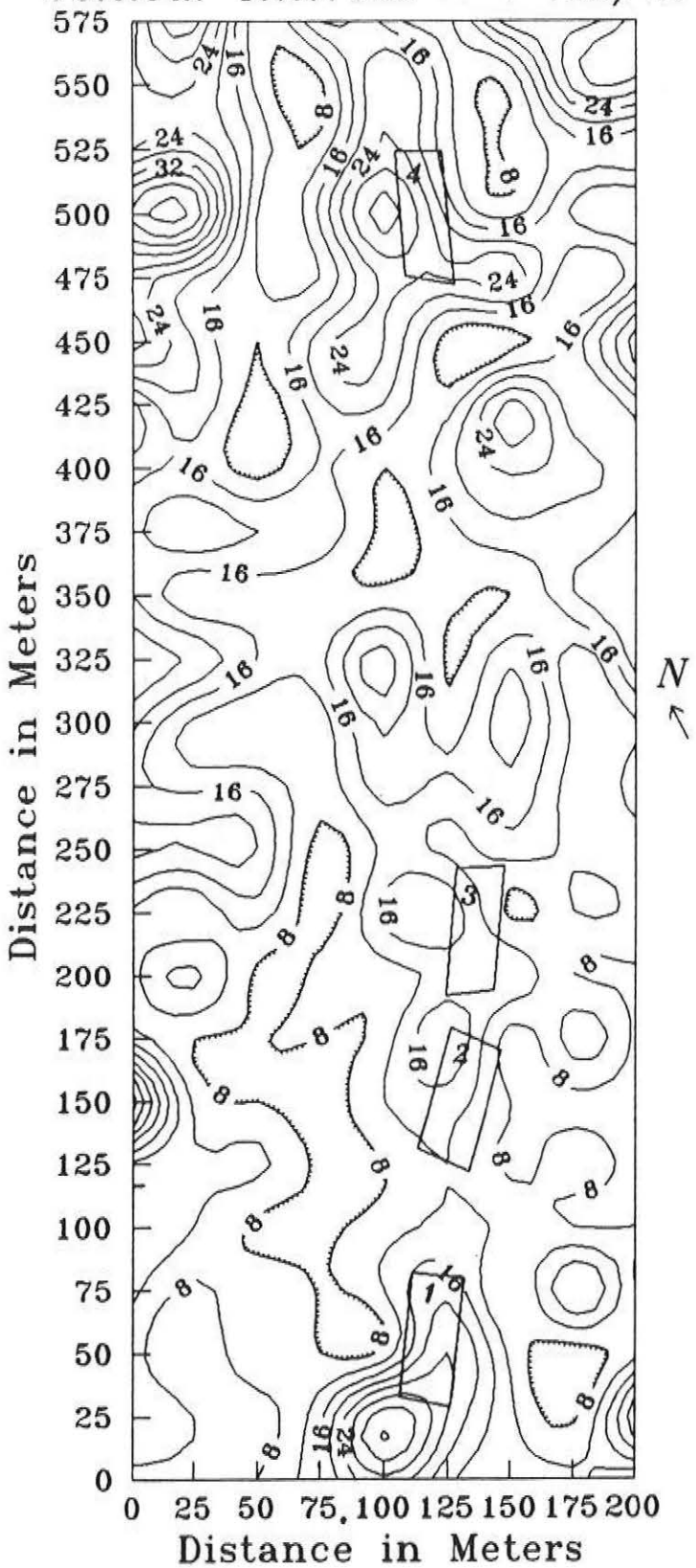
EM SURVEY OF MILLS SITE

EM38 Meter
Vertical Dipole Orientation
Contour Interval = 4 mS/m



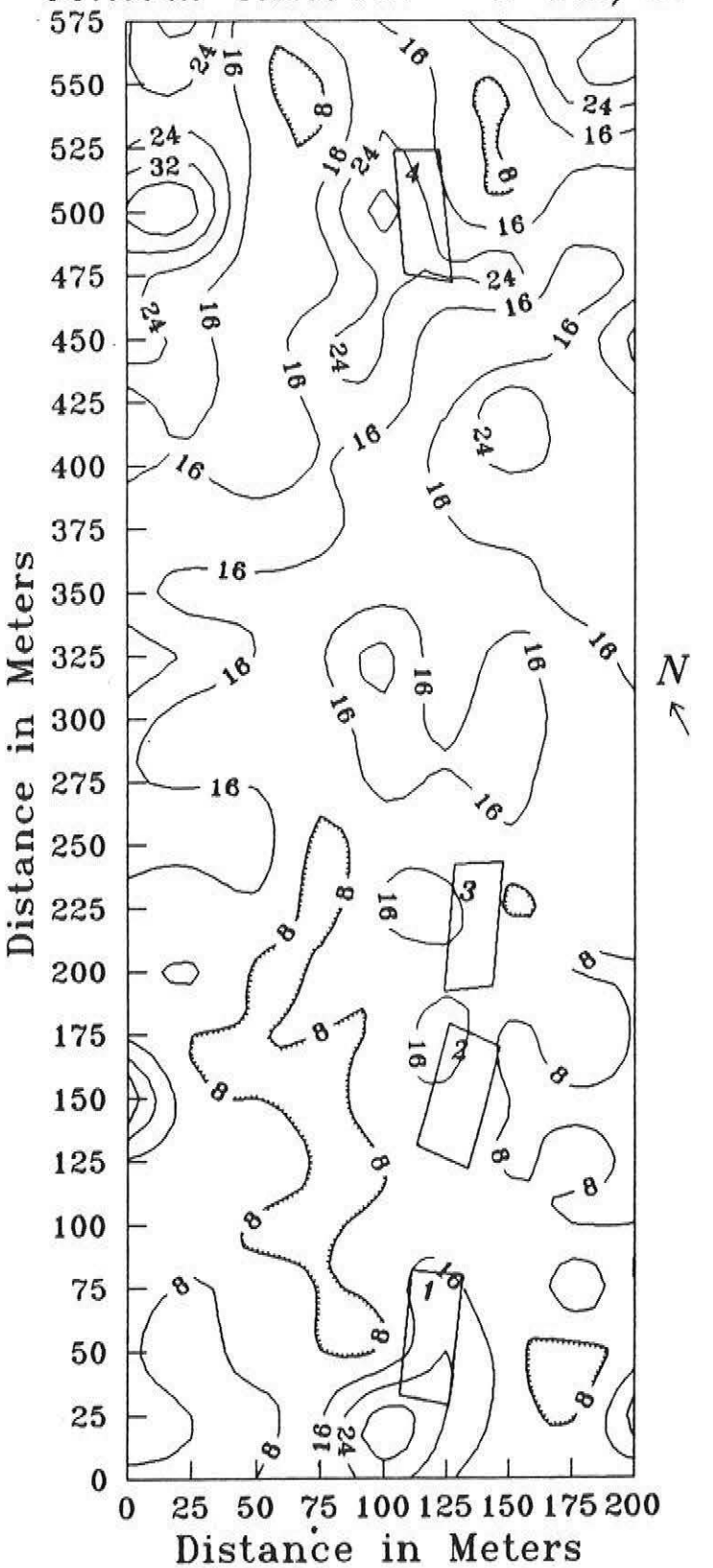
EM SURVEY OF MILLS SITE

EM31 Meter
Horizontal Dipole Orientation
Contour Interval = 4 mS/m



