A GEOPHYSICAL INVESTIGATION OF THE HYDROGEOLOGICAL CHARACTERISTICS OF THE UDELL HILLS AREA, MANISTEE COUNTY, MICHIGAN

Thesis for the Degree of M. S.

MICHIGAN STATE UNIVERSITY

Richard L. Kellogg

1964

ABSTRACT

A GEOPHYSICAL INVESTIGATION OF THE HYDROGEOLOGICAL CHARACTERISTICS OF THE UDELL HILLS AREA, MANISTEE COUNTY, MICHIGAN

by Richard L. Kellogg

A geophysical investigation utilizing the seismic refraction and earth resistivity geophysical techniques was conducted in the Udell Hills area of Manistee County, Michigan. The objectives of the study were to obtain characteristic seismic velocities and electrical resistivities of representive glacial drift materials, to determine the thickness of the unsaturated overburden, and to delineate the configuration of impermeable clay layers known to occur in the area from drill hole information.

A total of 45 seismic and 24 resistivity profiles were made. The electrical resistivity well-logging method was attempted in several wells in the study area, but only one test gave usable data.

The seismic refraction method generally indicated a two layer earth consisting of a surface layer composed of dry, well sorted sand, and an underlying layer composed of saturated sand. Surface velocities vary from 600 to 2,000 feet per second with an average of 1,140 feet per second, while saturated layer velocities range from 4,000 to 6,750 feet per second with an average of 5,460 feet per second.

Electrical resistivities obtained from the Mooney and Wetzel curve matching method and the Barnes layer method vary from a few thousand to several million ohm-centimeters. The Mooney and Wetzel method indicated all saturated resistivities are less than 75,000 ohm-centimeters while a significant number of unsaturated layers also have resistivities in this range. The Barnes method of interpretation indicated that the majority of resistivities less than 75,000 ohm-centimeters fall within the saturated zone. Resistivities in excess of 250,000 ohm-centimeters as determined by both methods of interpretation, occur within the unsaturated zone.

The interpretation of both the seismic and resistivity data indicates a ground water mound, with a total relief of about 100 feet, associated with the Udell Hills.

Seismic results were found to be 10% in error when compared with control data, while resistivity results averaged 14% in error.

The geophysical methods employed in the study were unsuccessful in detecting the clay layers. This failure may be attributed to the low resolving power of the seismic refraction and earth resistivity geophysical methods.

In this area, the seismic method gave the most precise and diagnostic results; however, the resistivity method contributed to the study in corroborating the seismic observations.

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By

Richard L. Kellogg

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Geology

1964

ACKNOWLEDGMENTS

I wish to express my sincere thanks to Dr. William J. Hinze for his invaluable guidance, helpful suggestions and criticisms, and thorough study of all phases and portions of this paper. Thanks are also due to Dr. Chilton E. Prouty, Dr. Harold B. Stonehouse and George B. Secor for their interest and helpful suggestions pertaining to this study.

This investigation was made possible by grants from the Lake States Forest Experiment Station of the U. S. Department of Agriculture, Forest Service and the National Science Foundation through the Institute of Water Research, Michigan State University. These grants are gratefully acknowledged.

Special acknowledgment is due to Dean H. Urie, Research Forester of the Lake States Forest Experiment Station who is directly responsible for laying out the investigation sites and surveying them and helping wherever possible with the field studies. Finally, I wish to thank John N. Roth, geophysics graduate student, who assisted in drafting the illustrations used in this report.

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INTRODUCTION

Present interest in the hydrogeological characteristics of the glacial drift aquifers of the Southern Peninsula of Michigan has focused attention on the application of geophysical methods to the investigation of ground water conditions of this area. A detailed survey was undertaken in the Udell Hills area of Manistee County, Michigan, for the purpose of ascertaining the potential of geophysical methods in this application.

The major objective of this study is the delineation of the subsurface geology and ground water drainage patterns of this area by the seismic refraction and surface resistivity geophysical methods. Specifically, the objectives of this study are as follows:

1. To obtain characteristic seismic velocities and resistivities of representative glacial drift materials,
2. To determine the thickness of the unsaturated overburden,
3. To determine the configuration of impermeable clay layers known to occur in the area from drill hole information.

