SURVEY OF ELECTRICAL RESISTIVITY IN THEORY AND PRACTICE: RESISTIVITY STUDY OF A SECTION OF THE BURIED STREAM CHANNEL IN THE CANNON RIVER VALLEY, NORTHFIELD, MINNESOTA

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CHAPTER 1: ABSTRACT

A study of electrical resistivity techniques combined with a resistivity mapping project of a section of the buried stream channel in the Cannon River Valley confirmed Tim Vick's discovery that a deeply buried channel emanates from Spring Creek and follows the Cannon River. A resistivity contour map of the field area extending from the Carleton Arboretum Tennis Courts to the Northfield Sewage Treatment Plant shows the path of the buried channel to pass under the Cannon at the mouth of Spring Creek, follow the left bank of the Cannon, and cross back to the right bank at the center of the field area.

Electrical resistivity was an inexpensive, rapid method to use for mapping this channel. The resistivity data ~~was~~ were easy to interpret qualitatively. However, quantitative interpretation and detailed resolution of buried features was not possible.

CHAPTER 2: INTRODUCTION

Electrical resistivity is a geophysical prospecting technique based on detecting differences in electrical conductivity or resistivity in the ground. I became interested in working with electrical resistivity upon the suggestion of Tim Vick, Technical Director of the Carleton College Geology Department. Tim felt that working with electrical resistivity would be particuliarly appropriate for me because of my strong mathematical background. I agreed with him and decided to study the technique.

The Carleton Geology Department had a seldom used resistivity instrument on hand. I was therefore ready to do a resistivity project but needed a geological problem to solve. After considering several possible problems, I decided to map a section of a buried stream channel discovered by a team led by Tim last summer.

My study mostly involved mastering the art of electrical prospecting. The map of the buried stream channel is the result of my successful use of resistivity. Among other things, I found that the literature lacked a simple good exposition of resistivity at the upper undergraduate geology major level. This paper is meant to help fill that void.

It is divided into three sections. The first two deal with the theoretical and practical aspects of resistivity.

The third deals with the mapping project of the buried stream channel in the Cannon River Valley. The sections are designed to be read in sequential order, each successive section assuming the knowledge of the former.

PART I: RESISTIVITY THEORY

This section deals with the theory of electrical resistivity. The electrical processes and some mathematically simulated resistivity data for certain elementary structural configurations are briefly presented and explained. The contents of this section are meant to give the reader a simple, qualitative understanding of electrical resistivity.

CHAPTER 3: ELECTRICAL DEFINITIONS

It is imperative that the reader understand the fundamental laws of electricity before proceeding. I present here a bare outline of those laws and refer the reader to any elementary book on electricity and magnetism for a more complete explanation.

ELECTRONIC CHARGE

Three sub-atomic particles make up the bulk of matter on earth. These are the electron, the proton, and the neutron. These elements have an electrostatic charge. The electron has a negative charge, the proton a positive one, and the neutron has no charge at all. Two elements with alike charges: two electrons or two protons, repel each other. Two elements with opposite charges: a proton and an electron, attract each other. The neutron is unaffected by electrostatic charge.

Coulomb's Law describes the relationship between the magnitude of the electrostatic charges and the magnitude of the resulting force of repulsion or attraction. It states that, "two electrostatic charges repel or attract one another with a force proportional to the product of the magnitude of the charges, and inversely proportional to the square of the distance between them." (Purcell, 1970) One Coulomb of Charge is defined to be 6.25×10^{18} sub-atomic elements of alike charge.

ELECTRIC FIELD

An electric field is where two opposite charges, fixed in space, exert an electrostatic force on any charge in their vicinity. An electric field is produced in a conductive medium when a current of electrons is introduced at a negative pole (anode) and taken away at a positive pole (cathode). The properties of electric fields in conducting mediums are fundamental to electrical prospecting.

ELECTRIC POTENTIAL (VOLT (V))

When one Joule of work is lost or gained in moving one Coulomb of electric charge through an electric field, the charge is said to have gone through a potential difference of one volt. A surface along which no difference of potential exists is an equipotential surface. It is always perpendicular to the direction of current flow.

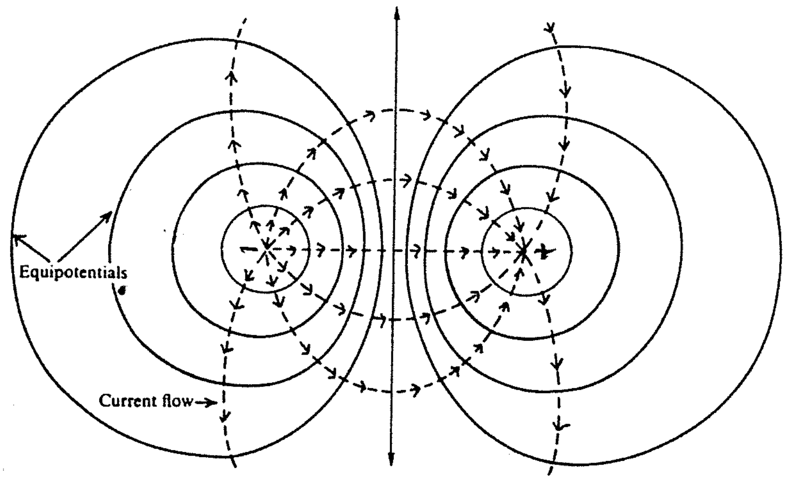

Figure 1. Example of an electric field. The arrows indicate the direction of the electric force exerted on a negative charge. (Adapted from Telford, et al. 1976.)

CURRENT FLOW (AMPERE(I)) AND DENSITY (AMPERE-METER^2)

When one Coulomb per second is flowing through a given conductor, the current flow through that conductor is said to be one Ampere. When one Ampere of current flows through a homogeneous conductor of one square meter cross-sectional area perpendicular to the direction of current flow, the current density is said to be one Ampere per square meter.

RESISTANCE (OHM(r)) AND RESISTIVITY (OHM-METER (R))

If one volt of potential draws one Ampere of current through a given conductor, that conductor has a resistance of one Ohm (Ohm's Law $r=\frac{V}{I}$). If one Volt of potential draws a current of density one Ampere-meter^2 across a conductor of resistance one Ohm and length one meter, the conducting material is said to have a resistivity of one Ohm-meter. $R=\frac{(rA)}{L}$ where R is the resistivity, r the resistance, L the length, and A the cross-sectional area of the conductor. The resistivity, R, is fundamental to electrical prospecting.

CHAPTER 4: RESISTIVITY MODELS

The following are a series of mathematically derived models to simulate earth resistivity configurations. To be successful, they must simulate the electric potential configurations at the surface between the current electrodes. From these, simulated resistivity data may be obtained. For all but the simplest of models the mathematics are complex and in most cases no exact solution is obtainable. These mathematical simulations are meant to aid in a qualitative way with the interpretation of resistivity field data.

RESISISTIVITY IN ELECTRICALLY HOMOGENEOUS AND ISOTROPIC MATTER

Single Point Source of Current at the Surface

Imagine an electrically homogeneous and isotropic earth with a flat surface. A current, I, is introduced at a point C on the surface. The air above the surface is considered to have infinite resistivity. The electrons would flow away from C radially, distributed equally in all directions. The surfaces of equal potential would be hemispherical bowls centered at C (Figure 2). The current density and thus the electrical potential decrease at greater distances from C. These can be calculated exactly using elementary integration (Van Nostrand & Cook, 1966, p.28). From these, the resistivity in Ohm-meters can be calculated,

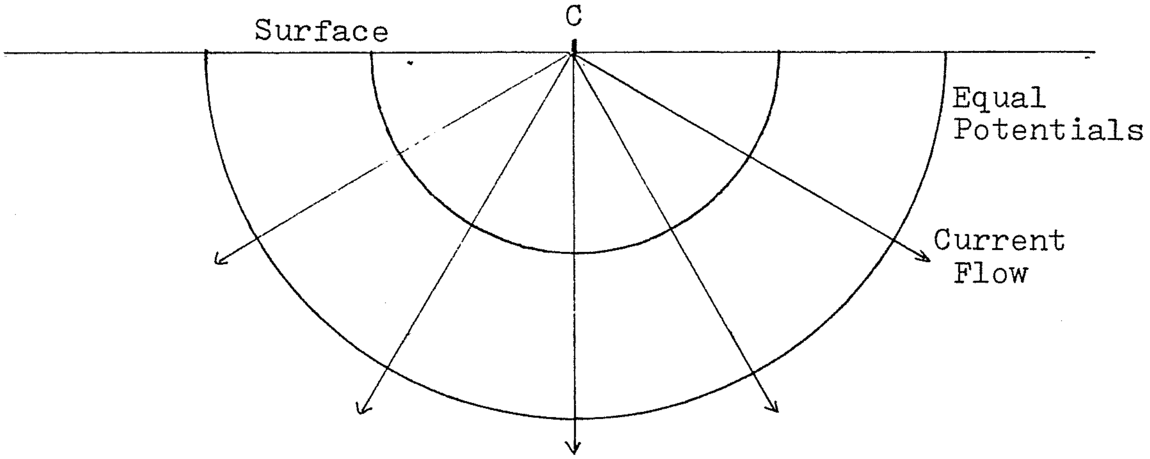

Figure 2. Electric field from single point source of current.

Point Source and Point Sink of Current

Now imagine that an electric current, I,enters the ground at C1 and leaves at C2. The lines of electron flow and the surfaces of equal potential would be distributed as in Figure 3 (p.10). Once again the current density, the potential, and hence the resistivity can be mathematically determined at any point on the surface.

ELECRICAL RESISTIVITY INHOMOGENEITIES

Homogeneous earth has been the sole consideration so far. Those models are useful in understanding the fundamentals of resistivity. However, the goal of electrical prospecting is to detect resistivity anomolies in the earth. When such anomolies are present, the current flow and equipotential lines are distorted. Analyzing these distortions at the surface is what allows buried structures to be mapped.

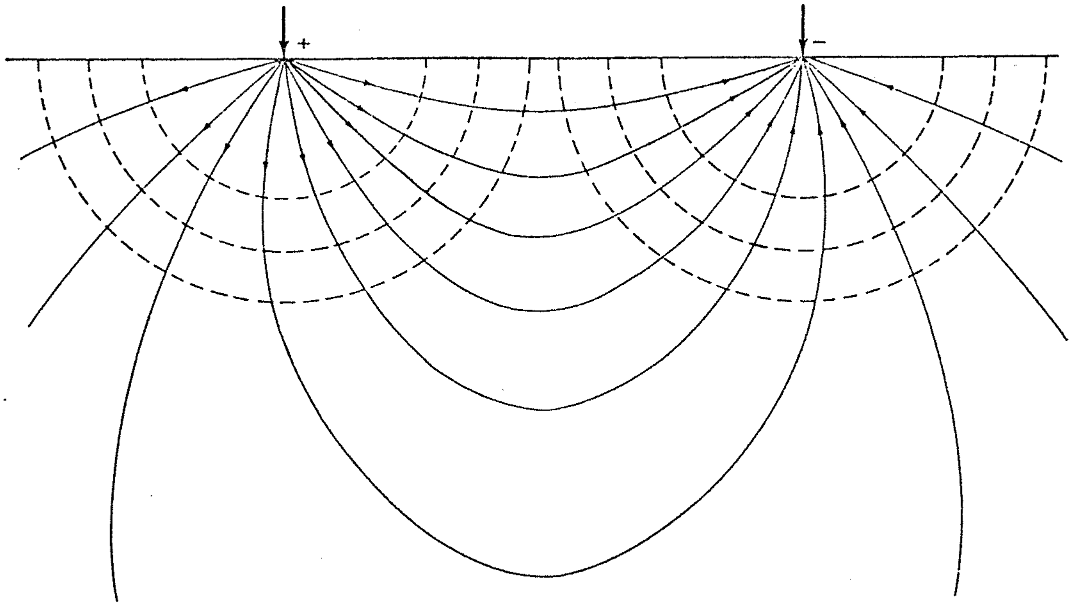

Figure 3. Vertical cross-section of the earth showing electric field. Solid lines represent the direction of current flow and the dashed lines represent the planes of equal potential. Note the symmetrical relationship of the positive and negative poles. (Adapted from Soiltest, Inc., 1979)

Distortion of Current Flow

The distortion of the current flow at the boundary interface between two mediums media of different resistivity is derived below. Imagine two mediums media of resistivity R1 and R2 separated by a plane boundary interface, an x-axis of unit i parallel to the boundary, and a y-axis of unit j perpendicular to the boundary. A current of density and direction J1=Jx1i + Jy1j crosses the boundary. (Figure 4, p. 11)

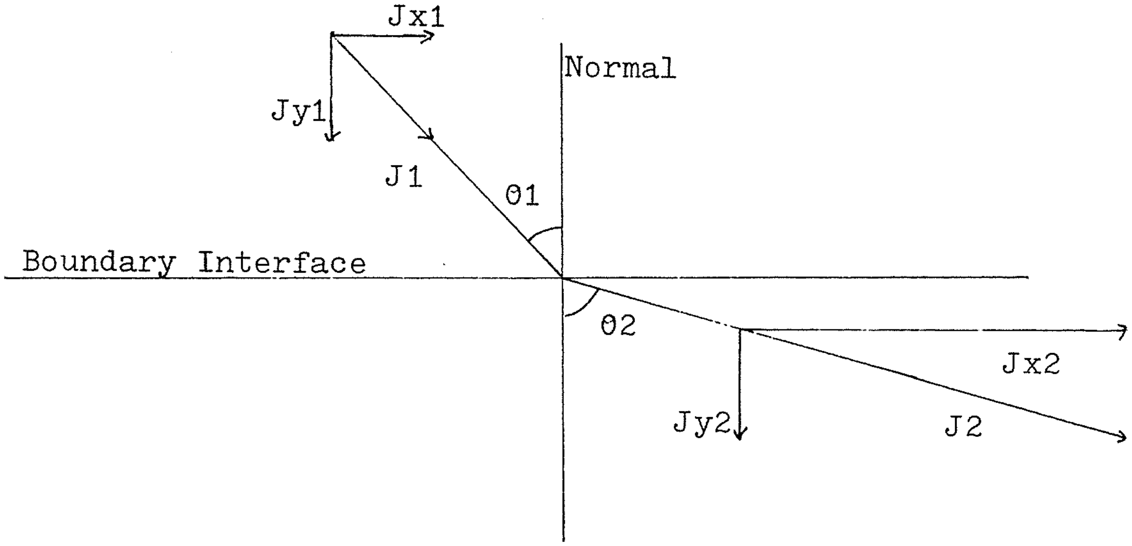

Figure 4.

Two assumptions are made (Telford et al., 1976 p. 633):

(1) The potential must be continuous across the boundary. Thus, the potential must be equal on either side in the immediate vicinity of the boundary interface.

(2) The normal component of the current density must be continuous across the boundary interface. Thus, the amount of current Medium 1 sends to Medium 2 equals the amount of current Medium 2 receives from Medium 1. No current is lost or created.

From (1) we have $Vx1 = Vx2$

From Ohm's Law we get $Jx1R1 = Jx2R2$ (3)

From (2) we have $Jy1 = Jy2$ (4)

Dividing (3) by (4) we get $R1\left(\frac{Jx1}{Jy1}\right) = R2\left(\frac{Jx2}{Jy2}\right)$

Trigonometry tells us that $\frac{Jx1}{Jy1} = \tan(\theta 1)$, where θ1 is the angle from the normal of the current flow in Medium 1.

$\frac{Jx2}{Jy2}$ = tan (θ2), where θ2 is the angle from the normal of the current flow J in Medium 2.

We get R1tan(θ1) = R2tan(θ2)

From which $\frac{R1}{R2} = \frac{\tan(\theta 1)}{\tan(\theta 2)}$

Hence the current flow lines are bent at the boundary. They are bent towards the normal when R1 is less that R2 and bent away from the normal when R1 is greater than R2.