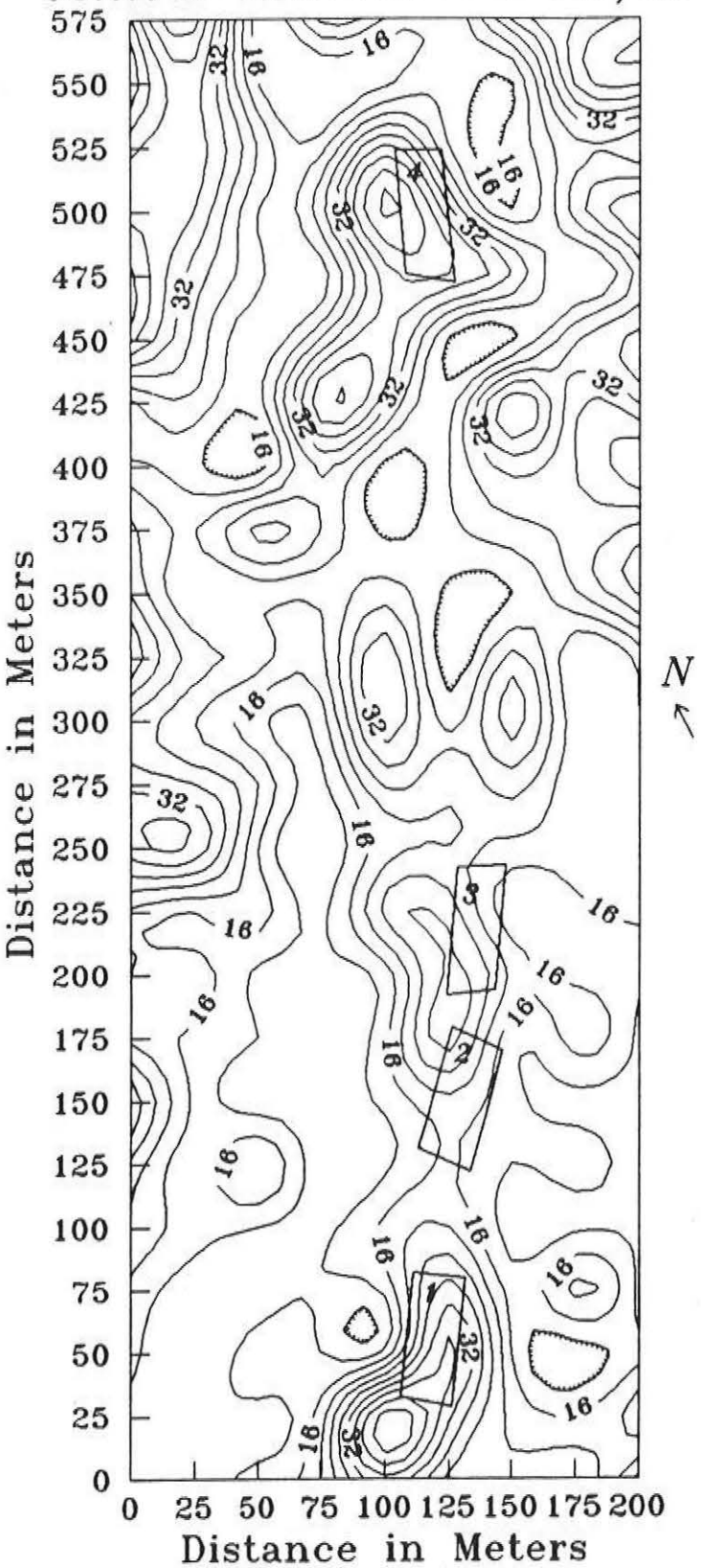
EM SURVEY OF MILLS SITE

EM31 Meter
Horizontal Dipole Orientation
Contour Interval = 8 mS/m



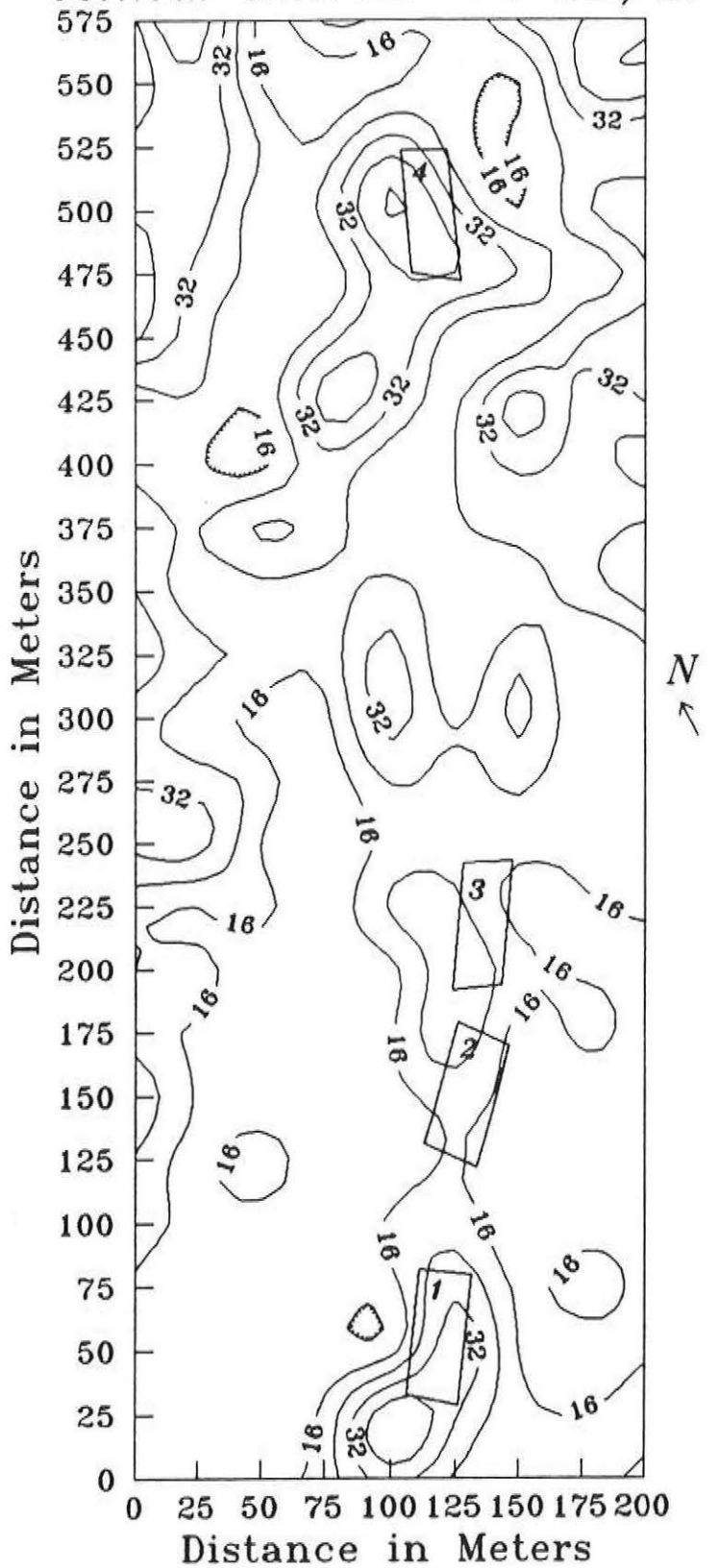
EM SURVEY OF MILLS SITE

EM31 Meter
Vertical Dipole Orientation
Contour Interval = 4 mS/m