The area under study is located in the west-central part of the Southern Peninsula of Michigan, in Manistee

County (Figure 1). The area is roughly 3 miles in diameter and covers portions of sections 13, 14, 15, 22, 23, 24, 25, 26, and 27 of T21N, R15W in Manistee County. It lies roughly 15 miles east of Manistee, Michigan in the Manistee National Forest.

A total of 45 seismic and 24 resistivity profiles were made. In addition, the electrical resistivity well-logging method was attempted in several wells in the study area, but only one gave usable data.

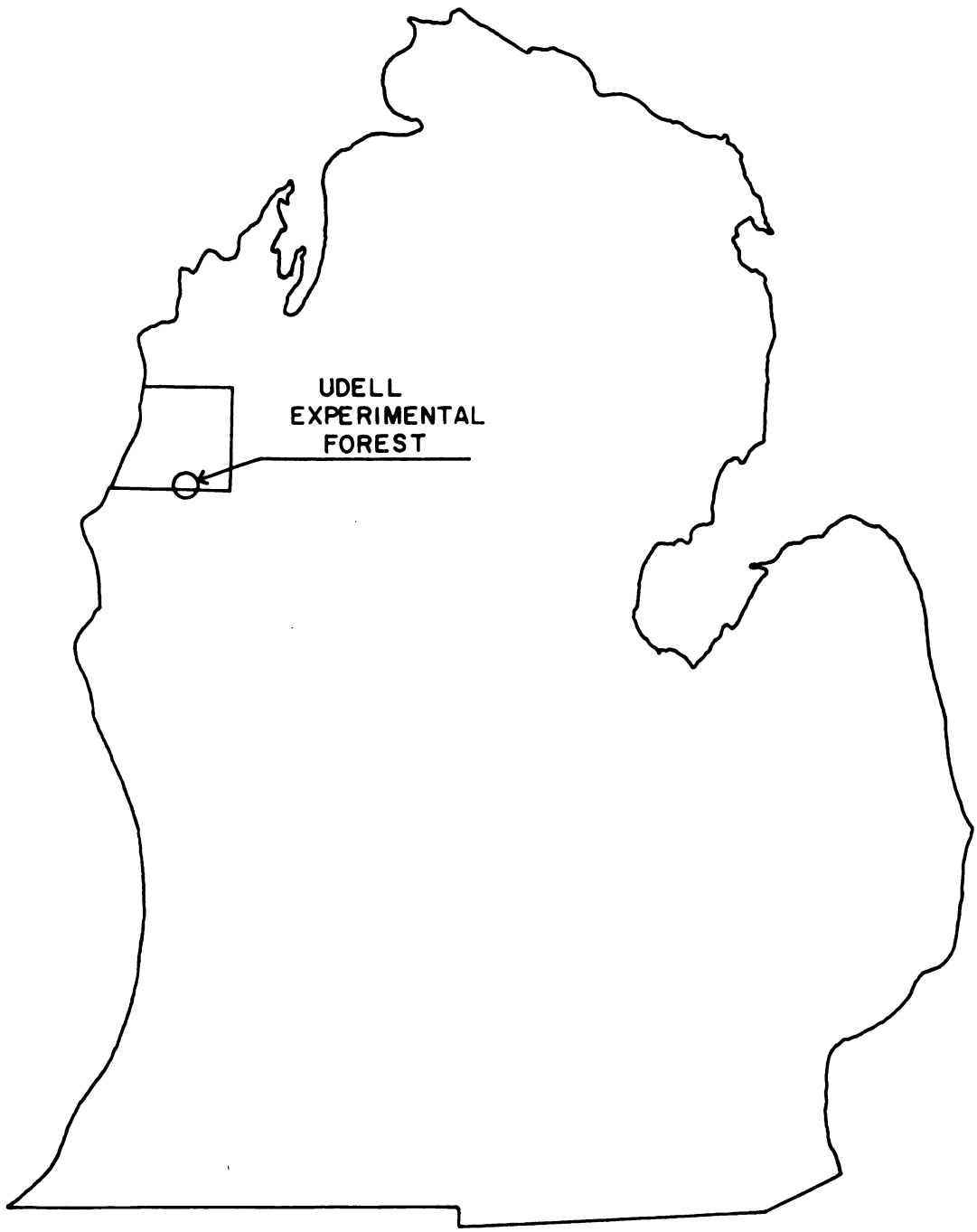


FIGURE I LOCATION OF AREA OF INVESTIGATION

GEOLOGY AND GEOGRAPHY

The Udell Hills rises to a maximum of 300 feet above the surrounding level sand plains. The feature has been interpreted as a glacial moraine of possible Valders age (Martin, 1955). The glacial drift in this area is believed to be about 500 feet thick. The Udell Hills is composed primarily of sand, but local gravel and boulder beds and clay lenses occur within it in no well defined pattern.