Image Theory Models

Image theory has been successfully used for simulating electrical potential distortion in some simple earth configurations (Van Nostrand & Cook, 1966). Image theory borrows the mathematics of the optical distortion of light passing from one medium to another and applies it to electrical current passing from one medium to another. This analogy has many definite limitations (Keller, 1953). The mathematics go quickly beyond the scope of this text. Therefore, only the resulting simulated field data will be presented. Van Nostrand & Cook have a complete exposition of image theory in their 1966 paper on resistivity.

Simulated Field Data

The field data for electrical resistivity are computed into "apparent" resistivity values in Ohm-meters. Four electrodes, C1, P1, P2, C2, are introduced into the ground in a straight line. The outer two, C1 and C2, supply a current, I, through the ground and set up an electrical field. The inner two, P1 and P2, measure the electrical potential in their interval (Figure 5).

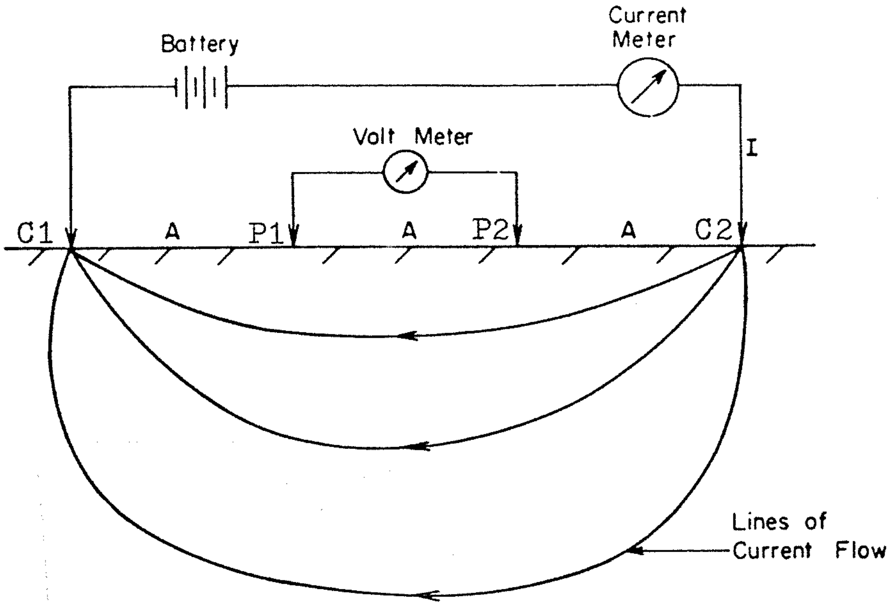

Figure 5. The battery sends a current, I, which is measured by the current meter, through the electrodes C1 and C2 into the ground. The Volt meter measures the drop in potential at the ground surface between the electrodes P1 and P2. (Adapted from Bison 1975)

Given the distances C1P1, C1P2, C2P2, and C2P1 along with the current and the voltage readings, the resistivity of an electrically homogeneous earth may be obtained (Van Nostrand & Cook, 1966, p.40). The equation for this is $R = \frac{KV}{I}$ where I is the current flow in Amperes between C1C2, V the potential measured between P1P2 and K the following ratio of the electrode spacings:

$$K = \frac{2\pi}{\frac{1}{C1P1} - \frac{1}{C1P2} - \frac{1}{C2P2} - \frac{1}{C2P1}}$$

Apparent Resistivity

Note that the resistivity value obtained is dependent solely on the current flow, I, the potential between P1P2, V, and the electrode spacing. A resistivity value can be obtained regardless of the subsurface electrical anomolies. This value which appears to reflect the resistivity of the ground surface may deviate from the true resistivity at the surface, hence the name "apparent" resistivity.

Electrode Configurations

There are numerous electrode configurations, each with advantages and disadvantages. Three major representative arrangements are the Wenner, the Lee partition of the Wenner, and the Schlumberger.

(1) The Wenner

In 1915 Wenner divised a simple configuration that is still widely used today. He spaced all four electrodes evenly. The equation for calculating the apparent resistivity simplifies to $R = \frac{2\pi AV}{I}$, where A is the electrode spacing. The reference point is the center of the line segment formed by the four electrodes used in mapping. The Wenner arrangement's simplicity allows large areas to be covered rapidly.

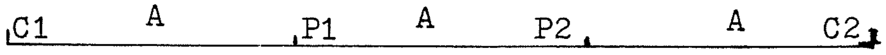

Figure 6. The Wenner configuration

(2) The Lee partition of the Wenner

The Lee partition of the Wenner configuration places a fifth electrode P0 at the point of reference. Potential measurements are taken between P1P0 and P0P2. Both data points are then plotted at the reference point. For both readings the apparent resistivity is $R = \frac{4\pi AV}{I}$. The purpose of this configuration is to detect lateral resistivity anomolies by comparing the right and left readings.

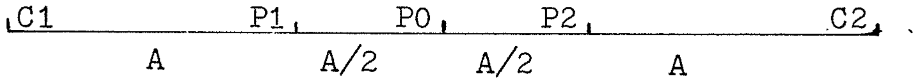

Figure 7. The Lee partition of the Wenner configuration.

(3) The Schlumberger

The Schlumberger configuration has the P-electrodes spaced close together about the center of the configuration. The apparent resistivity is $R = \frac{\pi L^2}{P1P2}$, where L is the distance from the midpoint to either of the current electrodes. The reference point is once again the center of the configuration. This arrangement is useful for detailed mapping because the small P-electrode spacing is more sensitive to minor anomalies about that point.

Figure 8. The Schlumberger configuration.

Sounding and Profiling

Two techniques are commonly used in resistivity mapping, sounding and profiling. In sounding, the reference point remains fixed while the electrode spacing is logarithmicly increased. This acts as a vertical resistivity probe and helps determine vertical anomalies. In profiling, the electrode spacing is fixed and the reference point is moved. This acts as a horizontal probe, probing for horizontal anomalies.

Horizontal Layers

Image theory was first successfully used in solving horizontal bedding problems by Hummel in 1929, and Roman in 1931. Sounding is the only technique employed in horizontal layer models since there are no lateral anomalies. Many sets of simulated apparent resistivity curves have been published and now a computer program, Resist , (Davis 1979, Mooney 1980) is on-line with the Carleton College computer system to generate a sounding curve for any horizontal layer configuration.

The two layer case is the simplest. It is used here to illustrate the effects of horizontal layers on apparent resistivity readings. Models of more than two layers follow the same principles, but the complexity of the interactions of the layers increases with the number of layers in the model.

Imagine two horizontal layers of resistivity R1 and R2, with the top layer of thickness Y and the bottom layer infinitely thick. The electrical current density will be highest in the layer of lowest resistivity. This is a consequence of Ohm's Law. If the top layer has a lower resistivity than the bottom layer, there will be an anomalously high current density in the top layer. Since more current is flowing through the fixed resistance of the top layer, there will be a high V reading between the P-electrodes and thus a high apparent resistivity reading.

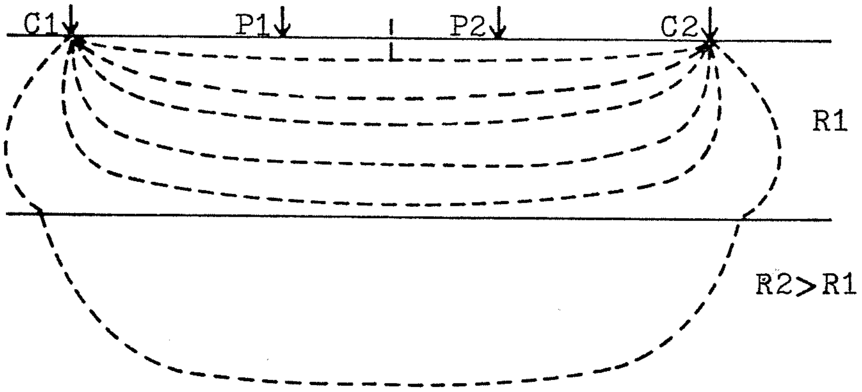

Figure 9. Current density distribution with low resistivity layer overlying high resistivity layer. High apparent resistivity reading will result at surface. (Adapted from Mooney, 1980)

If the top layer has the higher resistivity, there will be a lower current density in the top layer. This will yield a low V reading and thus give a low apparent resistivity reading.(see Figure 10, p.18).

When the electrode spacing A is small relative to the thickness of the top layer, the electric field will be largely unaffected by the bottom layer and the apparent resistivity will approximate R1 (Figure 11, p.18).

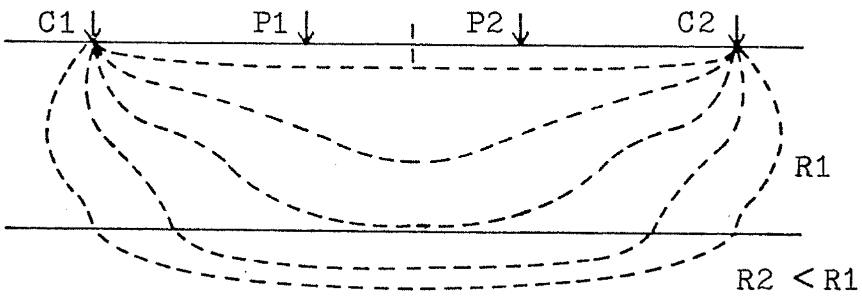

Figure 10. Current density distribution with high resistivity layer overlying low resistivity layer. Low apparent resistivity reading will result at surface. (Adapted from Mooney, 1980)

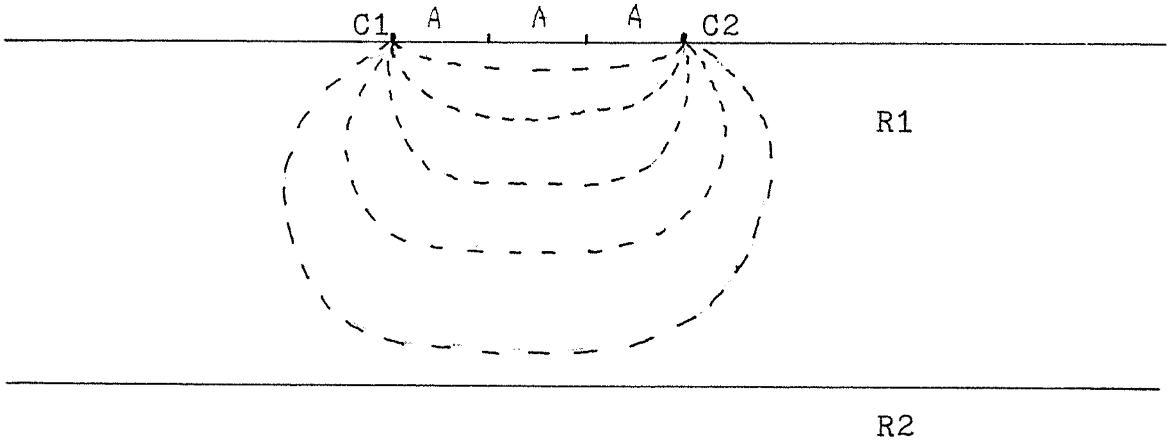

Figure 11. Electrode spacing, A, small relative to layer thickness, Y. Apparent resistivity approximates R1.

As the electrode spacing, A, increases, the electric field is influenced more by the bottom layer. The apparent resistivity value will be intermediate between R1 and R2 (Figure 12, p. 19).

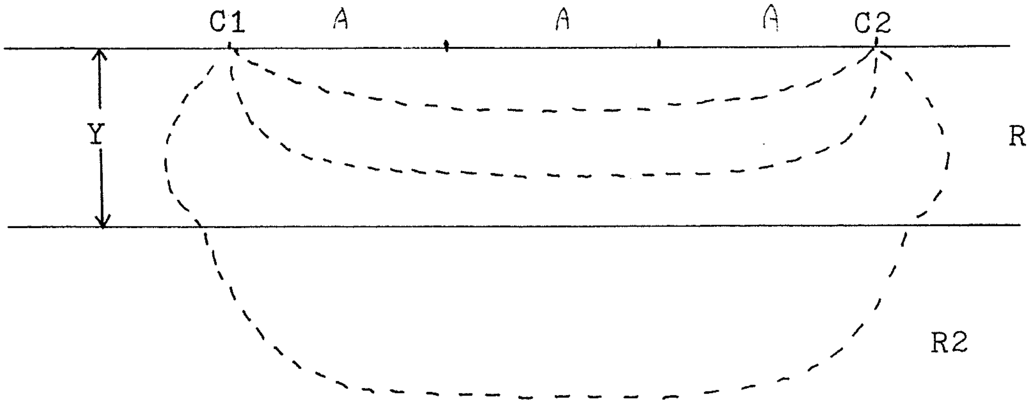

Figure 12. Electrode spacing, A, comparable to thickness Y. Apparent resistivity intermediate between R1 and R2.

As the electrode spacing, A, becomes very large with respect to the thickness, Y, the electrical field is but slightly affected by the top layer and the apparent resistivity approximates R2.

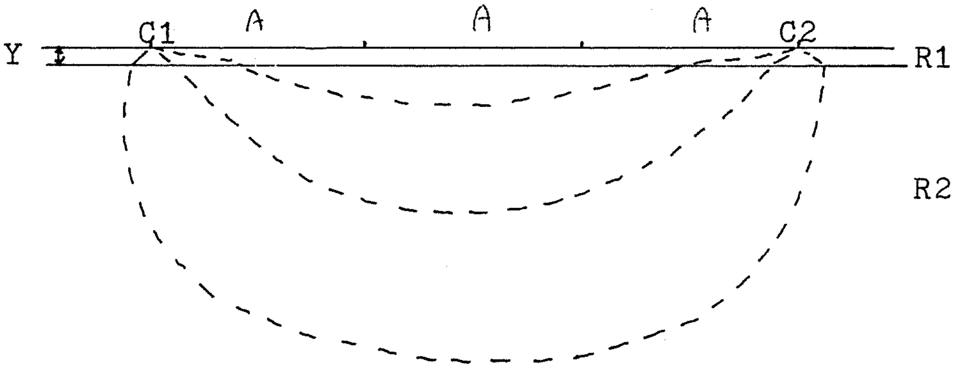

Figure 13. Electrode spacing, A, large compared to thickness Y. Apparent resistivity approxiamtes R2.

The following is an example of a computer generated sounding curve.