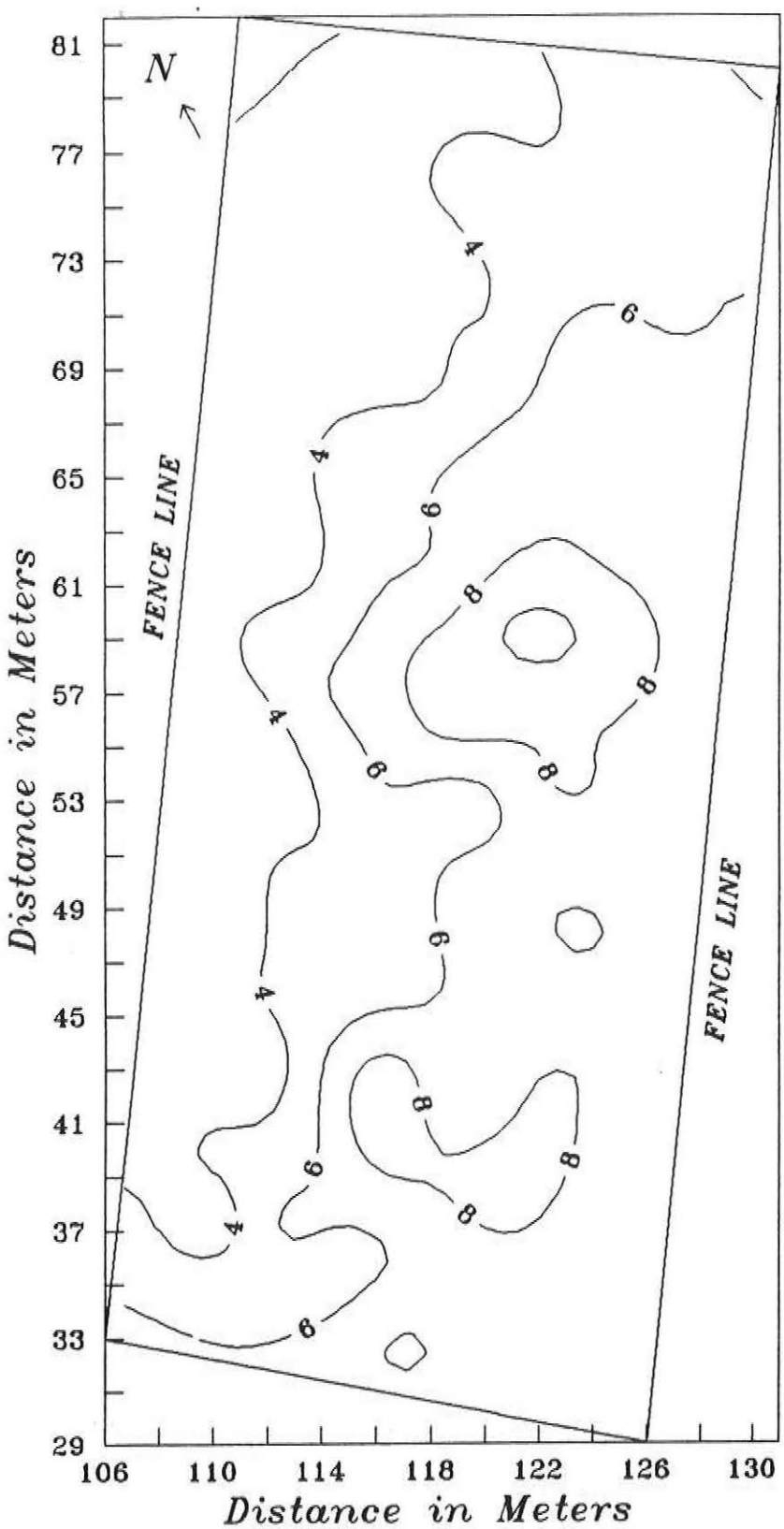
EM SURVEY OF MILLS SITE

EM31 Meter
Vertical Dipole Orientation
Contour Interval = 8 mS/m



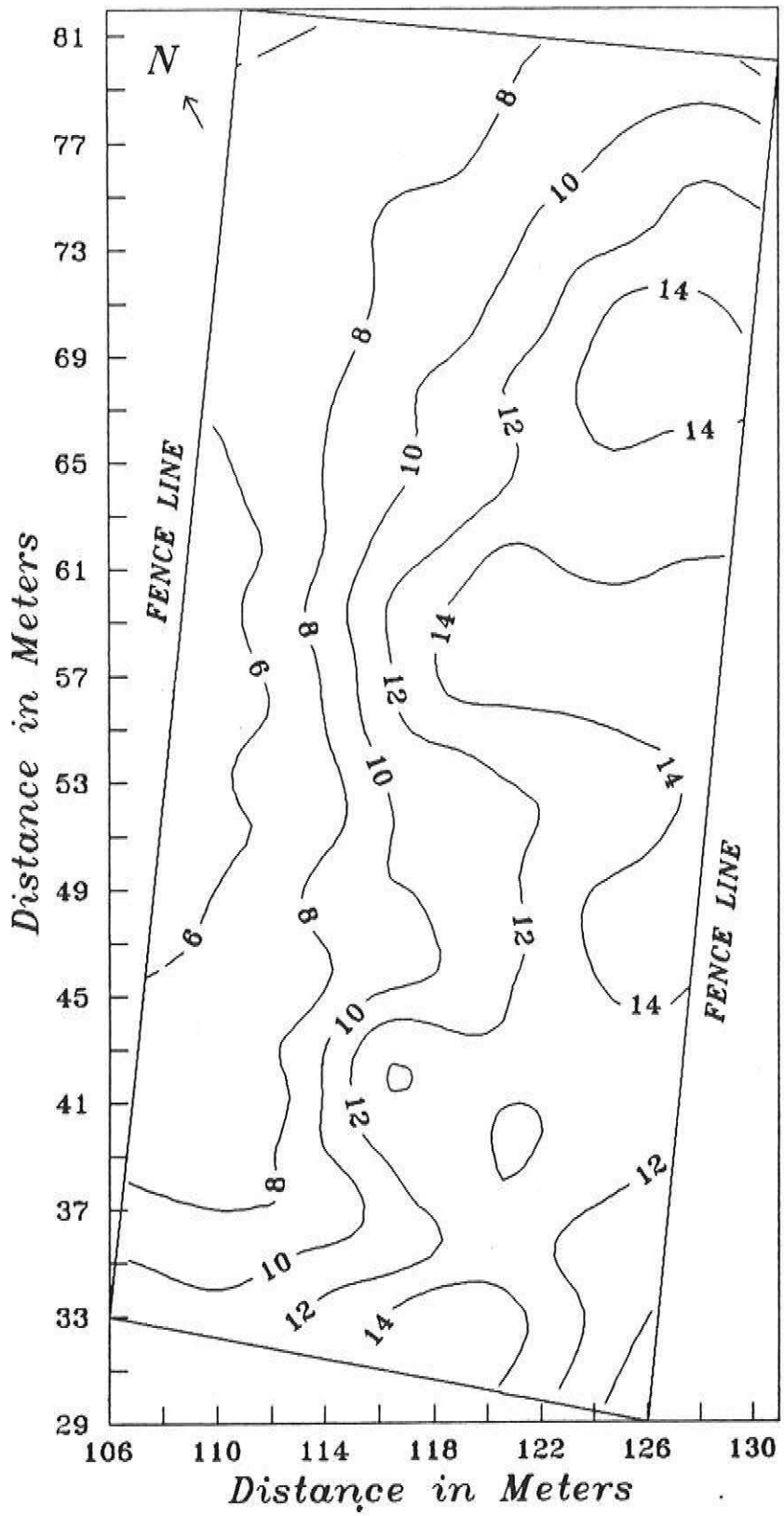
SURVEY OF ENCLOSURE 1

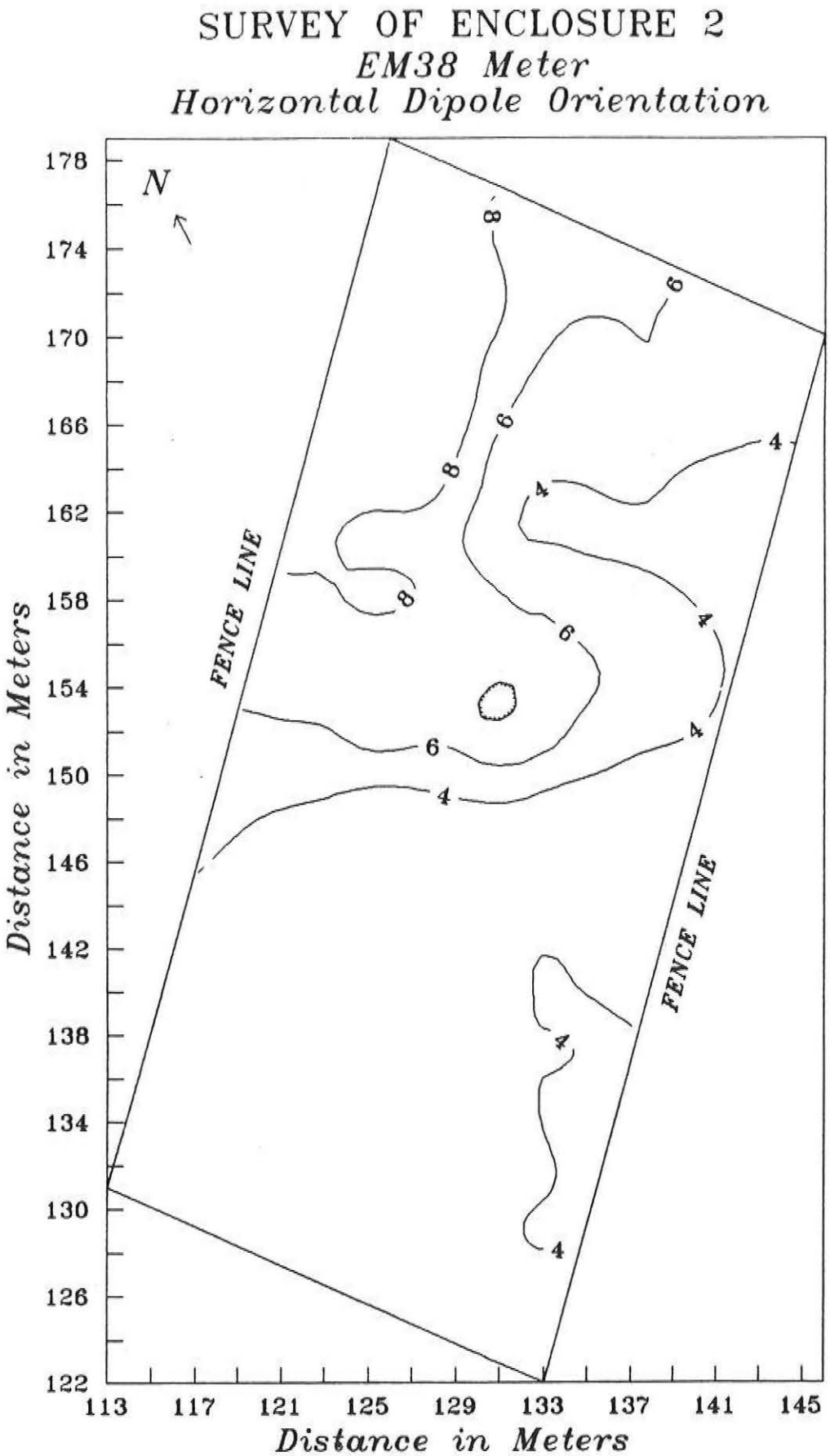
EM38 Meter
Horizontal Dipole Orientation