The topography of the Udell Hills is rugged in comparison to the surrounding area, with steep slopes occurring along the northwestern and southeastern flanks. The feature is marked locally by knob and kettle topography. Two prominent ridges occur, one along the northwestern perimeter and the other along the southeastern perimeter (Figure 2). A central valley of generally low relief occupies the depression between the ridges.

The Udell Hills is forested except for occasional cleared fields. It is accessible by roads leading from State Highway 55 which connects the cities of Manistee and Cadillac.

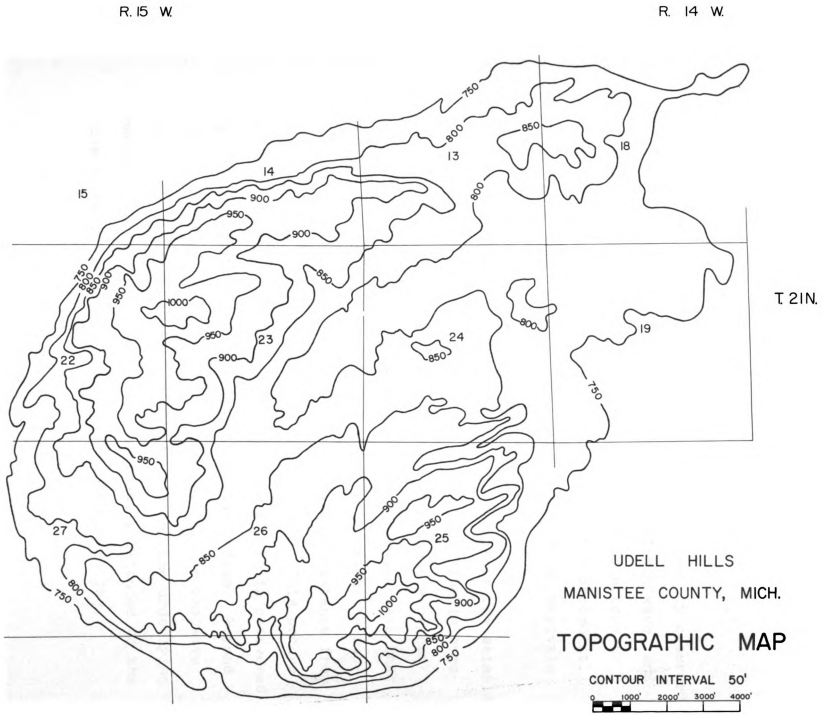

R. 15 W.
R. 14 W.
T. 21N.
UDELL HILLS
MANISTEE COUNTY, MICH.
TOPOGRAPHIC MAP
CONTOUR INTERVAL 50'
0 1000' 2000' 3000' 4000'

FIGURE 2

SEISMIC REFRACTION METHOD

Refraction Theory

In the seismic refraction method, the quantity observed is the time between the initiation of the seismic wave, and the arrival of the first wave at a series of detectors or geophones placed at measured distances from the shotpoint. The minimum time path, corresponding to the first arrivals is ordinarily considered in the theory.

At detectors located close to the source of the seismic energy, the minimum travel path is a straight line in homogeneous, isotropic material. For the case where a higher velocity medium underlies the surface material, a wave that has been refracted along the interface will reach the surface at the same time as the direct wave at a distance from the shotpoint known as the critical distance. This occurs when the time lost in traveling the longer path is recovered by taking advantage of the higher velocity medium. Beyond the critical distance, the first arrival will be the wave that has been refracted along the surface of the underlying medium. These relationships may be readily extended to the case of two or more interfaces (Dobrin 1960, p. 74).

Field Equipment

The basic equipment used in the seismic refraction method consists of explosives for initiating a seismic wave, geophones which respond to the arrival of the wave, cables for carrying the electrical responses of the geophones, and a seismograph recorder which receives the impulses from the geophones, amplifies them, and records them on film.