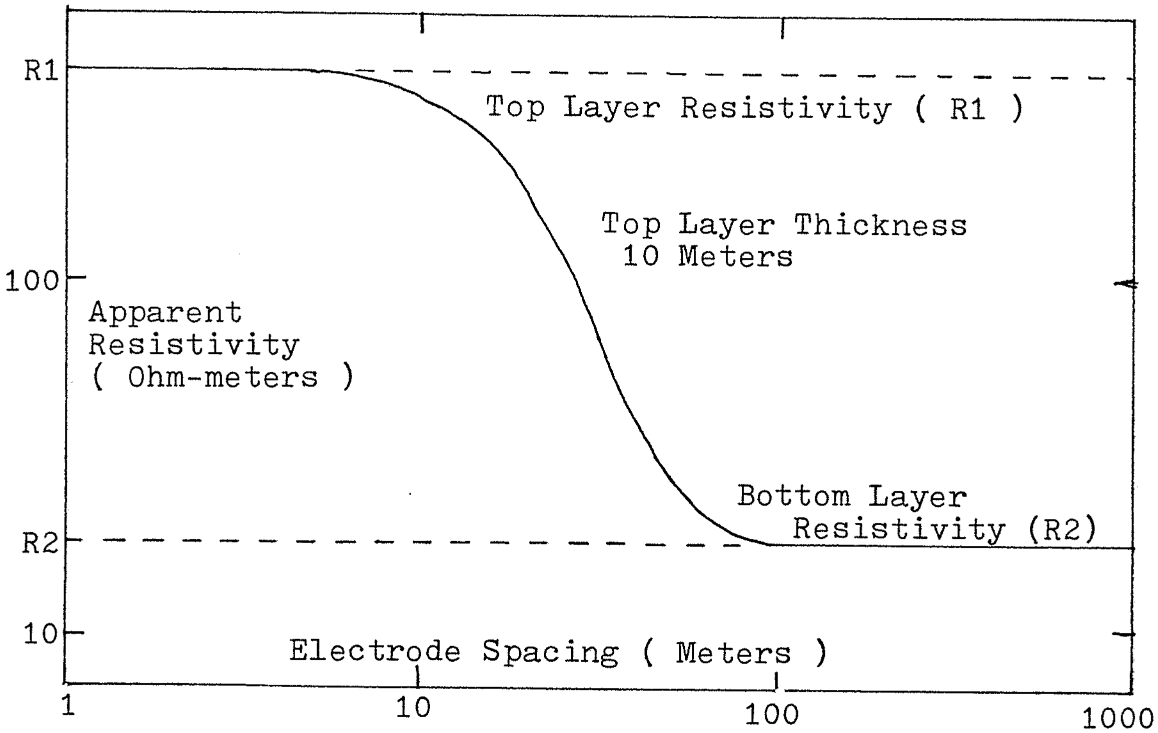

Figure 14. Sounding graph for two layer model. (Adapted from Mooney, 1980)

Prior to the age of computers, field data was were interpreted by curve matching. One set of curves covers the range of all possible two layer configurations. Figure 15, on page 22 is such a set of curves. This is a logarithmic resistivity plot for the Wenner configuration of the entire range of resistivity contrasts. The reflection factor, K, is the ratio $\frac{(R2-R1)}{(R2+R1)}$. On this graph the resistivity and the thickness of the top layer have been normalized to 1. The horizontal axis is the electrode spacing and the vertical axis is the apparent resistivity. Note that the depth index line is where the electrode spacing equals the thickness of the top layer.

Models with more than two layers have many more variables, such as the relative thicknesses of the layers, and the three or more relative resistivities of the layers. Many sets of multi-layer curves have been published. Below is presented an example of a three layer model set of resistivity curves in which all parameters are fixed except for the thickness of the middle layer. The data was were generated by the Bison computer program Resist (Figure 16, p.23).

Lateral Variations

Several simple lateral earth configurations have been modeled by image theory. Three of the most notable are the vertical fault by Tagg, the dipping fault by Hubber, and the vertical dike by Van Nostrand & Cook. These models are presented in Figures 17, 18, and 19 (pages 24, 25, and 26, respectively).

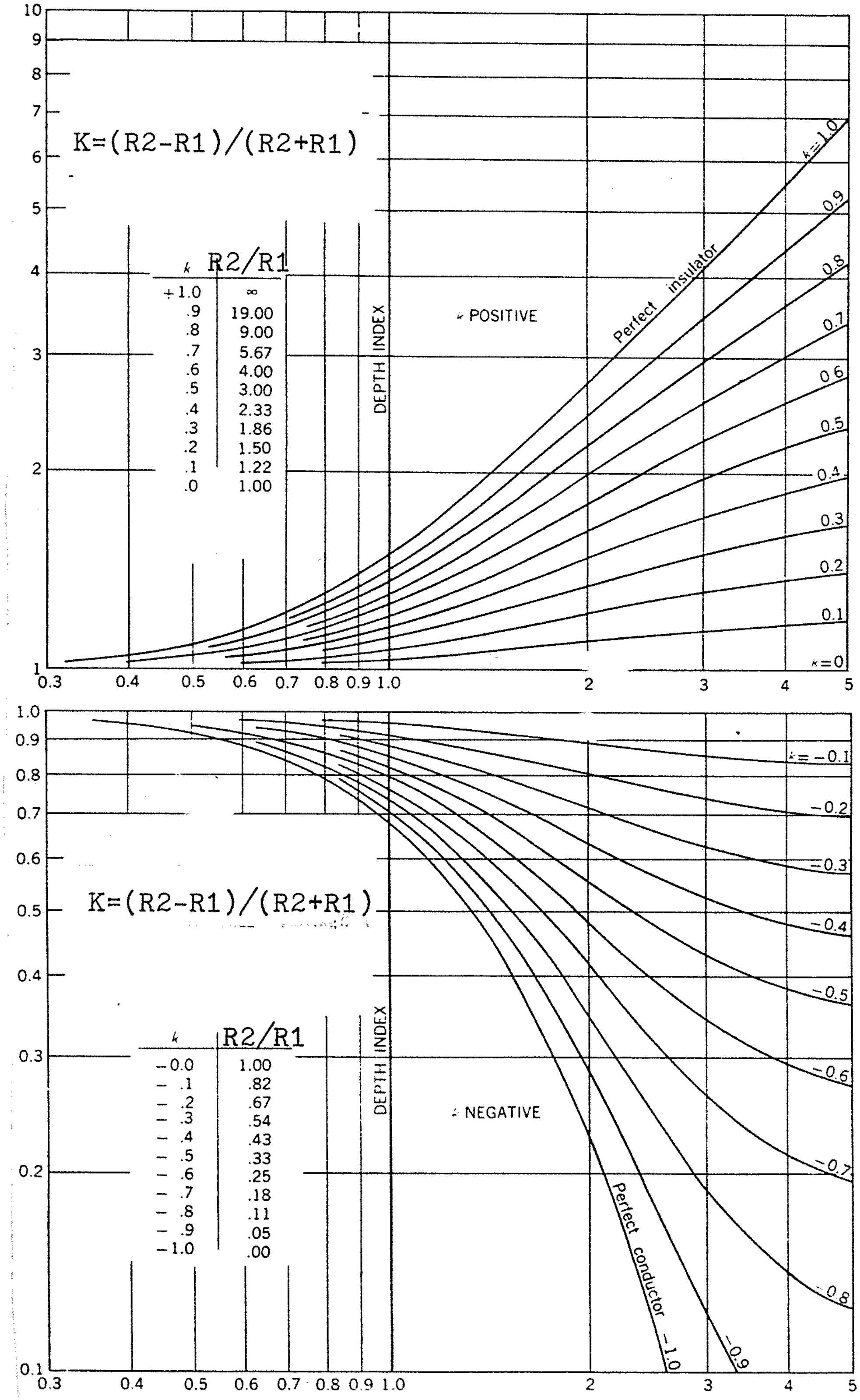

Figure 15. Resistivity curves for two layer model.
(Adapted from Roman, 1941, by Van Nostrand & Cook, 1966)

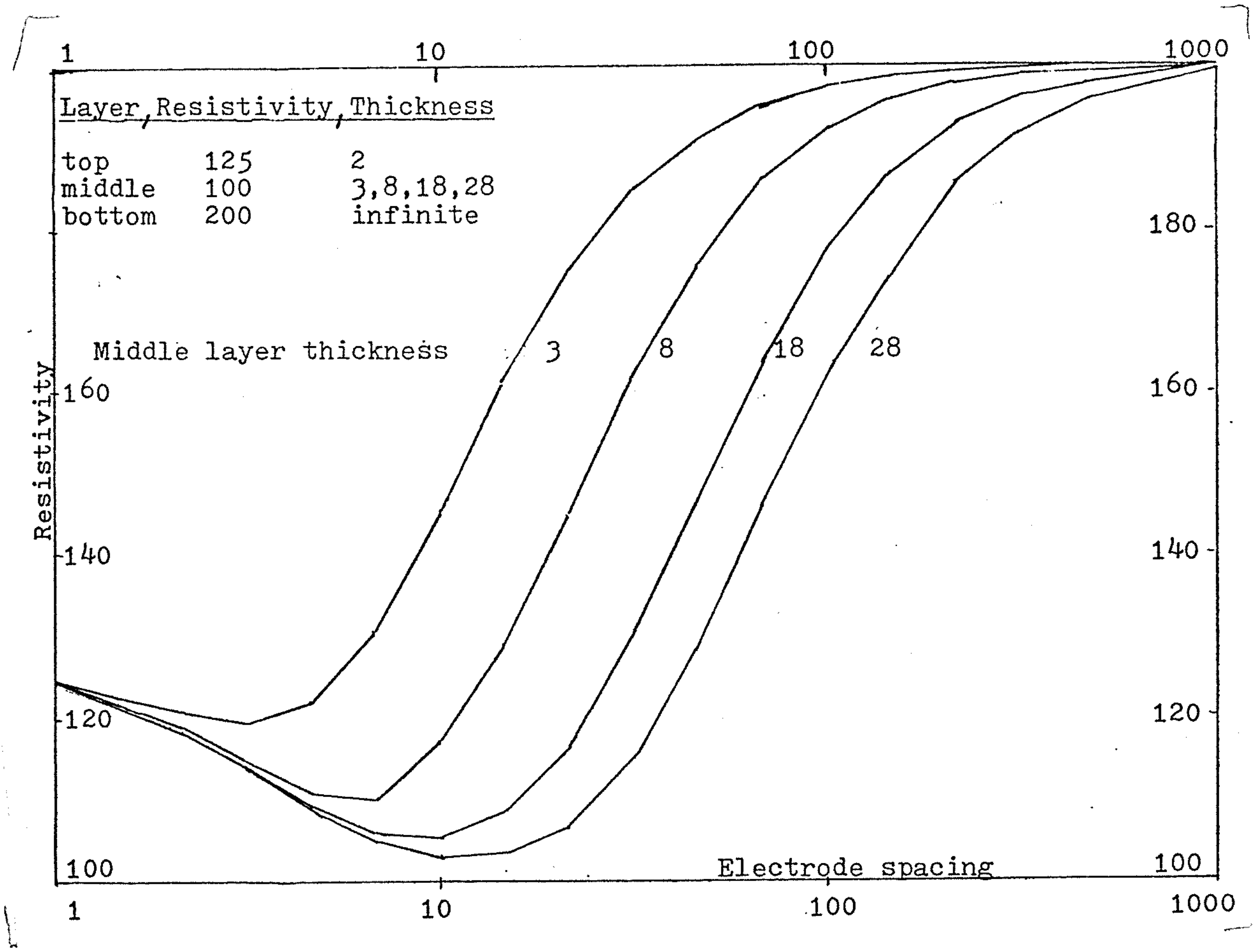

Figure 16. Three layer set of computer generated resistivity curves. Resistivities are fixed. Middle layer thickness is varied.

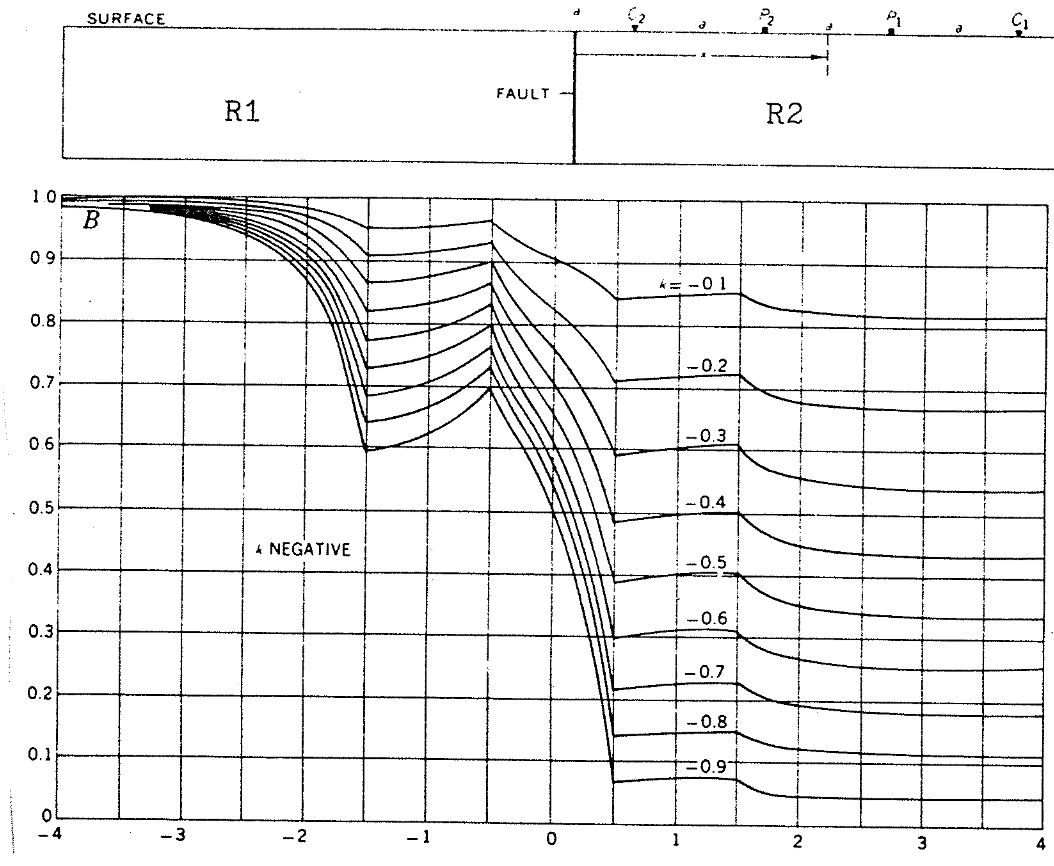

Figure 17. Vertical Boundary Between Two Distinct Electrical Units. Wenner profile across a vertical fault of infinite depth. Resistivities of R1 and R2 on the left and right sides of the fault respectively. Horizontal axis is the ratio of the distance from the fault trace to the center of the electrode configuration divided by the electrode spacing. The vertical axis is the ratio of the apparent resistivity value, Ra, divided by the resistivity, R1, left of the fault. K is the reflection factor. (Van Nostrand & Cook, 1966)

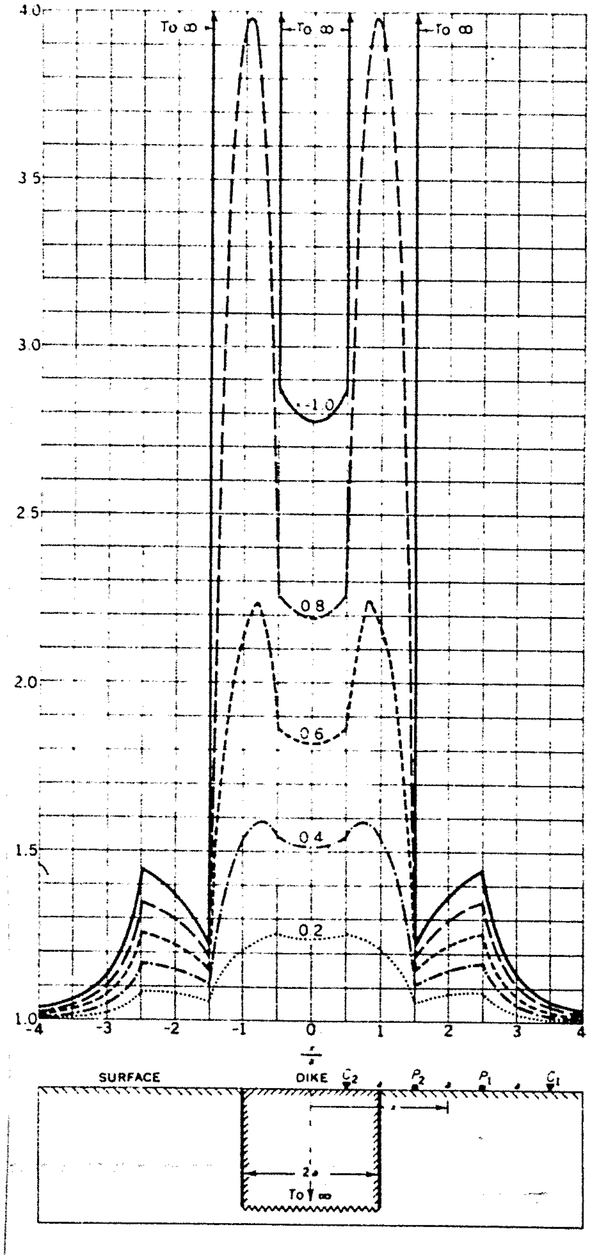

Figure 18. The Vertical Dike. Wenner configuration profile across a vertical dike. Varying degrees of resistivity contrast between the dike material and the surrounding earth.(Adapted from Van Nostrand & Cook, 1966)