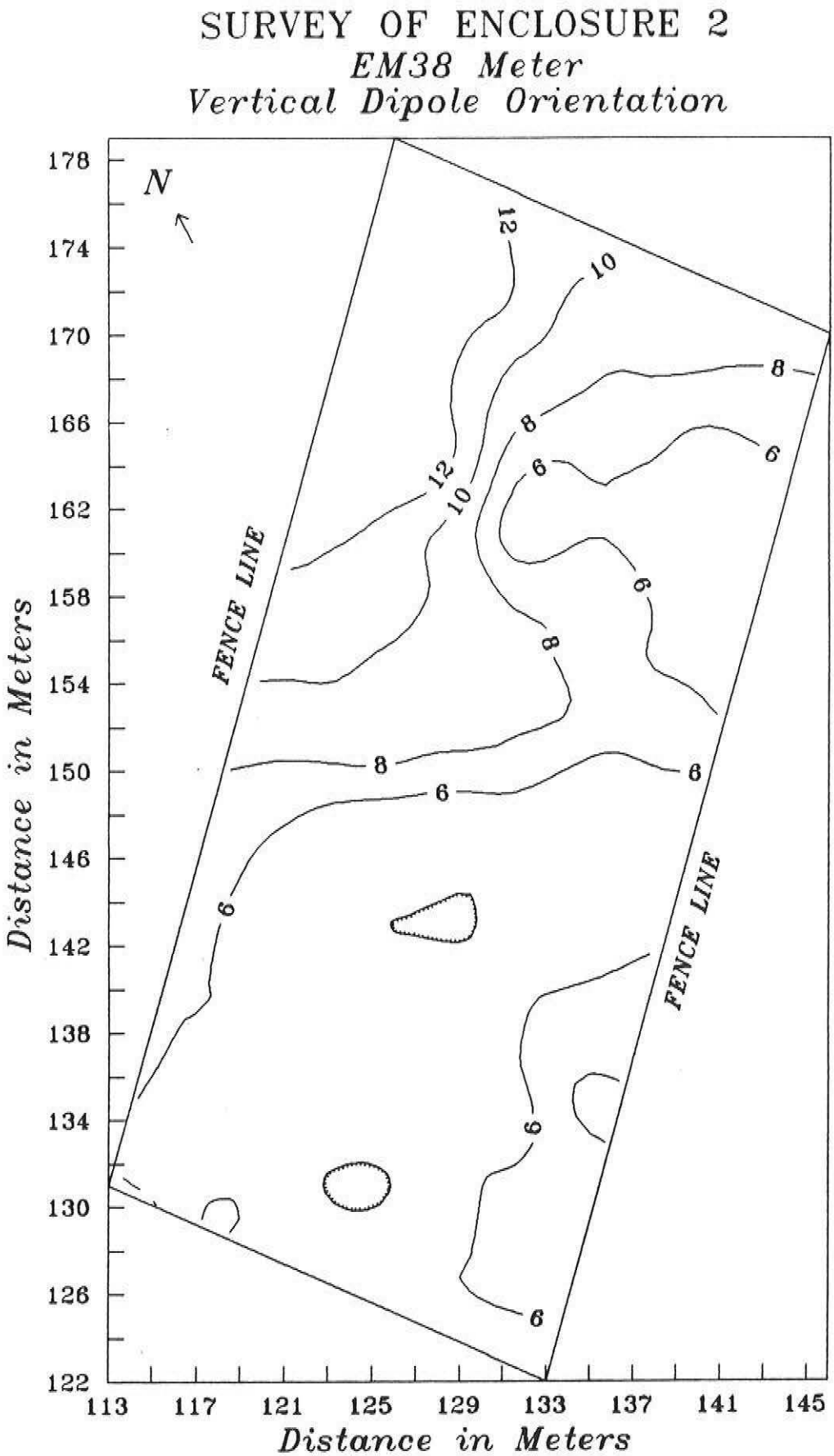


SURVEY OF ENCLOSURE 1

EM38 Meter
Vertical Dipole Orientation

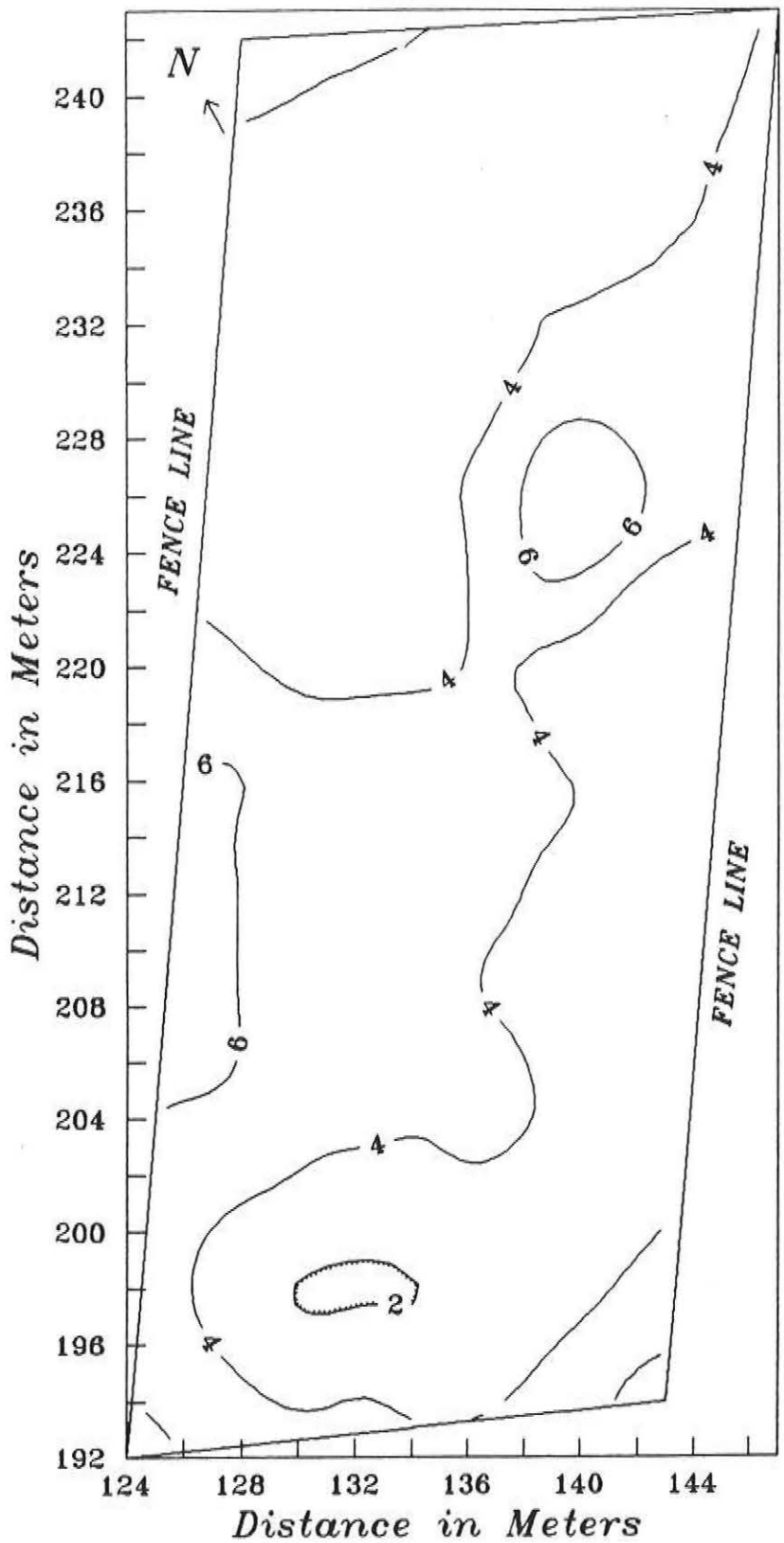



SURVEY OF ENCLOSURE 2
EM38 Meter
Horizontal Dipole Orientation
N
FENCE LINE
FENCE LINE
8
6
4
178
174
170
166
162
158
154
150
146
142
138
134
130
126
122
113
117
121
125
129
133
137
141
145
Distance in Meters