The seismograph recorder used in this study was the Porta-Seis model manufactured by the Electro-Technical Laboratory Division of Mandrel Industries, Inc. Permanent records are made on Polaroid film which is readily developed in the field. The instrument is a portable 12 trace unit with a built in blasting device which records the instant of detonation of the explosive charge on a separate trace. Timing marks interrupt each trace at 10 millisecond intervals. A 12.7 volt nickel cadmium battery supplies power to the galvanometer lamp. This battery was recharged following each days field operations.

A truck mounted, general purpose seismograph was used where the required length of recording time was not available on the Porta-Seis. Field operations with this instrument are time consuming and expensive; consequently it was used only when absolutely necessary.

Two geophone cables were used in this study. The shorter has 12 geophone take-outs at 20 foot intervals, and the longer 12 take-outs at 100 foot intervals.

Geophones having a peak output frequency of 7-1/2 cycles per second were used, with the exception of detectors on the far end of 1,000 foot profiles where four cycle phones were used.

A commercial blasting agent, detonated by a special primer, was used for a seismic energy source in the majority of the survey. An electric blasting cap was used to detonate the primer, and the blasting agent. Ordinarily 60% dynamite was utilized occasionally when the blasting agent could not be obtained.

Shotholes were drilled with a hand powered bucket type auger which, with the aid of an extension handle, could reach a depth of 12 feet. Although drilling in sand presented no problems, drilling in clay and coarse gravels was extremely difficult, and sometimes impossible.

Selection of Sites

A series of seismic spreads were made along a traverse running generally northwest from the Manistee ski area well to the base of the northwest upland ridge near Well 1-1 (Figure 5). Additional profiles were established at accessible points in the interior basin.

The specific location of each seismic spread was determined by the objectives of the survey as well as by accessibility, topography, vegetation, and proximity to

control wells. The topography is an especially important factor in shallow refraction studies in view of the effect it may have on the precision of the seismic results. Every effort, consistent with the objectives of the survey, was made to locate the seismic spreads on flat or constantly sloping surfaces. Genrally, sites with less than 20 feet of variation from a constant slope were selected, but this was not always possible in the uplands area. A topographic correction was applied to spreads located in areas that did not conform to a flat or constantly sloping surface.

Geophone Layout

Seismic spreads varied in length between 140 and 1000 feet depending upon the objectives of the particular profile. To determine depths uniquely, the shotpoint and distant geophone were interchanged, and reversed records were obtained. At the onset of the seismic program, symmetrical geophone spreads were employed by means of which the operators could shoot at both ends of the spread without the necessity of picking up and redistributing the cable. However, it soon became evident from time distance plots of these spreads, that there was a lack of coverage in the important region near the shotpoint because of the wide spacing of the detectors used in the symmetrical spread. Accordingly, spreads were adjusted to obtain maximum coverage near the shotpoint, and to obtain a

minimum of three arrivals on each recorded layer, wherever possible. This goal was accomplished at the price of a slight decrease in the overall efficiency of the seismic field program.

The spreads and geophone spacings were varied to avoid artificially filled areas and loose gravel which might cause erroneous results. Geophones were placed in shallow holes from which loose surface materials had been removed.

Elevations were surveyed at 100 foot intervals along each spread, and in areas of rapid changes in elevation, at closer intervals.

REDUCTION OF SEISMIC DATA

The seismic refraction record shows the time delays between the detonation of the shot and the arrival of the first wave at the geophones. The basic data of the refraction method includes the relative time measurements taken from the record, the elevation and spacing of the geophones and shotpoint, and the depth of the explosive beneath the surface.

The seismic data was initially plotted in the form of a time-distance graph with time as the ordinate and distance as the abscissa. Following this the effects of the elevation of the geophones, and the depth of the shot hole were determined by a graphical technique, and applied to the observed time delays. The corrected data were then treated analytically on a high speed digital computer to determine the number of, depth to, and velocity of each individual layer.

Although the computations made by the computer are unique, the final results are subject to the interpreters experience and judgment in removing the parameters used in the computations from the time-distance graphs. In addition, the seismic refraction method is subject to a number of geological and seismic limitations which are discussed and related to this survey below.