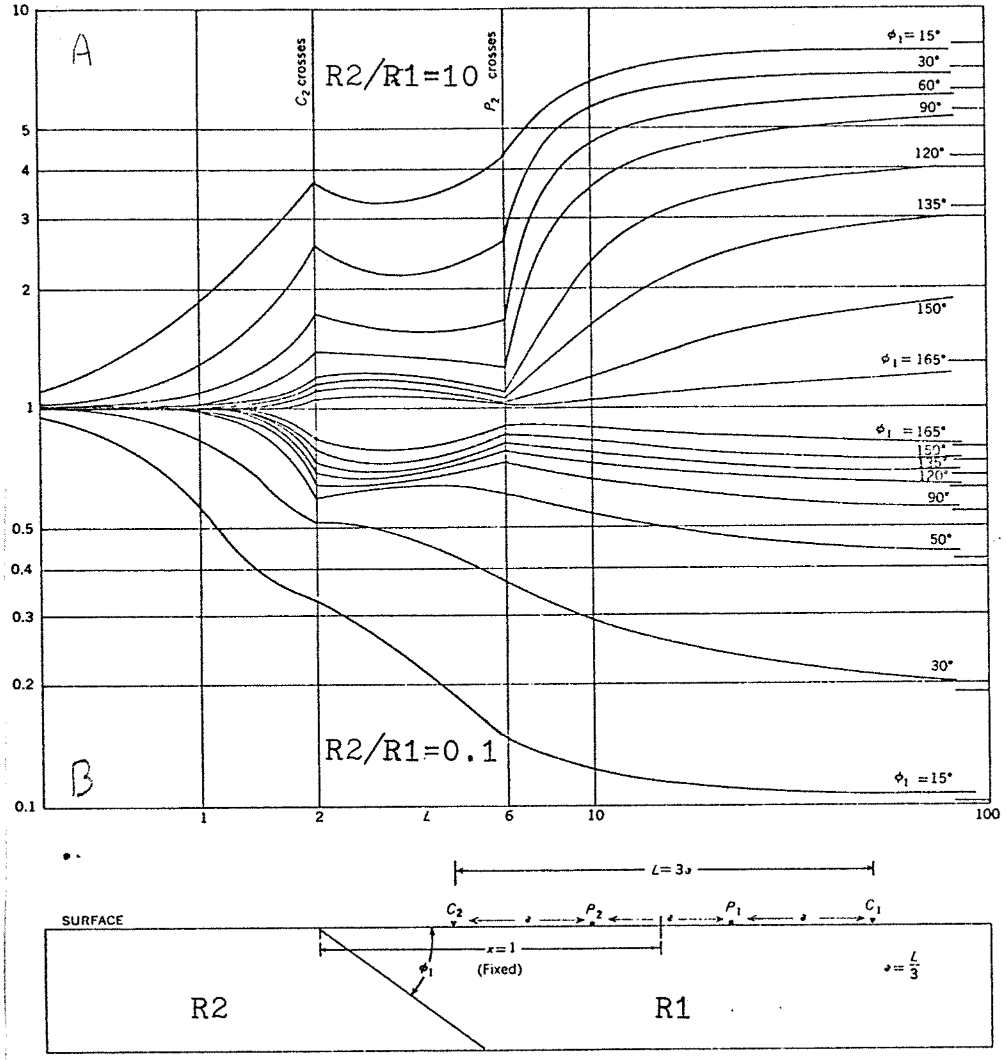

Figure 19. Dipping Boundary Between Two Distinct Electrical Units. Graph of apparent resistivity values for a Wenner sounding across a dipping boundary of various angles. Point of reference is fixed at 1 unit of distance from boundary outcrop.

(A) Upper diagram has a resistivity contrast of $\frac{R2}{R1} = 10$ or a reflection factor of about +0.9.

(B) Lower diagram has a resistivity contrast of $\frac{R2}{R1} = 0.1$ or a reflection factor of about -0.9.

(Adapted from Hubber by Van Nostrand & Cook, 1966)

PART II: RESISTIVITY IN PRACTICE

This section describes the practical aspects of resistivity prospecting. It applies primarily to buried stream channel mapping problems. However, much of the content will help with other types of mapping problems as well.

CHAPTER 5: FIELD DEVIATIONS FROM MODELS

Resistivity field data is compared with simulated data from earth configuration models to determine the subsurface features. These models are highly oversimplified and invariably deviate from geologic reality. Some common deviations are presented below.

GEO-ELECTRICAL INHOMOGENEITY

Rarely is a given geologic unit truly electrically homogeneous. A high resistivity sand deposit often has pockets of low resistivity silts and clays. A high resistivity bedrock may have water-filled fissures of low resistivity. It must be remembered that resistivity data is sensitive to different electrical units and may not distinguish geologic units.

RANGE OF RESISTIVITIES

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Most earth types fall under a certain range of resistivities. Many earth types have widely spreading ranges. A broad classification is presented in Figure 20, page 29. This table can help qualitatively when determining the resistivity contrast between units of interest. Extensive tables are presented by Telford et al.(1976, pp.454-455).

As a rough guide, we may divide earth materials into

--low resistivity	less than 100 ohm meters
--medium resistivity	100 to 1000 ohm meters
--high resistivity	greater than 1000 ohm meter

Some representative resistivity values are:

Regional soil resistivities	
--wet regions	50-200 ohm meters
--dry regions	100-500
--arid regions	200-1000 (sometimes as low as 50 if the soil is saline)

Waters	
--soil water	1 to 100
--rain water	30 to 1000
--sea water	order of 0.2
--ice	10^5 to 10^8

Rock types below the water table	
--igneous and metamorphic	100 to 10,000
--consolidated sediments	10 to 1000
--unconsolidated sediments	1 to 100

Ores	
--massive sulfides	10^{-4} to 1
--non-metallics (gypsum, quartz, dry rock, salt)	order of 10^{10}

Effect of water salinity	
.005g/liter	1050
.10	110
.5	12

Figure 20. Range of resistivities table. (Mooney 1980)

SUBSURFACE TOPOGRAPHY

The subsurface topography is rarely as regular as in the models. The bottom of a buried stream channel is full of humps and hollows. The channel walls are neither vertical nor inclined at a constant angle. Therefore, the field data curves will not be as smooth and regular as the model curves.

MISLEADING MODELS

Often several geo-electric models can explain a given resistivity anomaly. However, only one of them is correct! Geologic constraints and other geophysical prospecting methods should be used to support the preferred explanation for the anomaly.

MAN-MADE RESISTIVITY ANOMALIES

Buried man-made features such as sewer lines and waterlines, particularly if the casing is cast iron, may drastically affect resistivity data. Figure 21 is an example of a profile across a sewer line. Close proximity to man-made features such as metal fences and railroad tracks will also yield anomalously low apparent resistivity values. These metal objects absorb a major portion of the current density, thus lowering the potential between the P-electrodes.

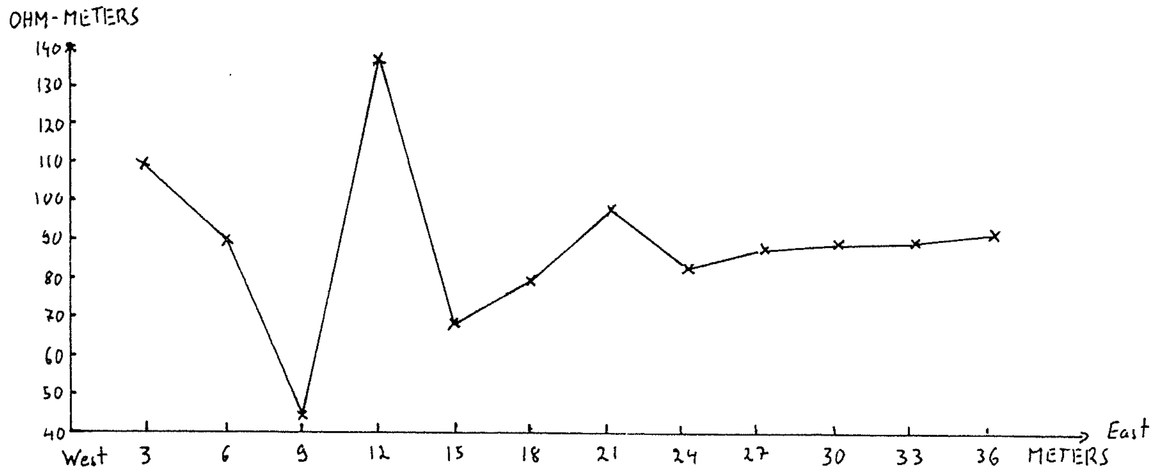

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Figure 21. Resistivity profile across the SW end of the Carleton College Football Field. Electrode spacing 3 meters. The major anamaly is the sewer line. The sewer line is probably surrounded by high resistivity sand and gravel fill. Profile roughly perpendicular to sewer line.

NATURAL ELECTRIC CURRENTS

Natural electrical currents in the earth will affect the resistivity data. Such currents may originate from electro-chemical processes, telluric currents rising from deep within the earth, or electrical storms. The literature suggests a periodic check for such natural currents. A quick way to do so is to reverse the polarity of the induced current, and look for a change in the apparent resistivity. I tried this throughout my field work and found no significant variations.

SURFACE TOPOGRAPHY

Most geo-electric models have assumed a level surface. Little has been written about the effects of topographic relief on apparent resistivity values. The Bison Handbook shows qualitatively why measurements made near a vertical cliff would yield higher apparent resistivity values (Mooney 1980, pp.28--5). According to the handbook, the current is deflected from the edge of the cliff since air has "infinite" resistivity. This increases the current density between the P-electrodes thus increasing the apparent resistivity. For this reason, field strategy should give priority to taking soundings and profiles on relatively flat topography.

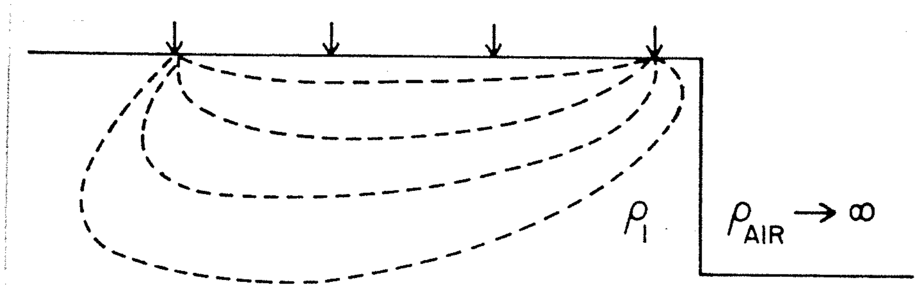

Figure 22. Lines of current flow for an electrode set-up near a vertical cliff. High apparent resistivity readings will result. (From Mooney 1980)

CHAPTER 6: THE INSTRUMENT

I used a Bison Earth Resistivity Sytems Model 2350 belonging to the Carleton College Geology Department. It is portable and is housed in a water-tight case with batteries that deliver 360 volts of low density current. Its 1980 value is about $2000.. For further description and operating procedures, consult the Bison Instruction Manual (Bison, 1975).

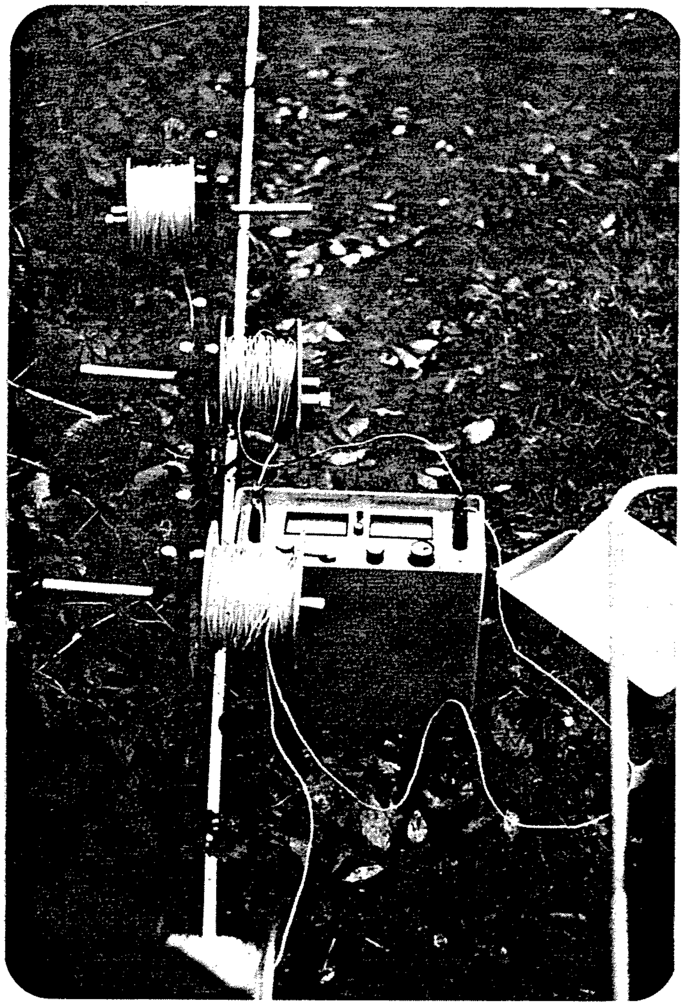

Figure 23. Bison Earth Resistivity Systems Model 2350.

There are features in the Bison system, and in all other resistivity systems, that cause it to deviate from the geo-electric models. Two such features came to my attention during my research. The first such feature is that in contrast to the geo-electric model assumptions, the electrodes that introduce the current into the ground are cylindrical stakes and not perfect points. In the immediate vicinity of the electrodes the electric field does not resemble that of the models (Van Nostrand & Cook, 1966, p.28). I found that a minimum electrode spacing of about one meter is required to insure conformity with the models.

The second feature that deviates from the models ~~are~~ is the resistance~~s~~ of the resistors in the instrument. They may vary slightly from their specifications (conversation with a Bison Engineer). The variations are usually insignificant and would only cause difficulties when comparing data taken from two different instruments. Moisture within the casing will cause the resistance to vary as well. Keeping the instrument dry and using it in dry field conditions helps avoid this problem.

CHAPTER 7: FIELD PROCEDURES

Outlined below is the progression of field procedures recommended to anyone planning to map a buried stream channel, or similar feature, using resistivity techniques. This applies to the Wenner, Lee, and Schlumberger configurations.

RESISTIVITY CONTRAST

Determine the resistivity contrast between the units of interest. Measure the apparent resistivity of each unit from surface exposures if possible. If no exposures are available, consult the table of earth material resistivities (page 29) for approximate values. Calculate the reflection factor K, $K = \frac{(R2-R1)}{(R2+R1)}$. A minimal reflection factor of K = ± 0.4 is required to overshadow electrical resistivity variations within each unit of interest.

SOUNDING

A combination of soundings and profiles are generally used in mapping an area. A series of initial soundings should be taken to determine the optimum electrode spacing for profiling. At the same time, an estimate can be either made or verified about the depth to the unit of interest.

Figure 24 is a two layer model, computer generated set of sounding curves for various thicknesses of the top layer. An electrode spacing of 20 meters (60 meters total electrode layout) yields the maximum resistivity contrasts for top layer thicknesses of five to ten meters. This would be a good spacing for mapping features buried at these depths. A spacing of ten meters would be too small and a spacing of 40 meters would be too large. Both would result in a diminished contrast (see Figure 24, below).