Distance in Meters


SURVEY OF ENCLOSURE 2
EM38 Meter
Vertical Dipole Orientation
N
FENCE LINE
FENCE LINE
12
10
8
6
178
174
170
166
162
158
154
150
146
142
138
134
130
126
122
113
117
121
125
129
133
137
141
145
Distance in Meters
Distance in Meters

SURVEY OF ENCLOSURE 3

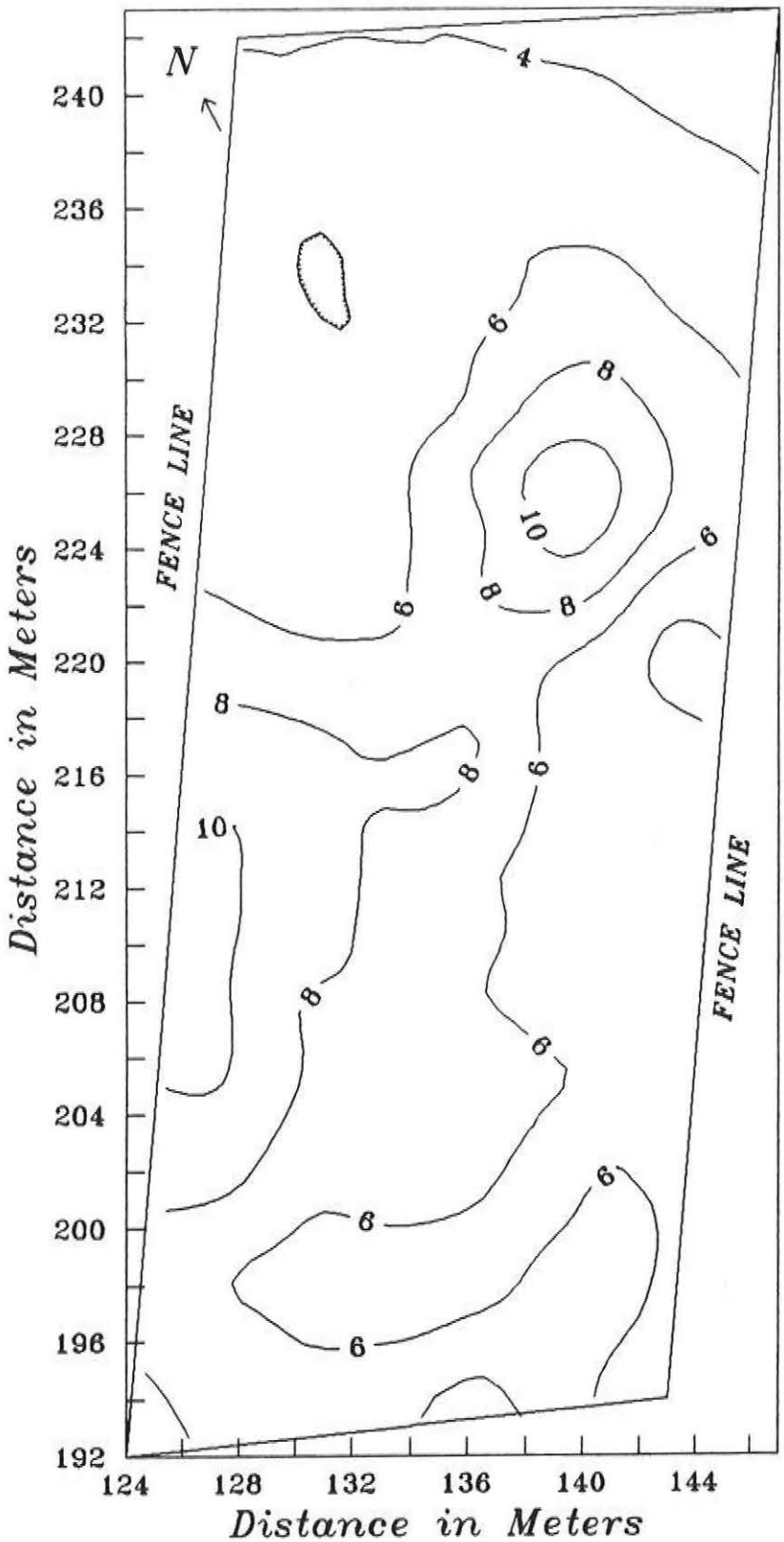
EM38 Meter
Horizontal Dipole Orientation