1. The velocities in successive layers increase as the depth increases. This assumption generally was met in this survey, the exceptions occuring where high velocity clay materials overlaid low velocity unsaturated sand layers.
2. Each layer transmits seismic waves at a constant velocity regardless of the direction of propagation. There is no evidence to suggest that this assumption was not met in the investigation.
3. Each layer is bounded top and bottom by planes. This assumption is a fair approximation over the short spread lengths used in this study.
4. Each layer is sufficiently thick to be detected at the surface. No doubt this assumption was not met in several spreads recorded in the upland area where time-distance plots indicate a layer at one end of the spread where it is thick, but not at the other, where it is too thin to be detected, or missing altogether.

The first two assumptions are the most important, since variations from the ideal frequently are unrecognized and lead to gross errors in the results. Assumption three was taken into account in this study in the data reduction process. The fourth assumption was also taken into account in the data reduction wherever seismic evidence indicated a discrepancy in the number of layers detected at the surface.

This was accomplished by inserting a layer of minimum thickness to be detected at the surface and of velocity suggested by the results from adjacent areas.

RESISTIVITY METHOD

Resistivity Theory

In the surface resistivity method of surveying, a known current is introduced into the ground through two current electrodes, and the resulting potential difference is measured between pairs of potential electrodes. The quantity actually measured in resistivity surveying is known as the apparent resistivity. The apparent resistivity is defined as that resistivity which would produce the same ratio of potential drop to impressed current for the same electrode configuration when used in a homogeneous semi-infinite medium whose resistivity is equal to the apparent resistivity. Thus, the apparent resistivity is a weighted average of whatever layer resistivities may exist in the region through which the current flows.

The apparent resistivity may be calculated from the following formula which applies to the Wenner electrode configuration, in which the electrodes are equidistant and colinear (Figure 3).

$$\rho = 2\pi A \left(\frac{V}{I}\right)$$

Where:

ρ = apparent resistivity in ohm-centimeters,

A = separation of adjacent electrodes in centimeters,

V = potential in volts between the inner or potential electrodes (C and D of Figure 3),

I = current in amperes between the outer or current electrodes (A and B of Figure 3).

Figure 4 shows lines of current flow between two electrodes in a two layer earth with a high conductivity layer, δ_2, underlying a low conductivity layer, δ_1. The depth of investigation is changed by varying the separation between the current electrodes. For the Wenner electrode configuration, the depth of investigation is often assumed to be equal to the separation of adjacent electrodes.

Field Equipment

The basic field equipment used in the resistivity method includes a resistivity meter for making measurements of V and I or the ratio $\frac{V}{I}$, electrodes, and associated cables.

The instrument used in this survey was a portable direct current resistivity meter manufactured by Keck and Associates, Okemos, Michigan. The ratio of $\frac{V}{I}$ is obtained directly from a null reading ohmmeter after a bucking potentiometer has been adjusted to eliminate spontaneous earth potentials. The power system consists of 45 volt "radio B" batteries which can be connected in series, together with an ammeter which permits the current in the circuit to be monitered. Additional batteries may be added or withdrawn as necessary to keep the current at approximately the same level.