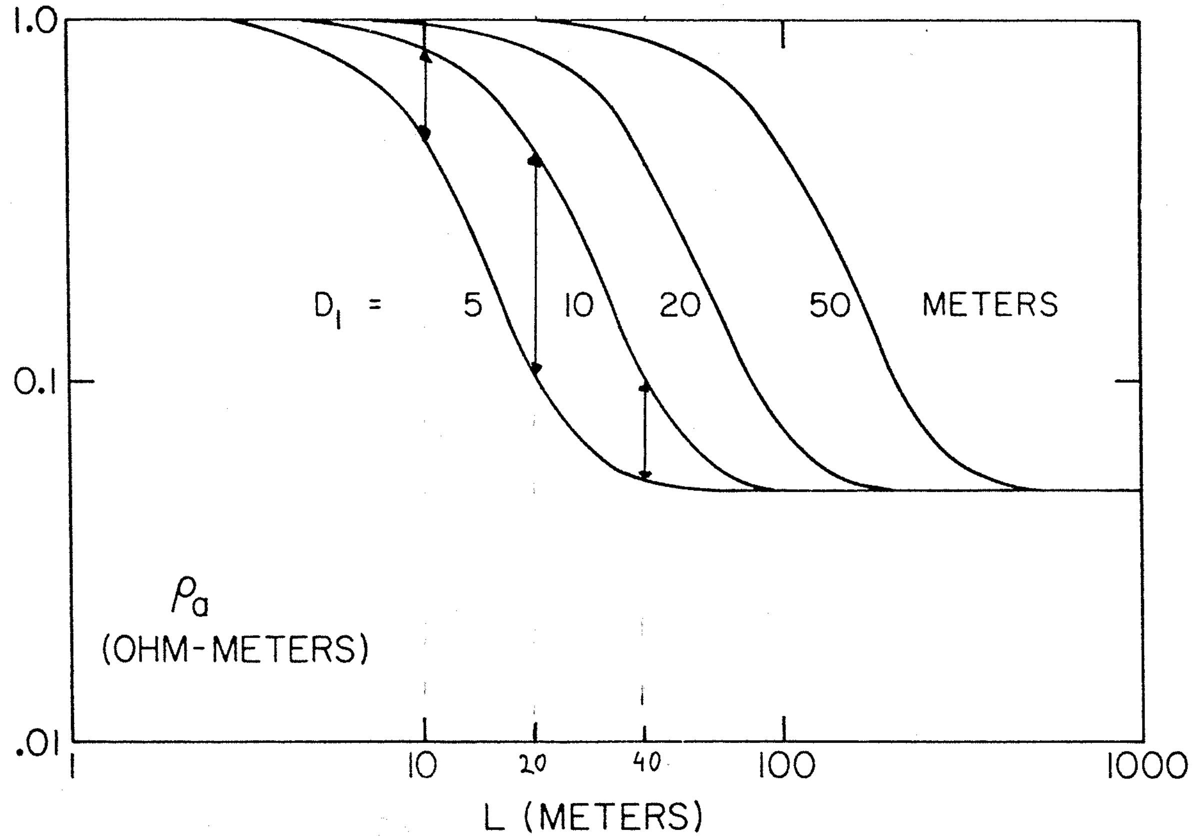

Figure 24. Two layer model computer generated sounding curves. Reflection factor, K, of about -0.9. Thicknesses of top layer: 5, 10, 20, and 50 meters. The vertical arrows measure the resistivity range for electrode spacings of 10, 20, and 40 meters, at a depth of interest between 5 and 10 meters. (Adapted from Mooney, 1980)

Usually a spacing of one and one-half to three times the depth of interest is required. This means a total electrode layout of four and one-half to nine times the depth of interest. ~~Often~~ commonly, field constraints or buried lateral structures will limit resistivity to the mapping of relatively shallow features.

DEPTH SOUNDING AND THE COMPUTER PROGRAM 'INVERSE'

Carleton College has the Bison computer program "Inverse" on line to help with the interpretation of field soundings (Mooney, 1980, Davis, 1979, Merrick, 1977). Supplied with sounding data and an initial horizontal layer model, Inverse does a least squares fit of the layer thicknesses and resistivities to the sounding data. It makes the best match of the model with the data. This program is useful for making depth determinations.

Caution must be exercised when using this program. It only does horizontal layer modeling and does not take into account lateral anomalies. Buried topographic relief between two geo-electric units can easily be misinterpreted to represent several horizontal units. Once again, other evidence should support your geo-electric models.

Figure 25 is a field example of a sounding encountering severe lateral anomalies. Geologically it is known that there are but two layers. However, the program gave a reasonable fit to a four layer model (see Figure 25, p.38).

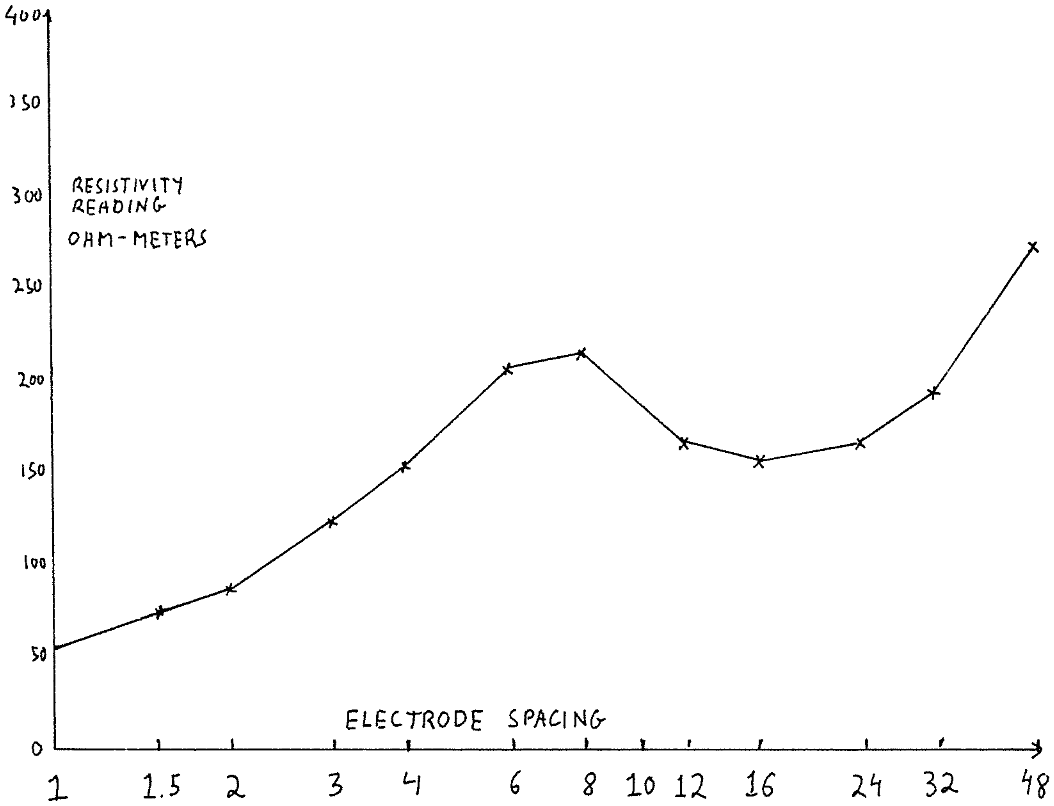

Figure 25. Example of sounding in the field encountering severe lateral anomalies. There are only two geo-electric layers. Can you see how this might be mistaken to represent four horizontal layers?

Don't put in the form of a question

PROFILING

The mapping area should be profiled using the best suited electrode spacing. While doing so, keep electrode layouts for successive traverses roughly parallel, so that lateral structures will show up uniformly. Plot the apparent resistivity values on a map and draw in the apparent resistivity contour lines. The approximate location of the buried stream channel or other features should be evident from the derived resistivity topography.

Figure 26, (page 40), is a resistivity contour map of a buried stream channel produced by Zohdy (1974). He did initial soundings, chose his electrode spacing to be 30 feet and did a series of profile traverses. The high resistivity contour lines in the figure indicate the path of the channel. This is because the channel is filled with high resistivity sands and gravels.

Areas appearing to be of special interest ought to be reapproached and mapped in more detail, or tackled by other methods such as seismic, drill core, or test well.

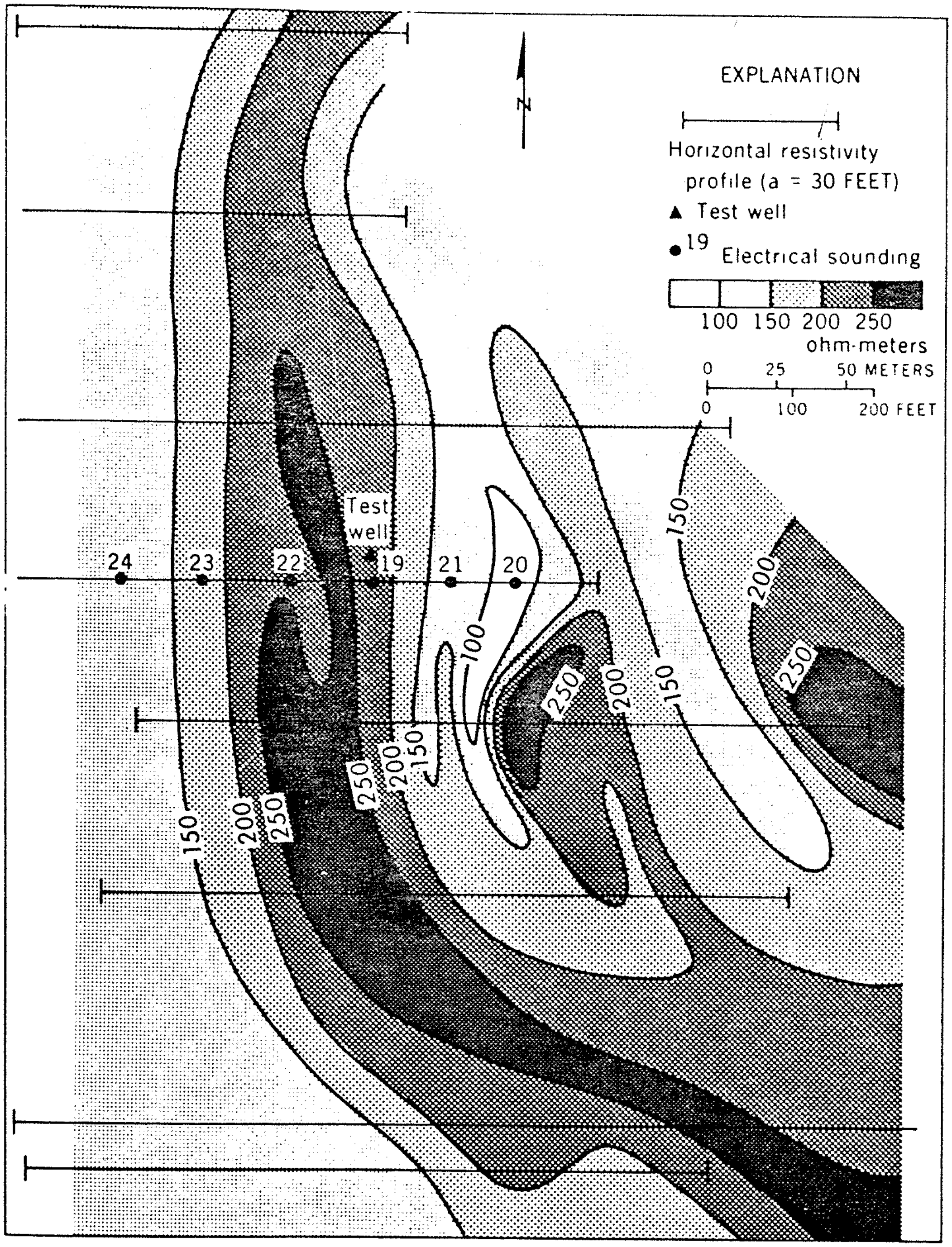

Figure 26. Resistivity contour map of a buried stream channel. The high resistivity contours (200 and above) indicate the buried stream channel bed (Adapted from Mooney 1980, from Zohdy)

CHAPTER 8: EVALUATION OF RESISTIVITY

Electrical resistivity can make valuable contributions to geophysical prospecting if its limitations as well as its uses are understood. Perhaps the best evaluation is to briefly list the pros and cons of resistivity and let the reader be the judge.

ADVANTAGES OF RESISTIVITY

--It is inexpensive.
--The equipment is portable.
--The physical impact on the field area is minimal.
--Large areas can be covered rapidly.
--One person can do the field work.
--Qualitative data interpretation is straightforward.

DISADVANTAGES OF RESISTIVITY

--Detailed mapping of all but the shallowest features (less than five meters) is difficult.
--Geo-electric models may not reflect the true geology.
--Resolution of deeply buried features is poor.
--Depth estimations are not accurate (relative to seismic).

PART III: RESISTIVITY MAPPING OF A BURIED STREAM CHANNEL ALONG A SECTION OF THE CANNON RIVER VALLEY

CHAPTER 9: INTRODUCTION

In addition to learning about resistivity, this study involved mapping the subsurface topography along a section of the Cannon River Valley just north of Northfield, Minnesota.

Over the past couple of years, Tim Vick has done seismic work revealing a system of deeply buried stream channels along the present Cannon River. In particluar, he did a detailed study of a buried gully under the Carleton College Atheltic fields (Vick, 1979). He mapped depths to bedrock of about 20 meters at the gully's deepest points. He also led a study entitled, "Survey of Buried Bedrock Topography in the Cannon River Valley between Northfield and Cannon Falls, Minnesota" (Vick, et al., 1980). This survey revealed depths to bedrock of over 30 meters near the Arboretum Tennis Courts from seismic sounding, and similar depths near the Northfield Sewage Treatment Plant from a soil bore hole. Clearly a deeper, larger stream channel exists in this area.

My contribution was to determine the size and path of this channel along the section of the Cannon River Valley extending from the Carleton College Arboretum Tennis Courts to the Northfield Sewage Treatment Plant (Figure 28 , page 46). Knowing the size and path of this channel will aid in unraveling the Quaternary history of Northfield, and will be useful to anyone doing detailed profiles of the channel in that field area.

CHAPTER 10: REGIONAL SETTING

The Northfield area sits upon flat-lying lower Paleozoic strata. The bedrock has been carved up by recent glacial activity and in many places is overlain by glacial sediments of Wisconsian Age or older. The present Cannon River Valley cuts through the St. Peter Sandstone and rests in the top of the Prairie Du Chien Group~~e~~. The buried stream channel is incised into the uppermost Prairie Du Chien formation, the Shakopee. The Shakopee is mostly dolostone, sandy dolostone, and sandstone with occasional thin beds of grayish-green shale (Adapted by Swanson, 1979, from Austin).

The buried stream channel and the sediments filling it are most likely glacial in origin. The question as to their exact formational environment is as yet unanswered. Was it a pro-glacial outwash stream or a sub-glacial stream? Was it formed by a steady water flow regime over many years, or in a matter of months from the catastrophic failure of an ice wall dam (Swanson, 1979) ?

CHAPTER 11: FIELD AREA

My field area was bounded by the Arboretum Tennis Courts upstream, the Northfield Sewage Treatment Plant downstream, the railroad tracks on the left bank, and the edge of the valley on the right bank. The area is roughly one kilometer long and 300 meters wide. It consists mainly of a corn field on the right bank, and woods with underbrush and nettles on the left bank.

Figure 27. The field area, a field of corn.