SURVEY OF ENCLOSURE 3

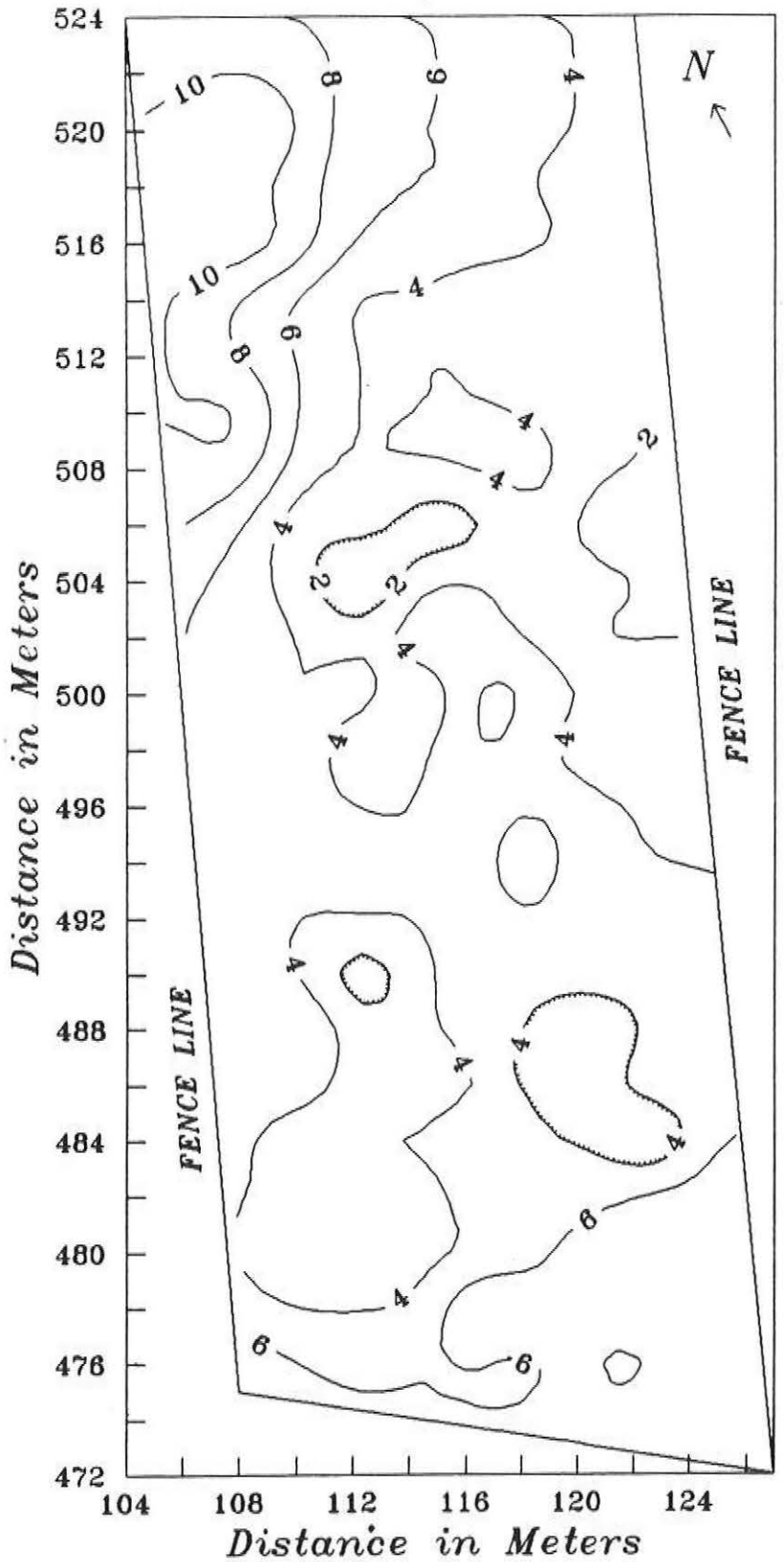
EM38 Meter

Vertical Dipole Orientation



SURVEY OF ENCLOSURE 4

EM38 Meter
Horizontal Dipole Orientation



SURVEY OF ENCLOSURE 4

EM38 Meter
Vertical Dipole Orientation

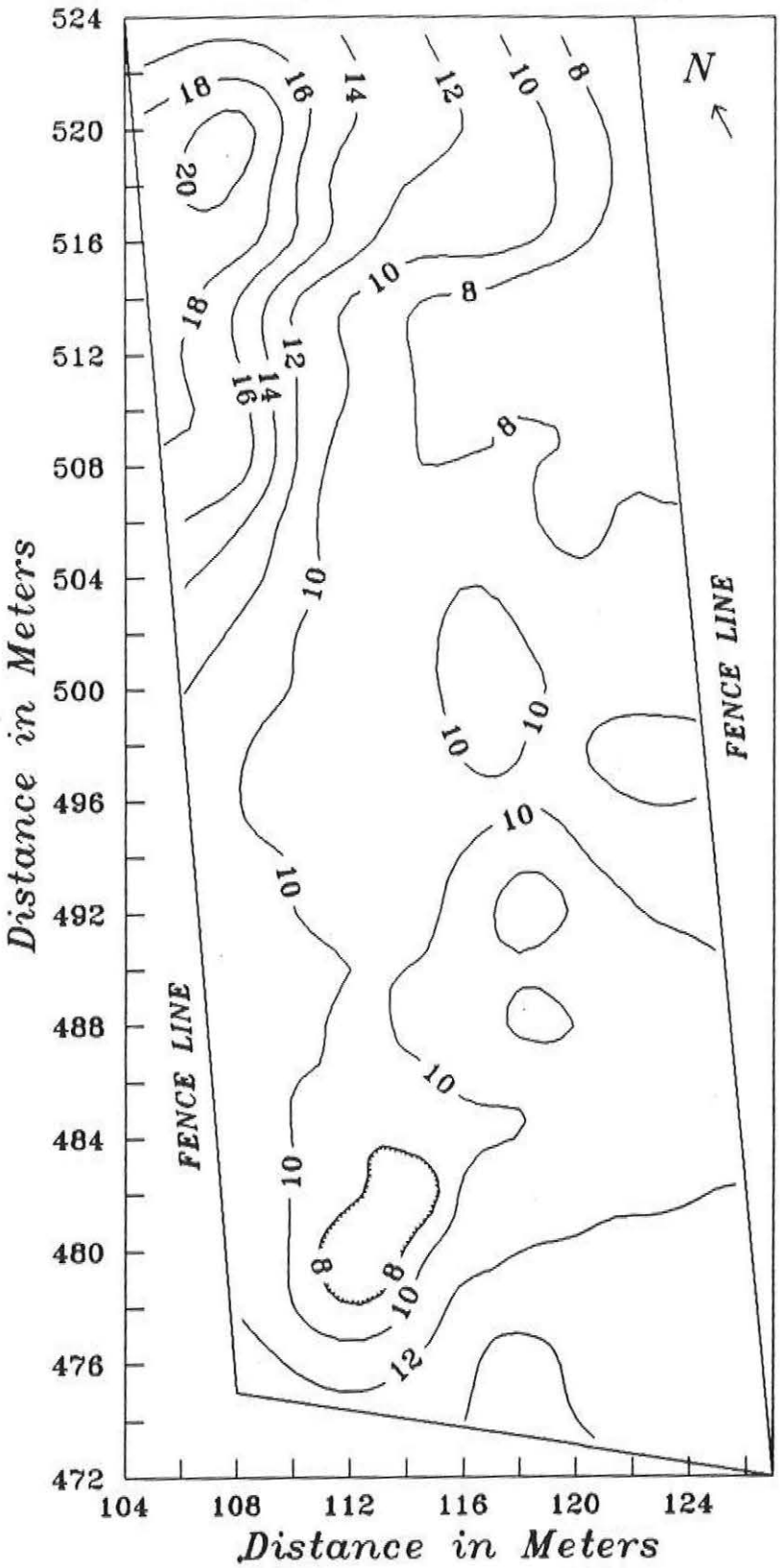
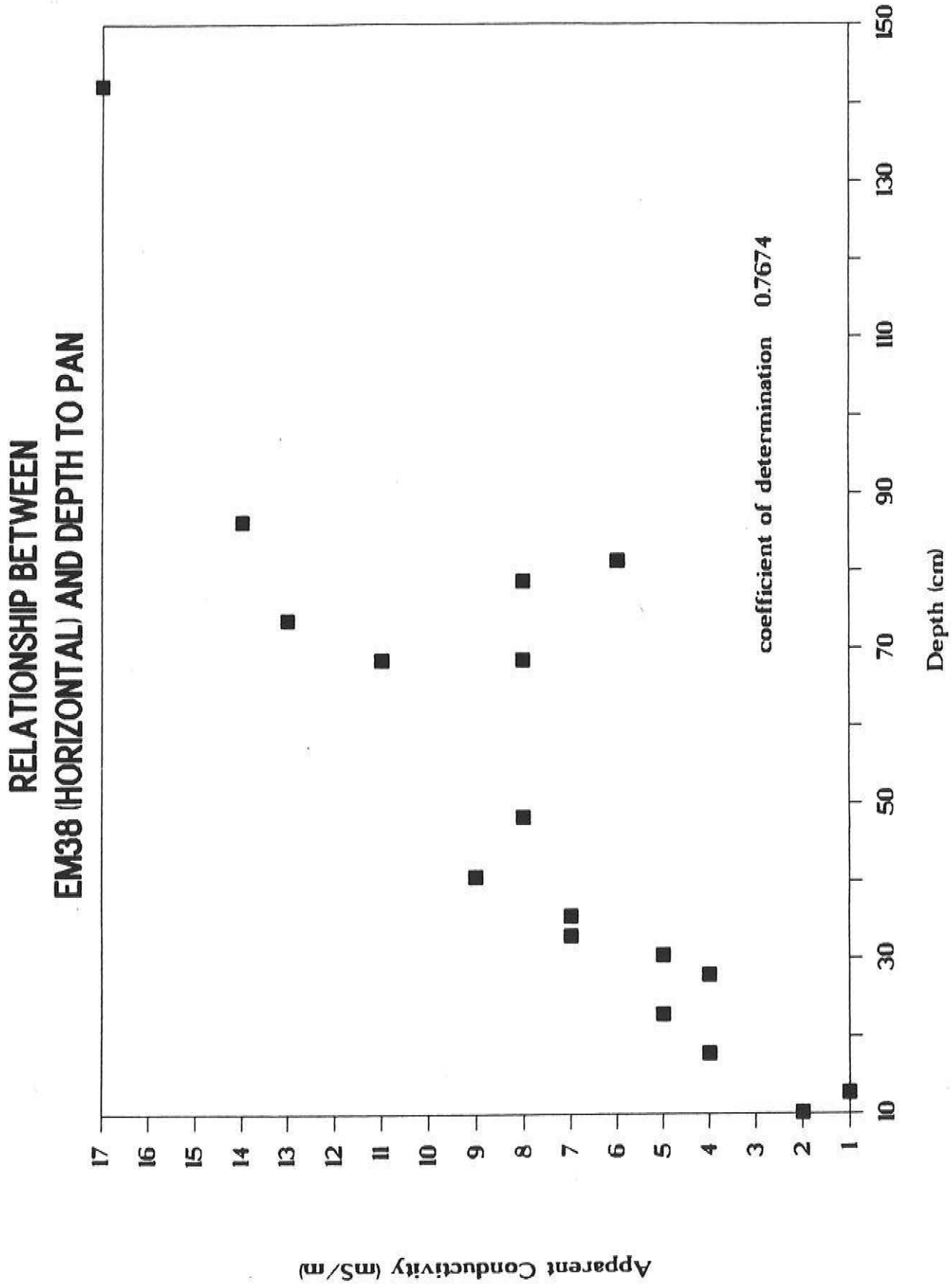


Figure 21


RELATIONSHIP BETWEEN
EM38 (HORIZONTAL) AND DEPTH TO PAN
coefficient of determination 0.7674
Depth (cm)
Apparent Conductivity (mS/m)
10
30
50
70
90
110
130
150
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