The field conditions were less than ideal. The resistivity soundings and profiles required a linear layout of 144 meters. Bodies of water are obstacles to electrical sensing and the present Cannon River compromised many possible traverses. Furthermore, to prevent damage

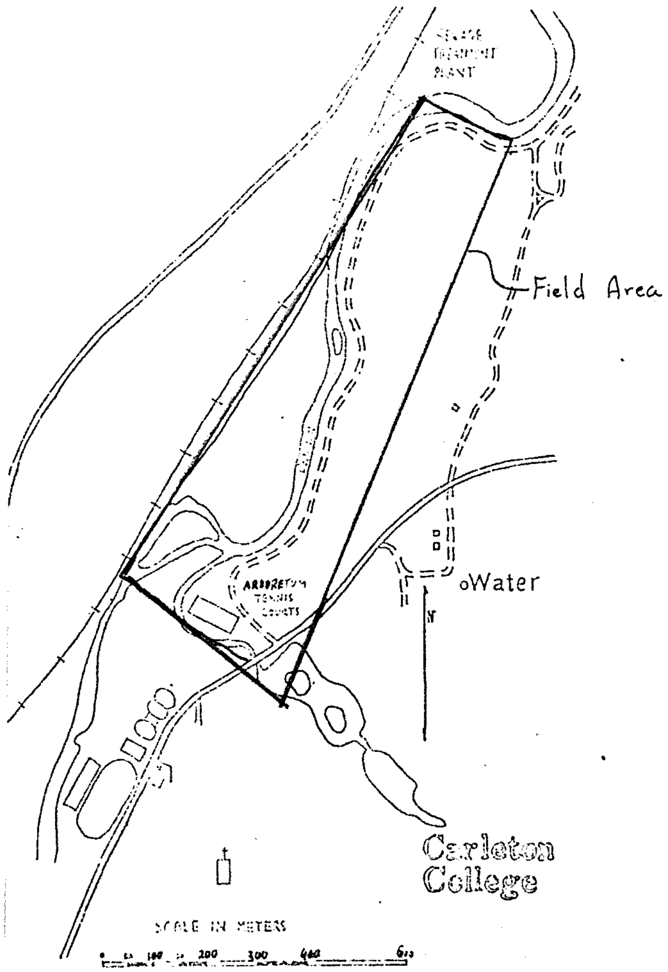

Figure 28. Field area.

to the corn crop, traverses in the corn field were kept roughly parallel to the corn rows. Also, there were few landmarks adequate for locating stations in the field.

As a result, the grid of data points are not uniformly distributed and the station locations are approximate in places. However, the precision and the distribution of stations are good enough to present an acceptable resistivity map.

Figure 29. Photograph of sounding being taken between corn rows.

CHAPTER 12: FIELD PROCEDURES

RESISTIVITY CONTRAST

Many surficial readings on the sand, clay, and gravel deposits over the channel indicated resistivities ranging from 50 to 200 Ohm-meters for the glacial fill. A sounding taken on the bedrock bluff behind Goodhue dormatory revealed the Shakopee to have resistivities on the order of 1000 Ohm-meters. Calculating the reflection factor, we get:

$$K = \frac{(1000-50)}{(1000+50)} \simeq +0.9$$

$$K = \frac{(1000-200)}{(1000+200)} \simeq +0.6$$

So the reflection factor, K, ranges from about +0.6 to +0.9. This is a sufficient contrast to do resistivity work.

SOUNDINGS

A series of initial soundings with maximum electrode spacings of 48 meters were taken. The most consistent slopes on the graphs were between the 32 and 48 meter spacings (see data appendix graphs). Hence, the minor variations of glacial fill had been averaged out. The high resistivity of the Shakopee Formation was the dominant influence. Thus a 48 meter electrode spacing offered the maximum discrimination of depth for mapping the buried channel. This meant a total linear electrode layout of 144 meters.

Greater electrode spacings would have offered more depth discrimination, but field constraints and equipment limitations would not permit them. Furthermore, larger spacings would undoubtedly hit more subsurface lateral anomalies in a single reading and cloud the subsurface resolution even more.

DEPTH SOUNDINGS

The same soundings used to determine electrode spacings were used for depth analysis. As previously stated, the largest possible practical spacing was 48 meters, a minimal spacing for determining depths that range upwards of 30 meters. Twenty-five depth soundings were taken. Thirteen of them encountered severe lateral anomalies making them unfit for depth determination. The data from the remaining twelve were analysed by the Bison computer program Inverse (Mooney 1980, Davis 1979, Merrick, 1977).

The resistivity data was transformed into equivalent readings of a logarithmic electrode spacing progression. They were entered into the terminal. By and large, the data would not converge to a two layer model. The two layer models obtained were geologically improbable. While some results suggested channel depths of eight to ten meters with bedrock resistivities of 200 to 400 Ohm-meters, others suggested depths to bedrock of 15 to 29 meters with bedrock resistivities on the order of 10,000 Ohm-meters. Attempts to fix parameters such as depth and resistivity yielded poor correlations between the data and model, and unlikely results.

The probable cause of the erratic results is the encounter of lateral anomalies such as dipping slopes over the 48 meter spacing between the P-electrodes. The horizontal models deviate too much from the field conditions to fit the field data. This shows one of the weaknesses of mapping deeply buried features with electrical resistivity.

RESISTIVITY CONTOUR MAP

The entire field area was profiled with a Wenner configuration spacing of 48 meters, or a total linear electrode layout of 144 meters. Most of the traverses in the corn field were made parallel to the corn rows thus minimizing crop damage. A plot of the field stations and electrode layouts is presented in Figure 30, page 51. Plotting the resistivity readings and drawing in resistivity contour lines reveals the contour map in Figure 31, page 52.

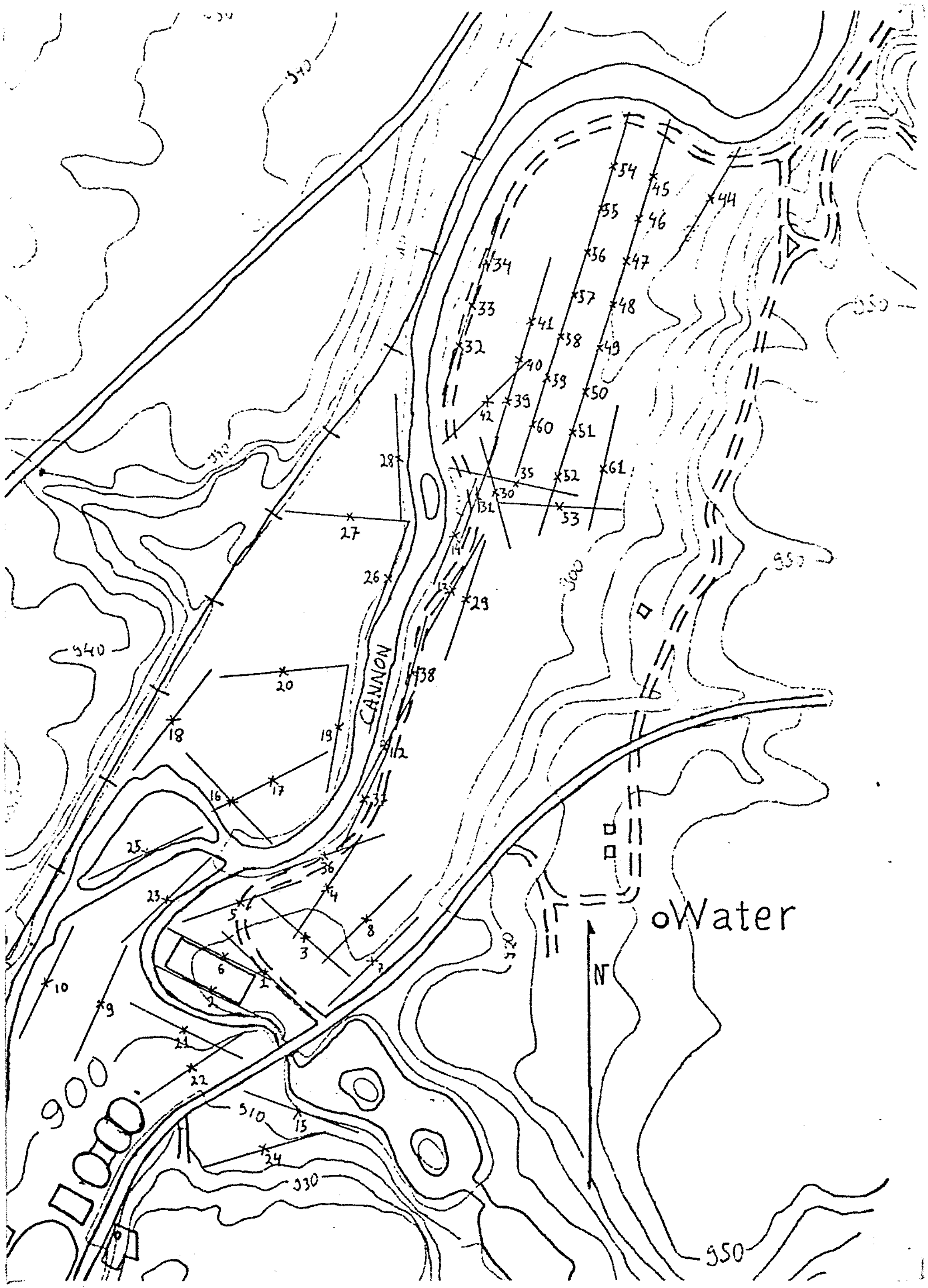

Figure 30. Plot of field stations and electrode layouts. X's are the center of the electrode configurations with accompanying station numbers. The lines are the paths of the electrode layouts.

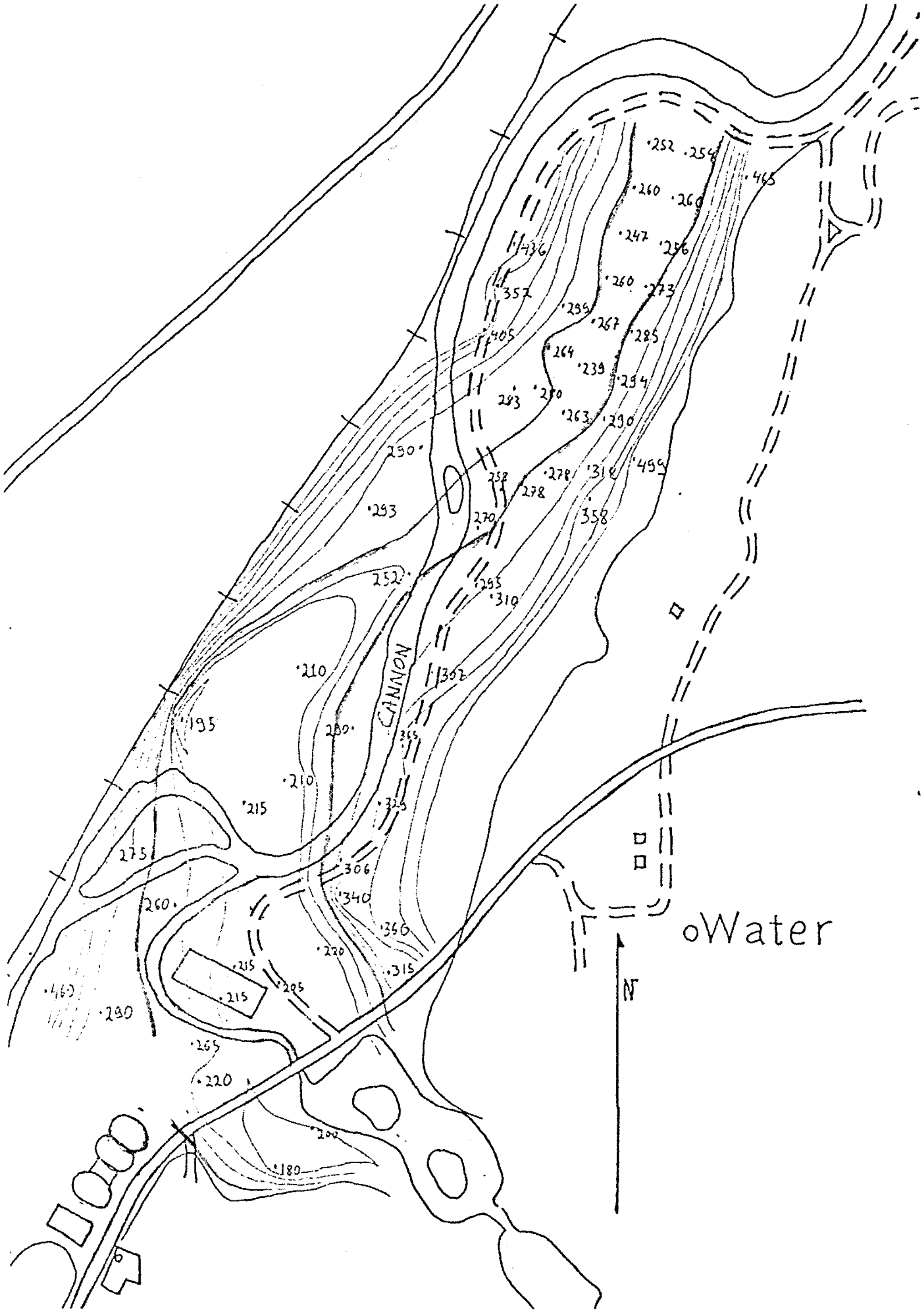

Figure 31: Topographic plot of resistivity values for 48 meter Wenner configuration. Contour interval 25 Ohm-meters. Thick line is the 275 Ohm-meter contour line.

CHAPTER 13: DISCUSSION OF RESULTS

The buried stream channel is delineated by the 275 Ohm-meter resistivity contour lines. It shows up nicely despite the poor bedrock topography resolution due to its depths of burial. It clearly confirms Vick et al.'s report that states that the buried channel connects with Spring Creek rather than following the Cannon into Northfield.

The map suggests that the water of this channel may have flowed in the opposite direction of the present Cannon River. However, Vick et al. have evidence indicating otherwise. They did a series of seismic soundings and obtained soil boring data that show the channel to have flowed in the same direction as the present Cannon River.

Perhaps the higher resistivity readings in the channel at the northern end of my field area can be explained by a narrowing of the buried channel to a point where the sides of the channel raised the resistivity values and hid the bottom of the channel. According to profiles of the channel farther downstream by Vick et al., the channel is indeed a deep narrow gorge.

The base water level was most likely much lower at the time of formation of this channel because of its depth of burial. It has been suggested that perhaps a flood of sediment-laden glacial meltwater buried the stream channel (Vick et al., 1980).

Another possibility is that the channel was a subglacial river flowing under hydrostatic pressure (Swanson, 1979). The high pressure would help explain the deep incisings. As the stream flow dwindled, it would have choked in its own sediments, thus burying itself.

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APPENDIX: FIELD DATA

TABLE ONE: RESISTIVITY SOUNDING DATA IN OHM-METERS (WENNER CONFIGURATION)
FROM THE CANNON RIVER VALLEY, NORTHFIELD, MINNESOTA
OCTOBER 1980

Electrode Spacings (meters)	Station # 1	2	3	4	5	6	7	8	9	10	11	12
0.5	99	126	76	*	57	44	58	47	*	*	107	110
1	96	174	59	93	59	42	37	49	54	63	168	59
1.5	*	204	56	*	60	39	33	53	*	*	227	62
2	112	204	56	113	62	37	35	59	64	54	284	58
3	135	196	61	152	83	39	42	70	70	61	354	54
4	146	175	68	163	99	42	49	76	72	74	436	56
6	152	151	80	149	118	54	61	92	81	100	554	67
8	148	138	89	143	114	64	75	113	86	127	625	84
12	133	142	98	149	106	86	104	145	107	175	700	118
16	114	171	111	181	114	105	134	178	125	241	658	162
24	129	165	124	232	144	120	189	235	170	303	545	242
32	139	180	168	285	168	143	240	281	212	391	*	287
48	204	215	221	339	214	197	317	360	285	452	*	364

* No Data

TABLE ONE, CONTINUED

RESISTIVITY SOUNDING DATA IN OHM-METERS (WENNER CONFIGURATION)

	Station #												
	13	14	15	16	17	18	19	20	21	22	23	24	25
0.5	97	52	142	169	900	65	250	89	58	76	62	82	735
1	106	55	131	168	201	56	198	132	62	85	64	100	608
1.5	108	70	150	213	93	53	121	177	81	98	82	176	417
2	117	86	148	242	67	47	89	206	94	106	94	156	252
3	127	122	143	293	69	47	81	254	115	116	103	193	105
4	128	154	136	303	81	48	83	275	126	124	109	210	105
6	124	207	110	260	89	48	92	242	119	148	109	235	96
8	126	214	100	201	96	51	102	201	115	172	107	227	109
12	131	164	98	134	99	59	118	138	116	223	107	179	95
16	144	152	109	136	109	70	140	107	132	256	111	158	129
24	179	164	136	144	138	100	184	119	168	271	133	143	160
32	213	193	161	172	164	135	223	151	205	277	191	146	201
48	298	273	202	214	211	199	291	219	267	221	254	181	277

Electrode Spacings (Meters)

TABLE TWO:

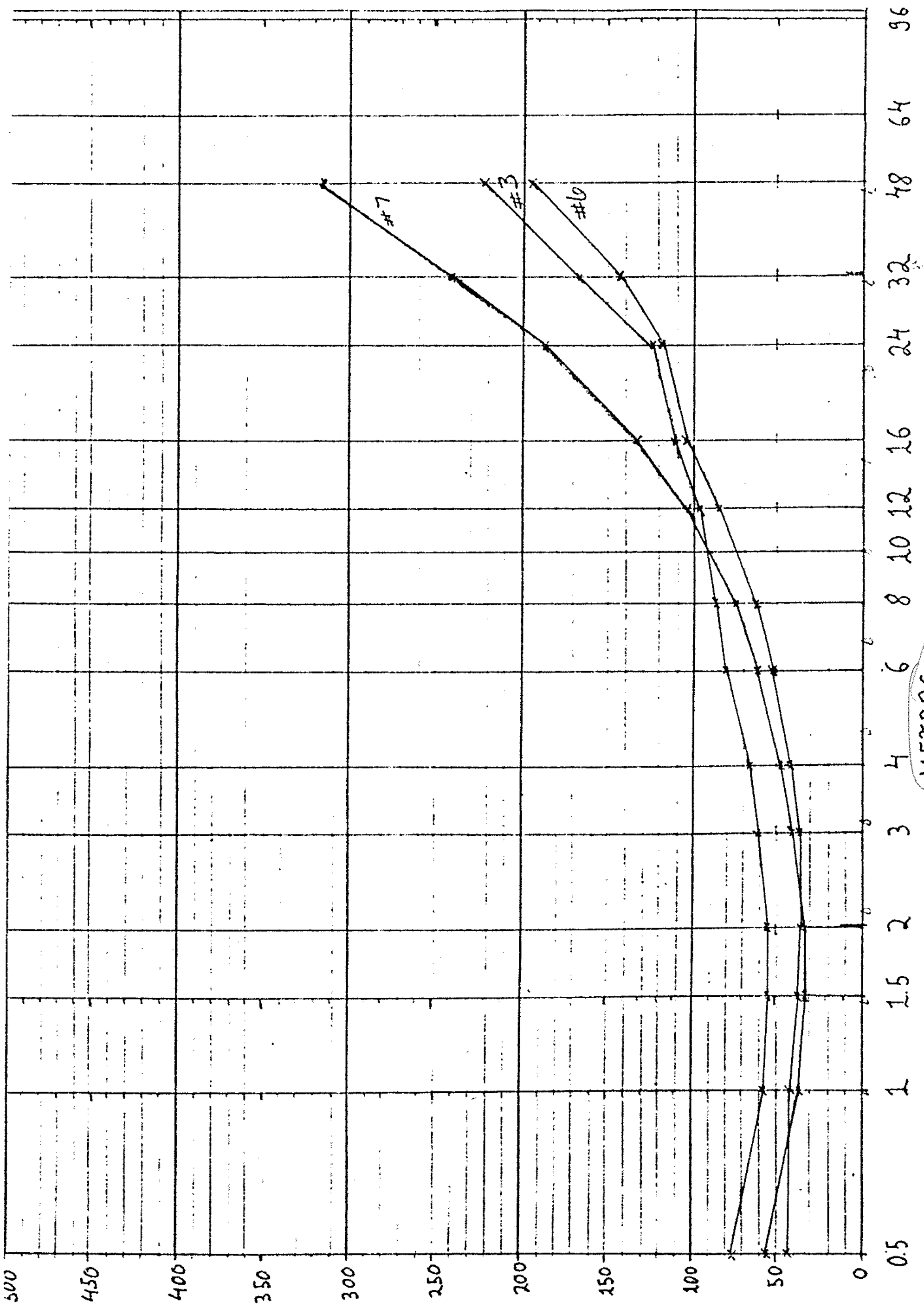
RESISTIVITY PROFILE DATA (WENNER CONFIGURATION)

FROM THE CANNON RIVER VALLEY, NORTHFIELD, MINNESOTA

OCTOBER 1980

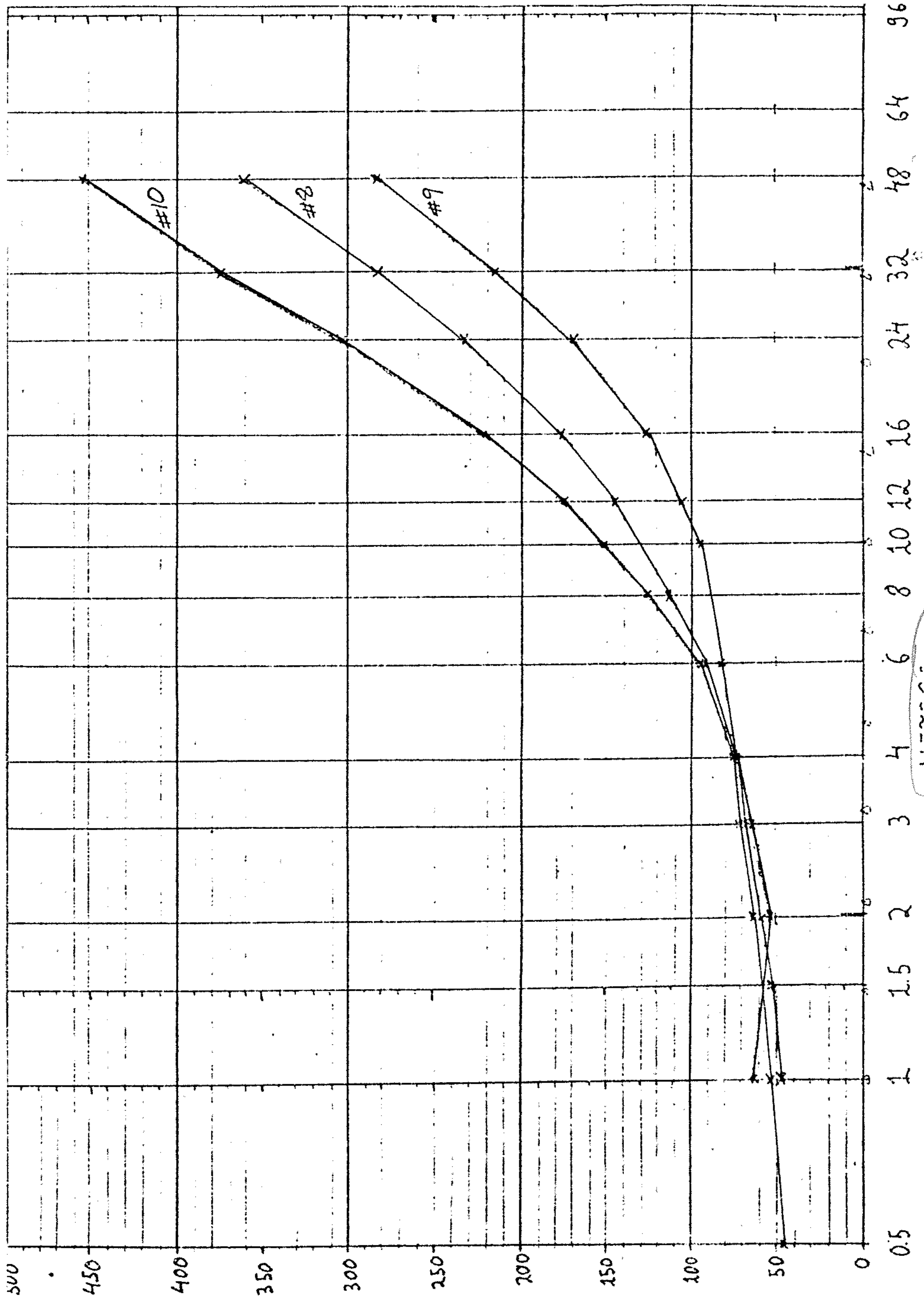
Station #	Resistivity Readings (Ohm-meters)
26	252
27	293
28	290
29	310
30	278
31	258
32	405
33	352
34	436
35	278
36	306
37	329
38	307
39	280
40	264
41	299
42	283
43	243
44	465
45	254
46	260
47	256
48	273
49	285
50	294
51	290
52	318
53	358
54	252
55	260
56	247
57	260
58	267
59	239
60	263
61	499