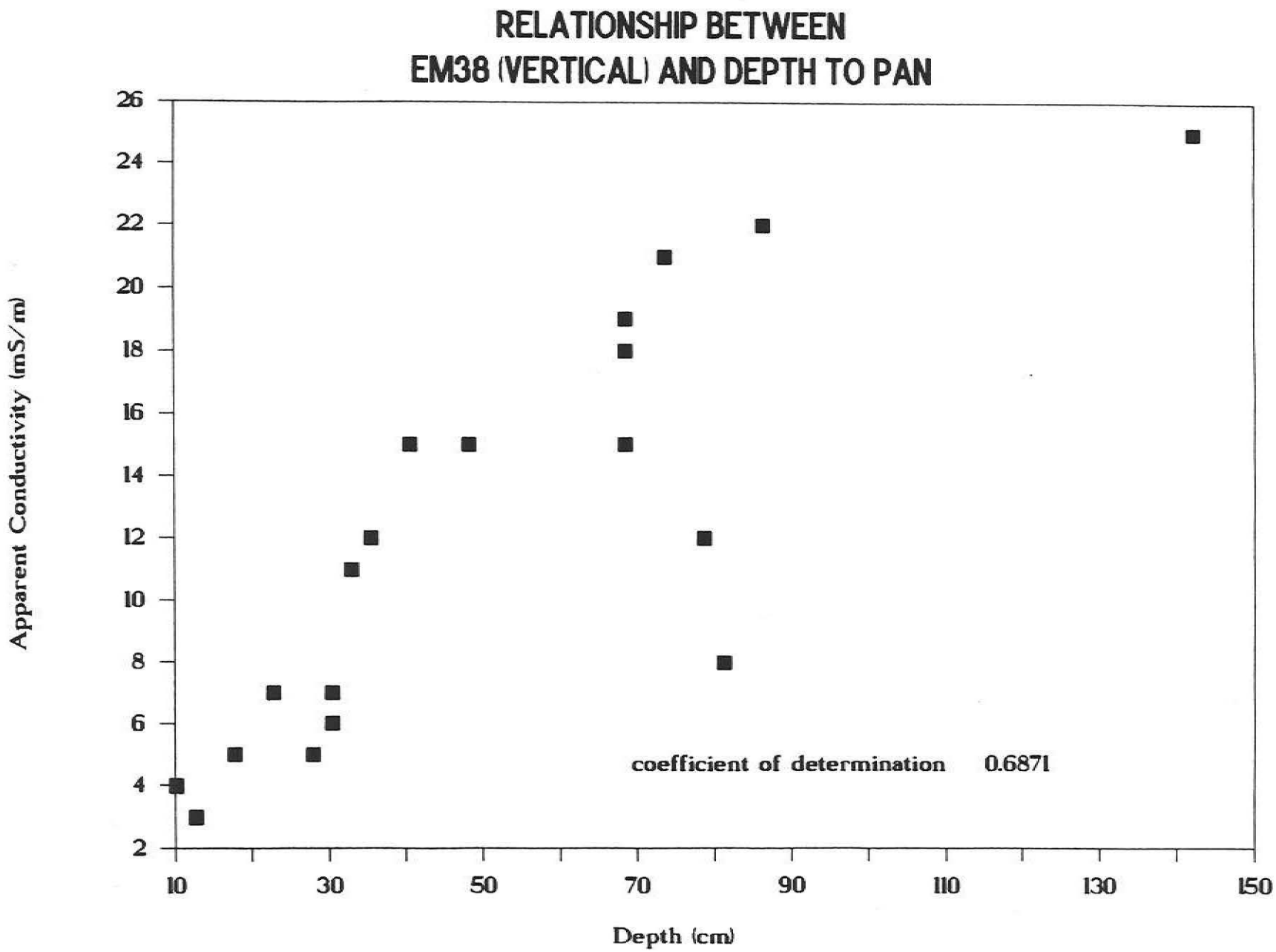
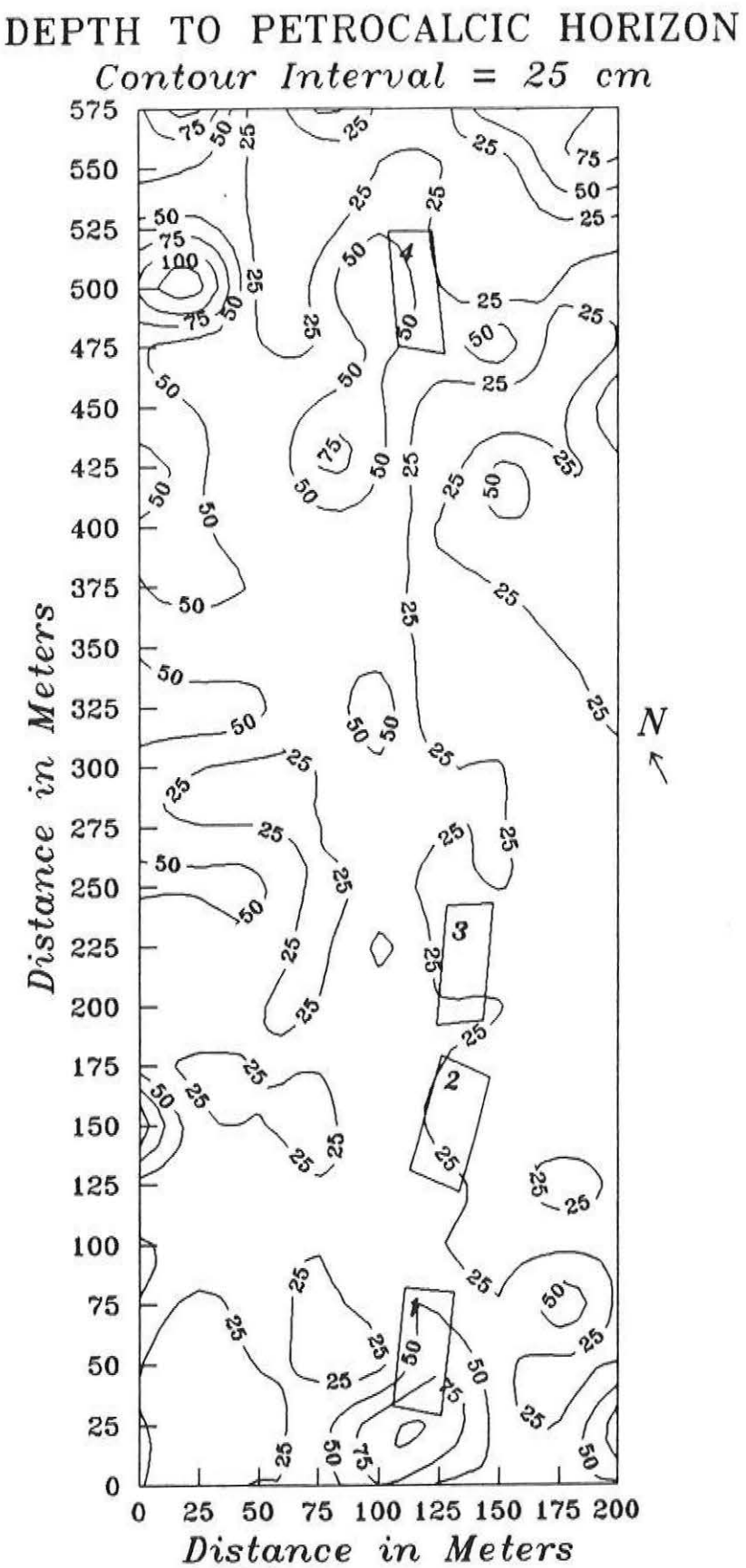
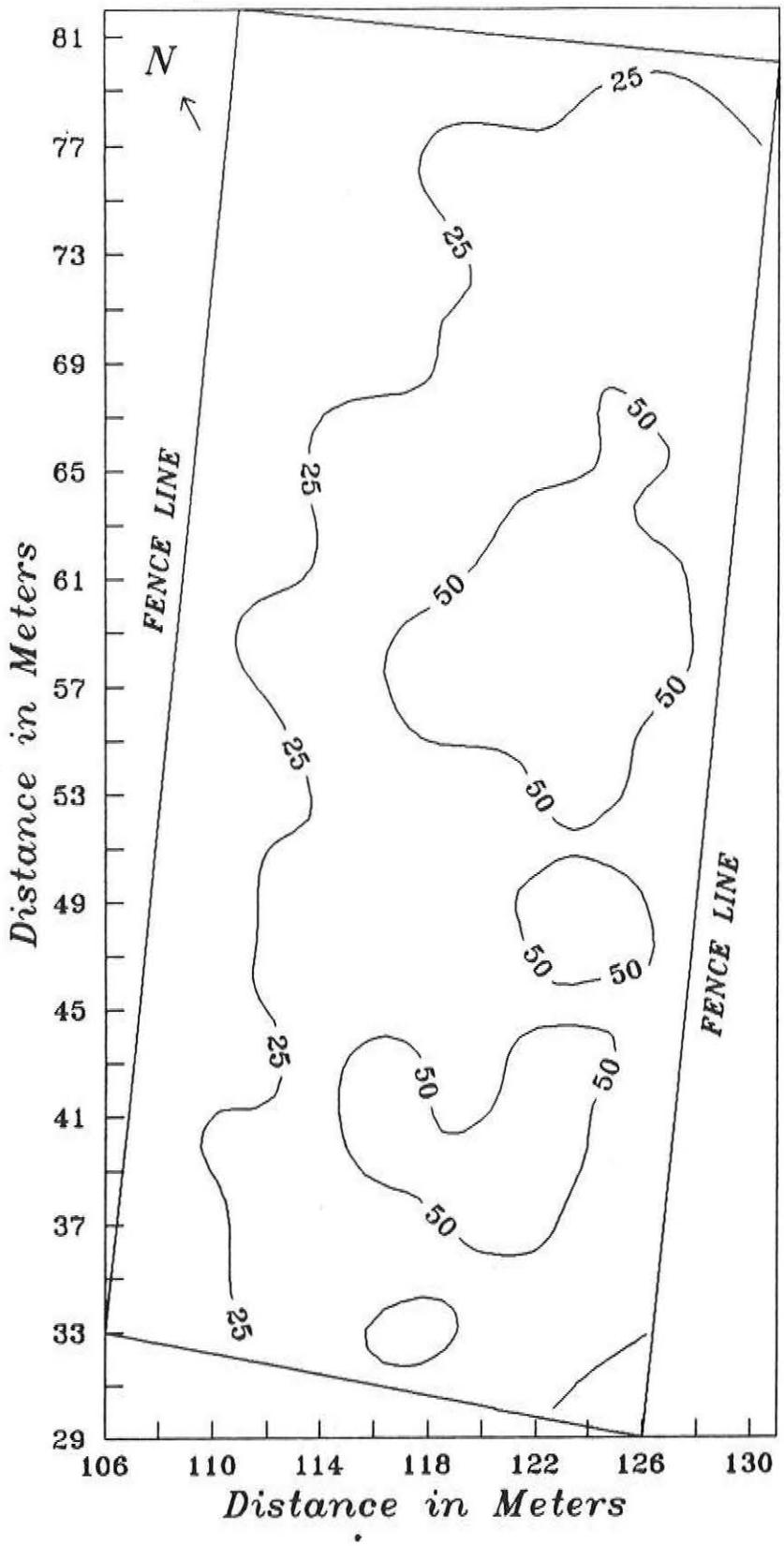

RELATIONSHIP BETWEEN
EM38 (VERTICAL) AND DEPTH TO PAN
Apparent Conductivity (mS/m)
26
24
22
20
18
16
14
12
10
8
6
4
2
10
30
50
70
90
110
130
150
Depth (cm)
coefficient of determination 0.6871

Figure 22


DEPTH TO PETROCALCIC HORIZON
Contour Interval = 25 cm
Distance in Meters
Distance in Meters
N
0 25 50 75 100 125 150 175 200
0 25 50 75 100 125 150 175 200 225 250 275 300 325 350 375 400 425 450 475 500 525 550 575
1
2
3
4

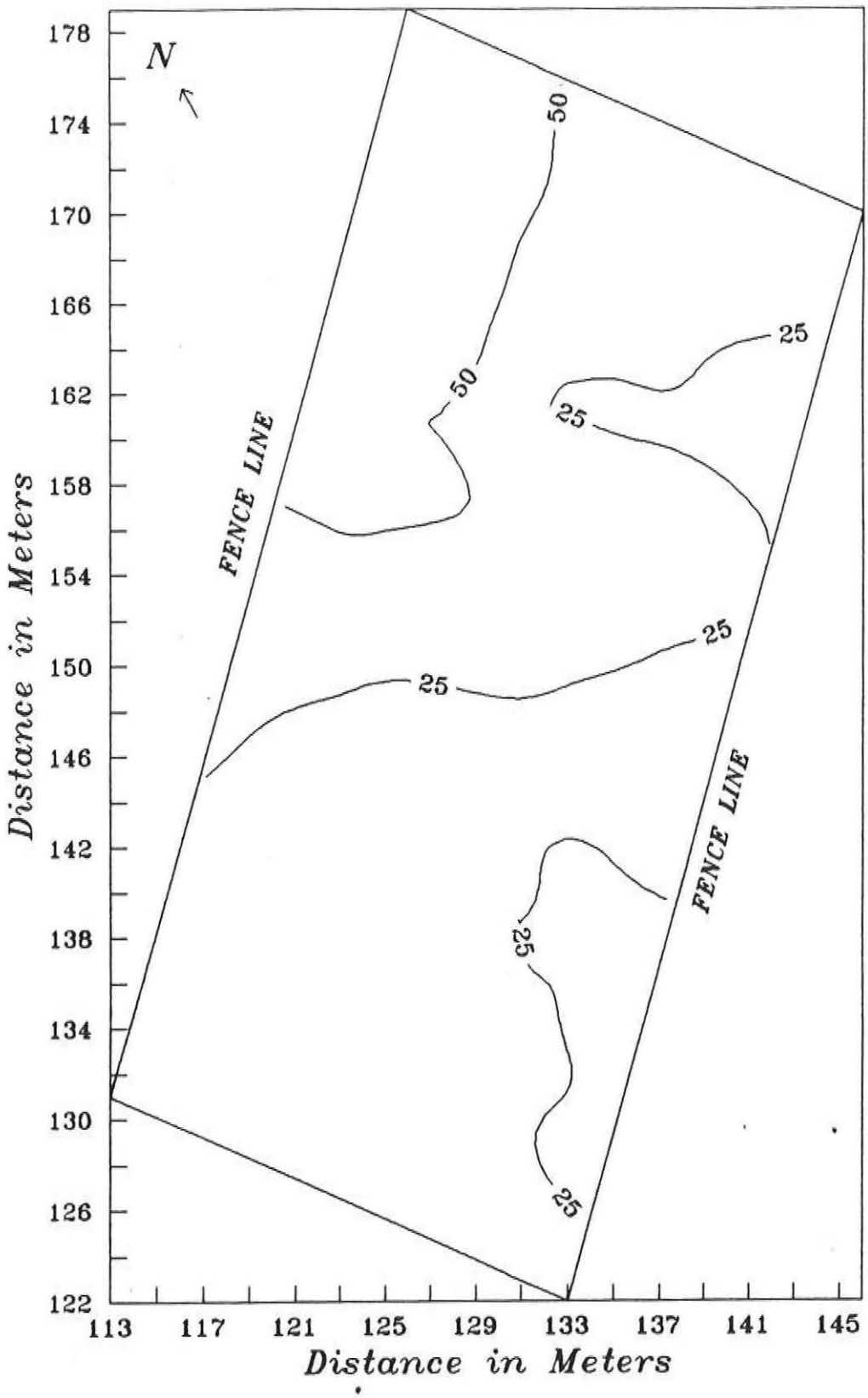
Enclosure 1

Depth to Petrocalcic Horizon
Contour Interval = 25 cm



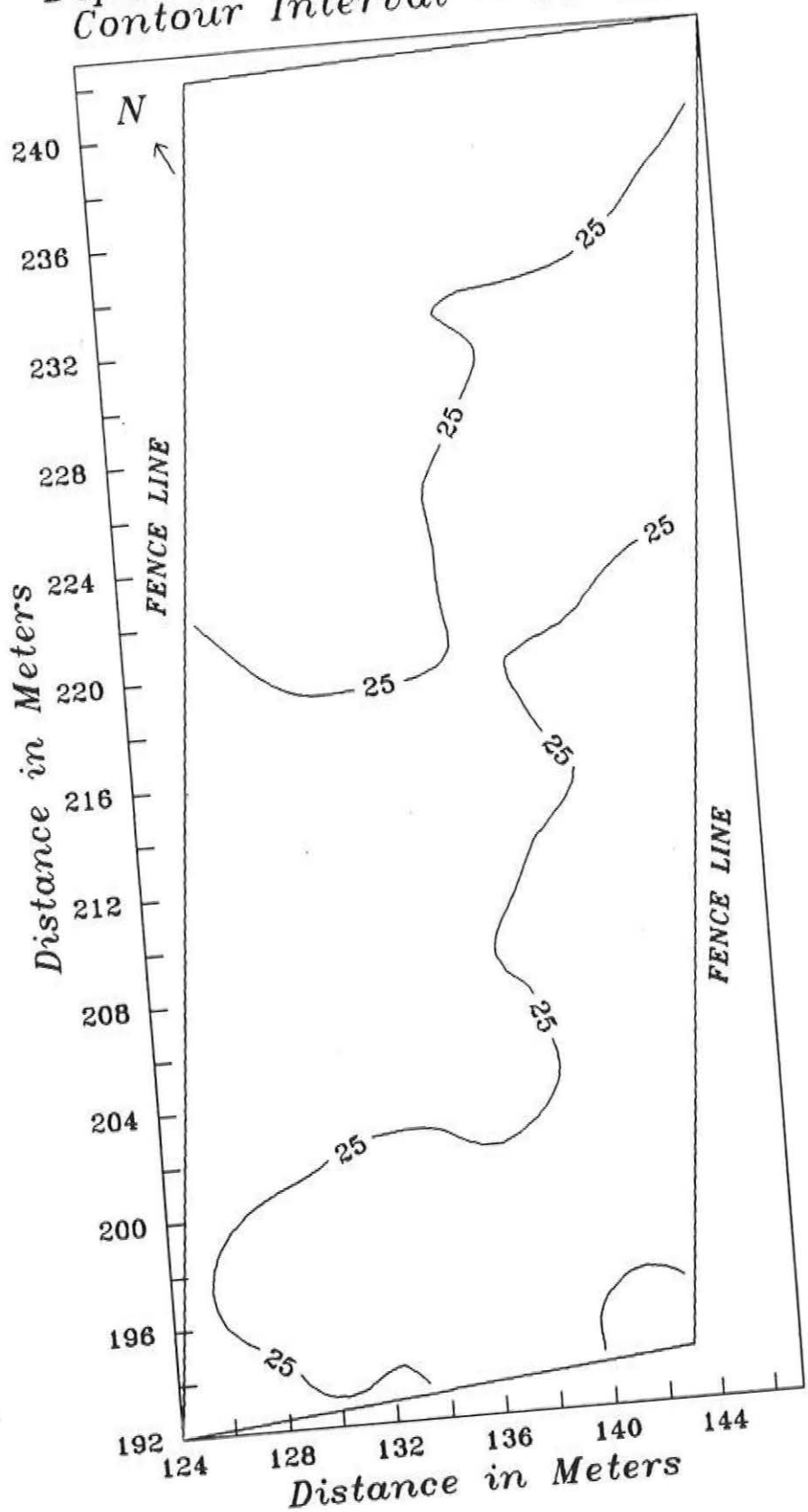
Enclosure 2

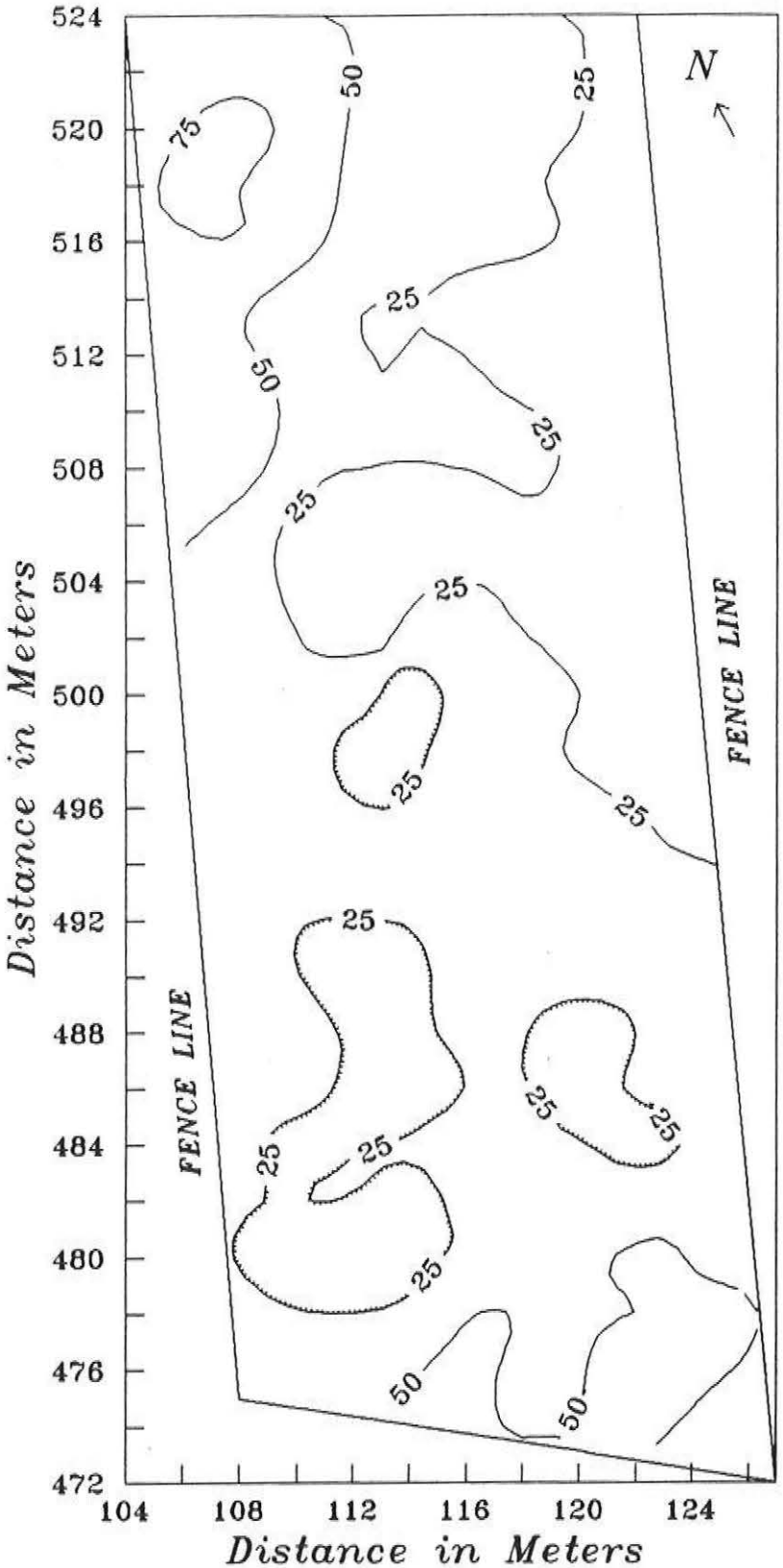
Depth to Petrocalcic Horizon
Contour Interval = 25 cm



Enclosure 3

Depth to Petrocalcic Horizon
Contour Interval = 25 cm



ENCLOSURE 4

Depth to Petrocalcic Horizon
Contour Interval = 25 cm