Soundings Used for Depth Analysis



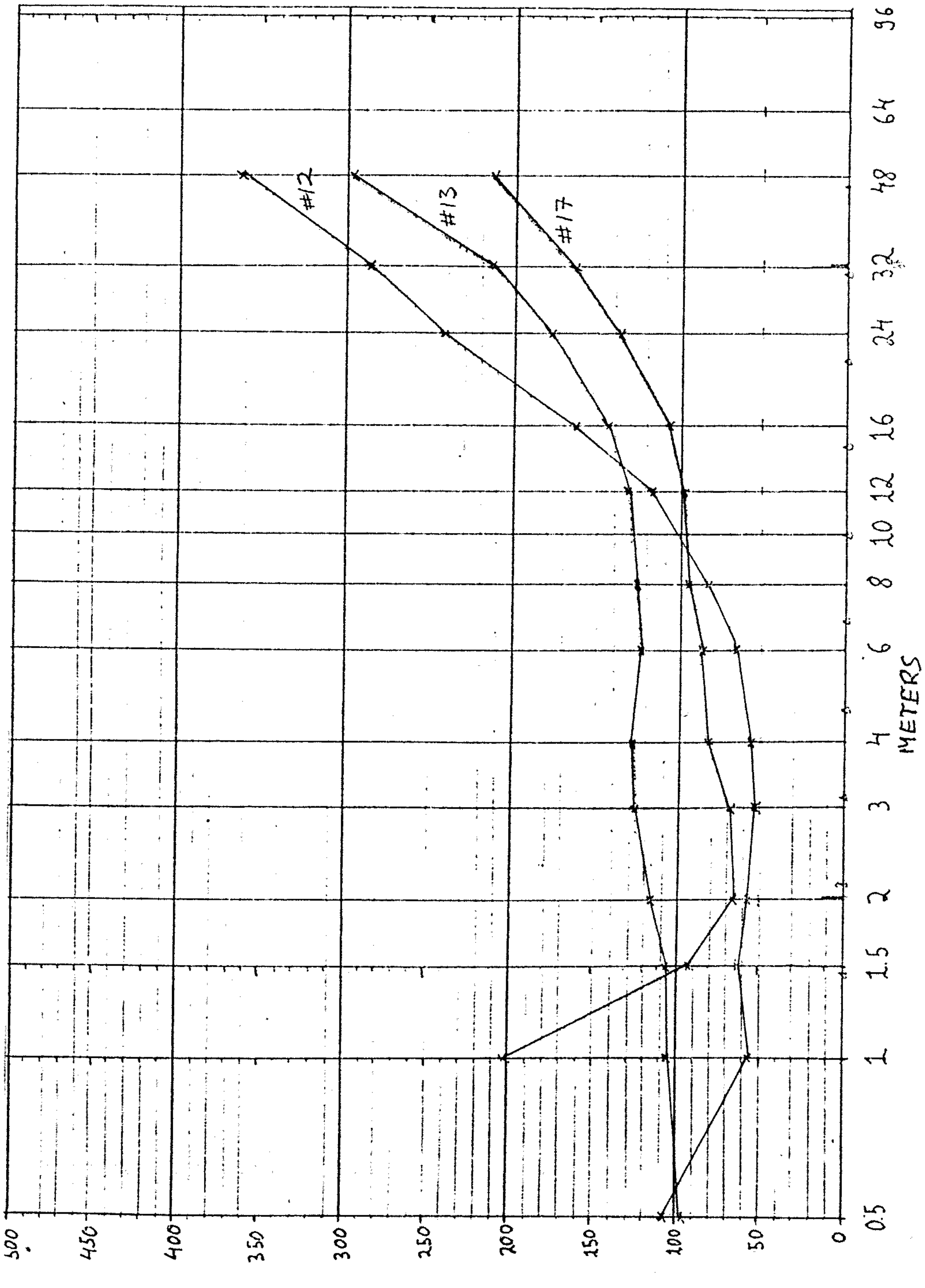
Ohm-meters

Soundings Used for Depth Analysis



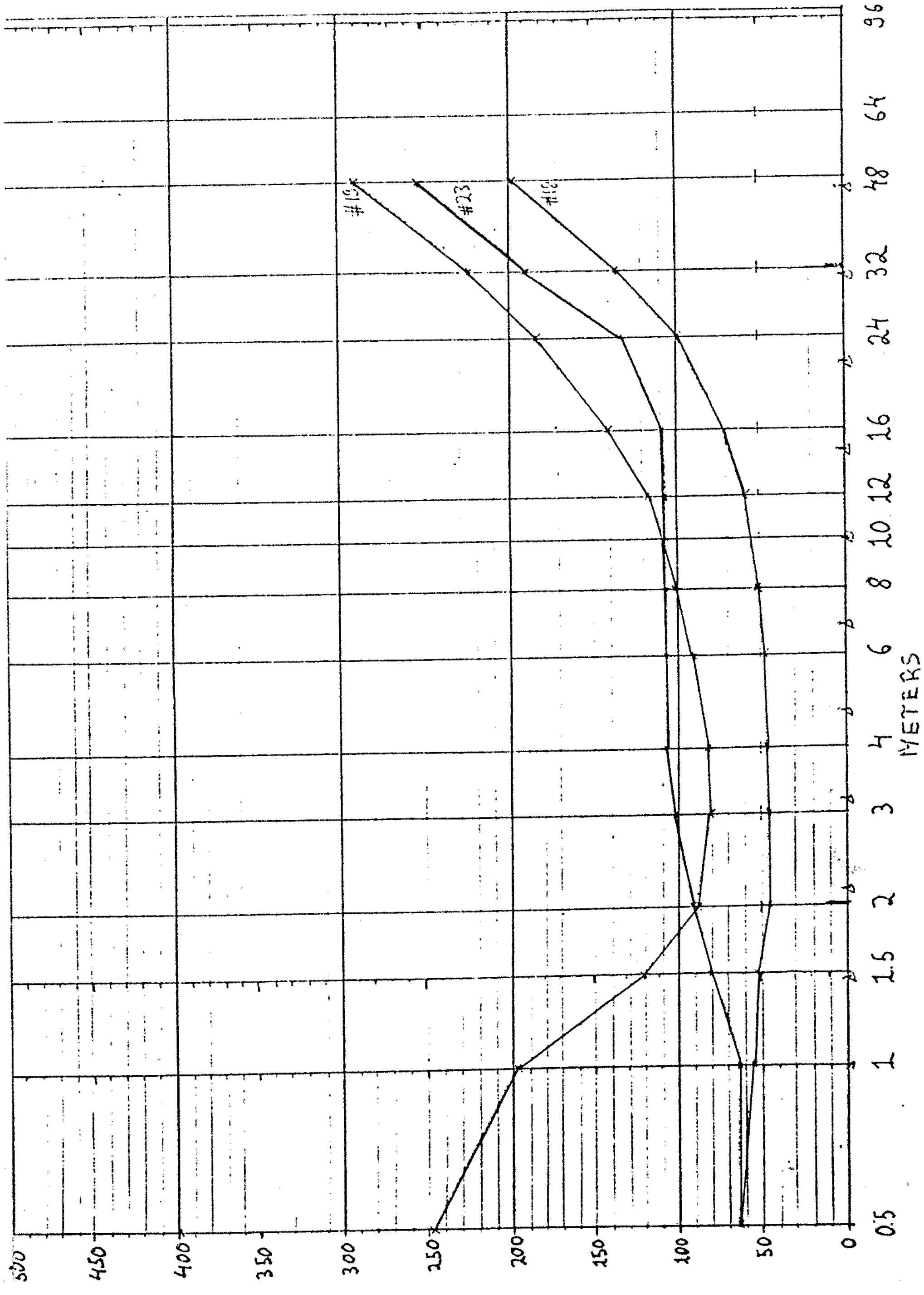
Ohm-meters

Soundings Used for Depth Analysis



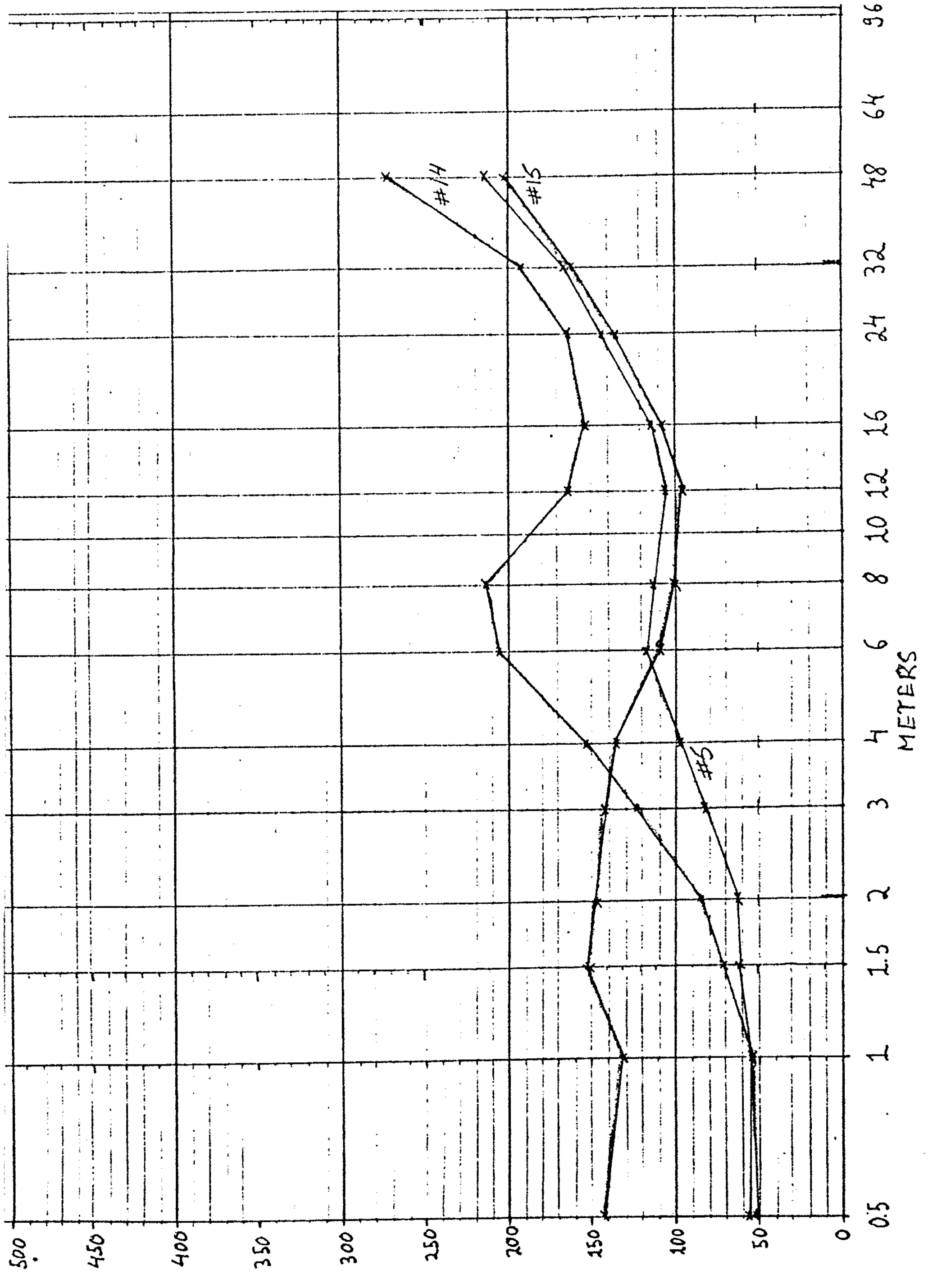
Ohm-meters

Soundings Used for Depth Analysis



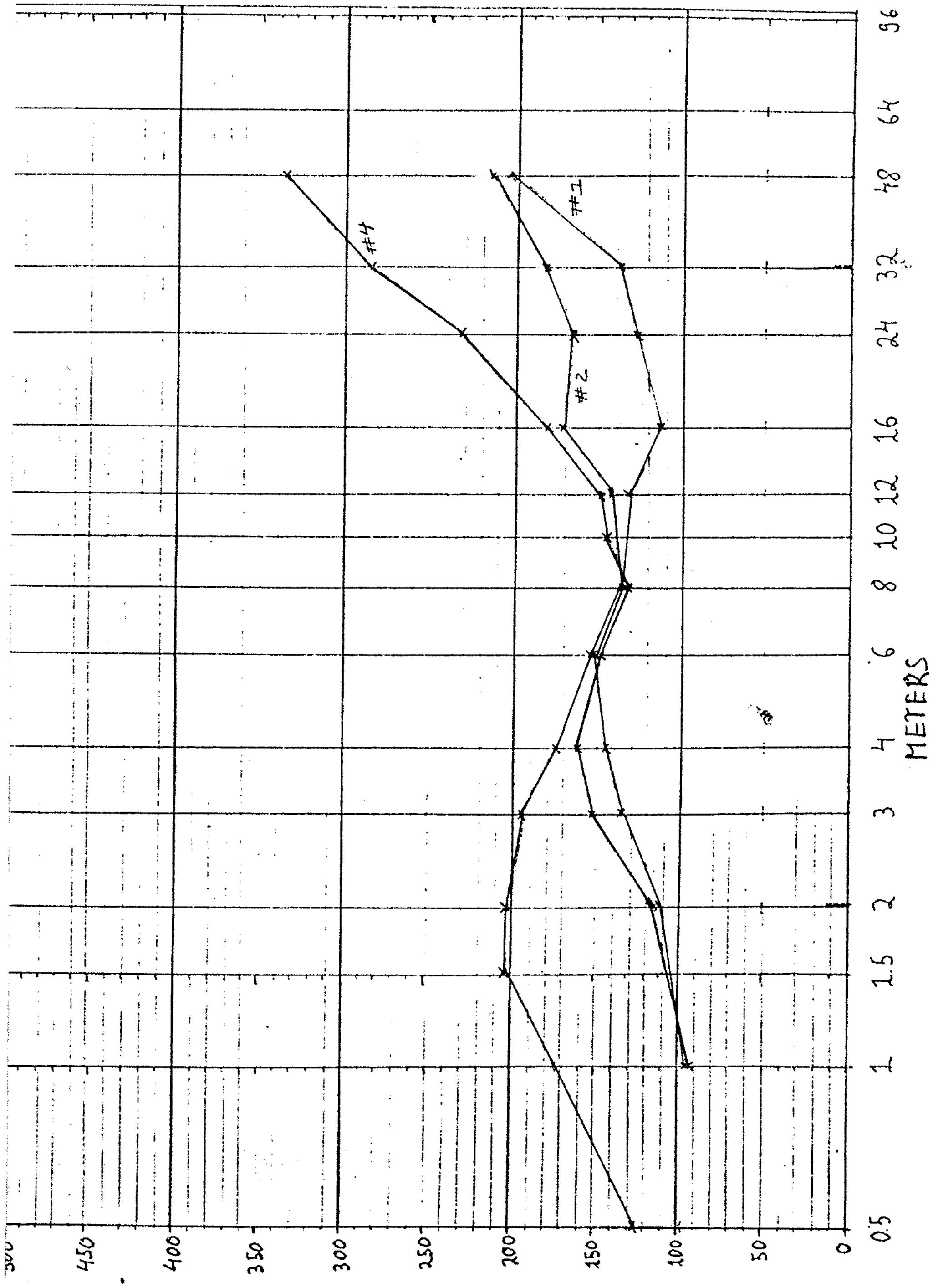
Ohm-meters

Soundings With Severe Lateral Anomalies



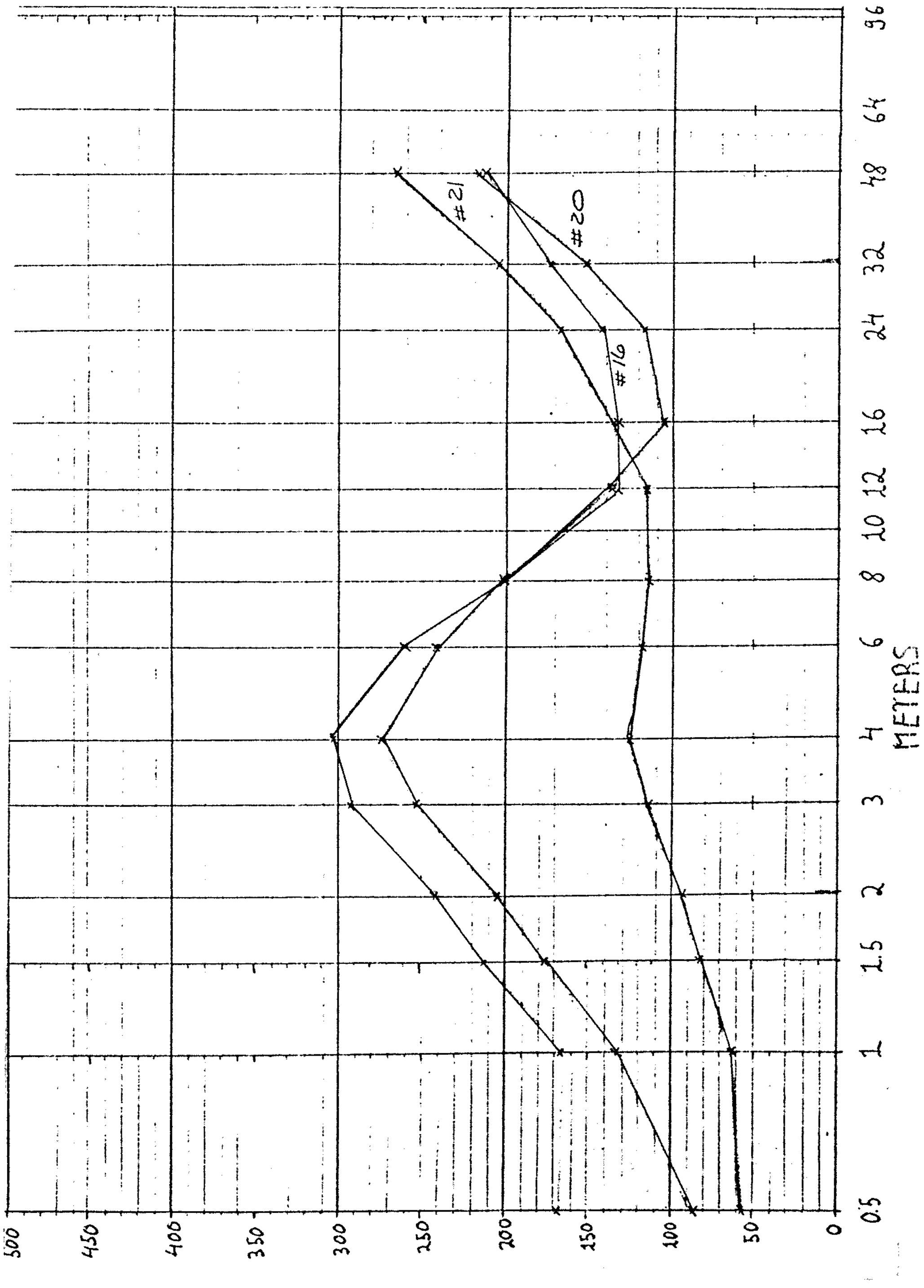
Ohm-meters

Soundings With Severe Lateral Anomalies



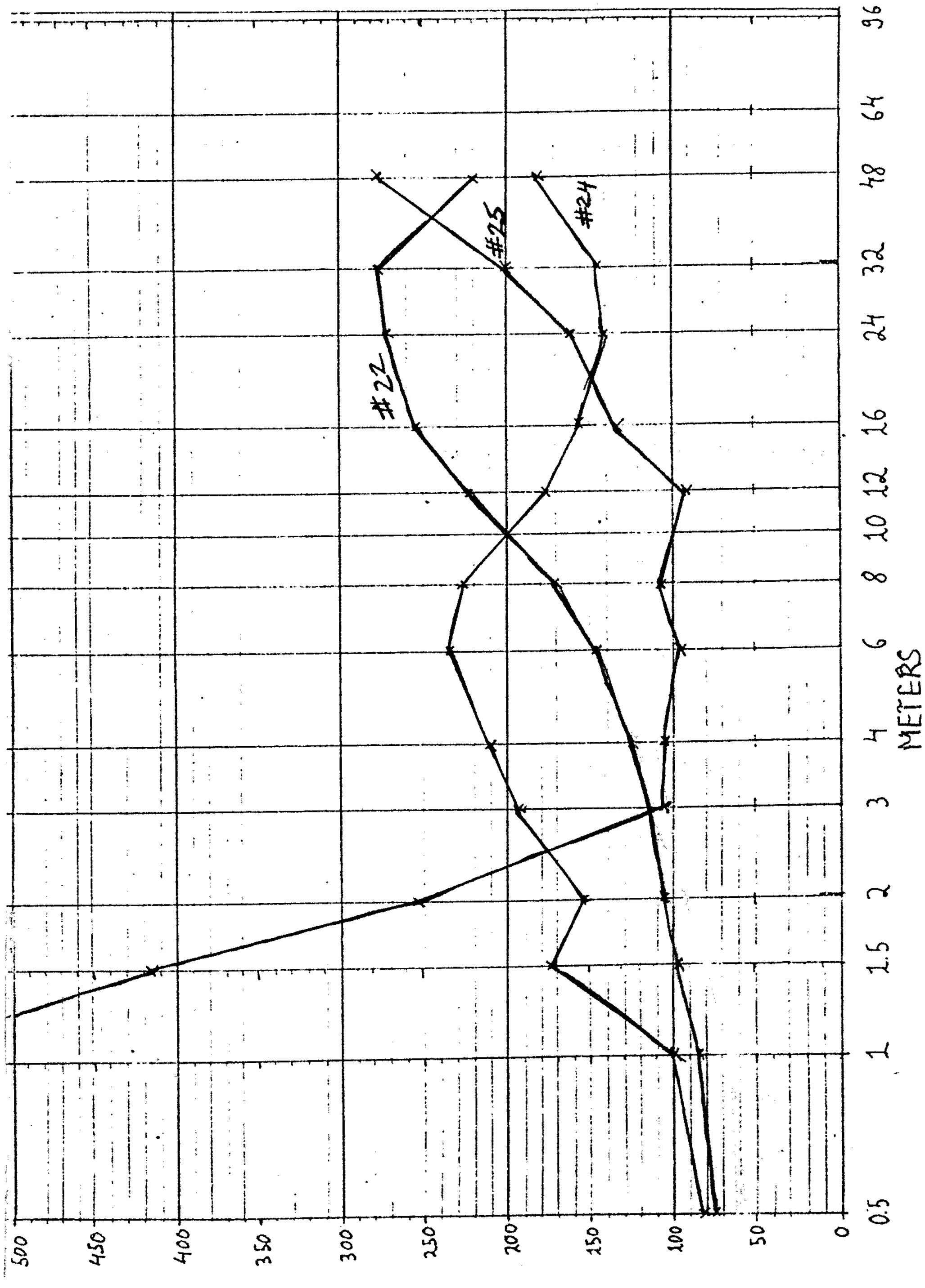
Ohm-meters

Soundings With Severe Lateral Anomalies



Ohm-meters

Soundings With Severe Lateral Anomalies



Ohm-meters