CONFIGURATION OF CURRENT & POTENTIAL ELECTRODES

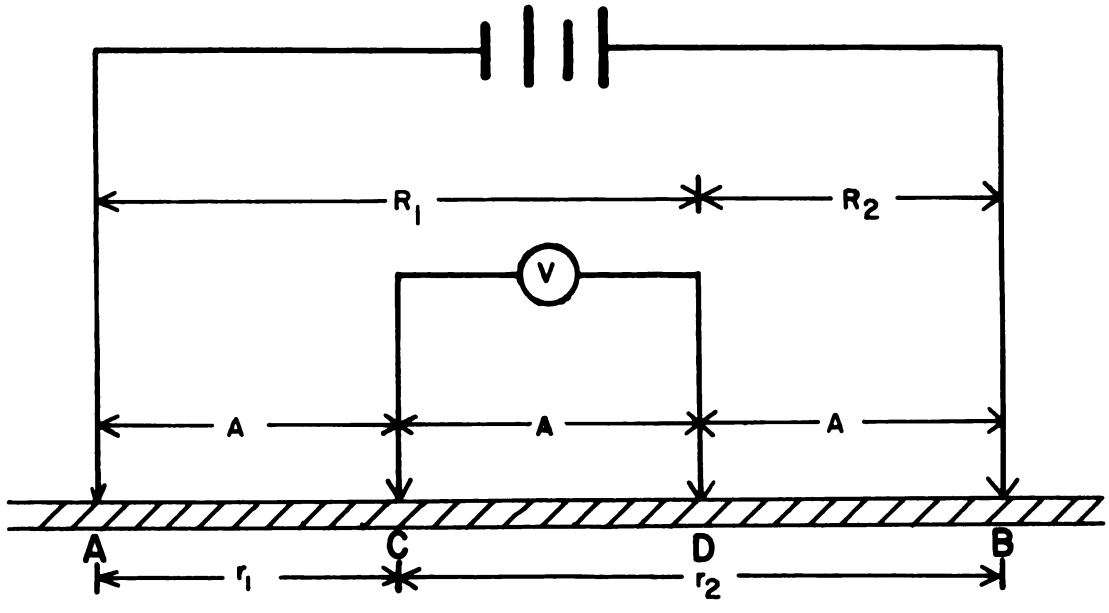


FIGURE 3

LINES OF CURRENT FLOW IN A LAYERED SECTION

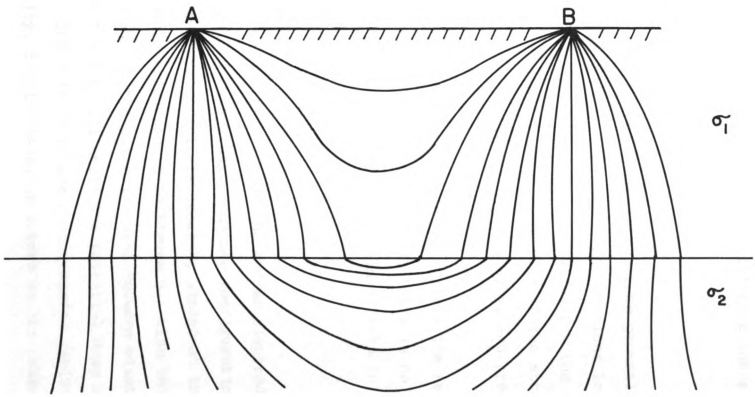


FIGURE 4

$\sigma_2 > \sigma_1$

The electrodes were 4 foot lengths of 1/2 inch cold rolled steel. Electrodes were connected to the resistivity instrument by cables marked for positioning the electrodes at predetermined intervals.

Site Selection

Resistivity sites followed the same general traverse as the seismic sites, with additional stations located in the interior valley. Selection of sites for the resistivity study was determined by the objectives of the study as well as accessibility, vegetation, topography, and proximity to control wells.

Although topography probably affects the resistivity method less than the seismic method, there is no satisfactory way of correcting for terrain effects in resistivity surveying.

Spread Layout

The Lee modification of the Wenner electrode system was employed in this study. The Lee configuration utilizes an additional potential electrode E, placed at the center of the Wenner spread shown in Figure 3. With this arrangement, the sum of the potential drop between electrodes C and E and D and E will equal the potential drop measured between C and D if there are no horizontal variations in resistivity, dipping beds, or errors in the measurements.

Observations of the ratio of potential drop to impressed current were made at a succession of decreasing electrode separations around a central electrode. Measurements generally were made beginning at a 280 foot separation between adjacent electrodes and decreasing to a 20 foot separation in increments of 20 feet. A 10 and a 5 foot spacing completed the observations at each station. Measurements were made at each separation between the two outer potential electrodes as well as between the center and each outer potential electrode. A second set of measurements was then made with the current flowing in the opposite direction at each separation.

In most areas, the earth immediately adjacent to each current electrode was saturated with a brine solution. This technique was necessary to decrease the contact resistance between the earth and the electrode, despite the fact that up to 580 volts was applied to the current circuit. An additional method for decreasing contact resistance occasionally was employed. This technique involves replacing each current electrode with a "multi point" electrode system in which a number of electrodes are connected together with jumpers. When using this technique, care was taken to arrange the electrodes so that they approximate a single large circular electrode, because a circular arrangement of electrodes produces a minimum distortion of the current lines (Jakosky 1960, p. 523).

Electrical Resistivity Well Logging

Electrical resistivity well-logging was conducted with an instrument similar to that used in the surface resistivity studies plus a hand operated well probe which was manually raised and lowered in the well. An electrode arrangement was employed in which one pair of current and potential electrodes is placed on the surface while the other pair is placed in the well. The pair of electrodes in the well were separated by 2.5 foot intervals, and readings were observed at 2.5 foot intervals as the probe was raised from the well.

SEISMIC INTERPRETATION

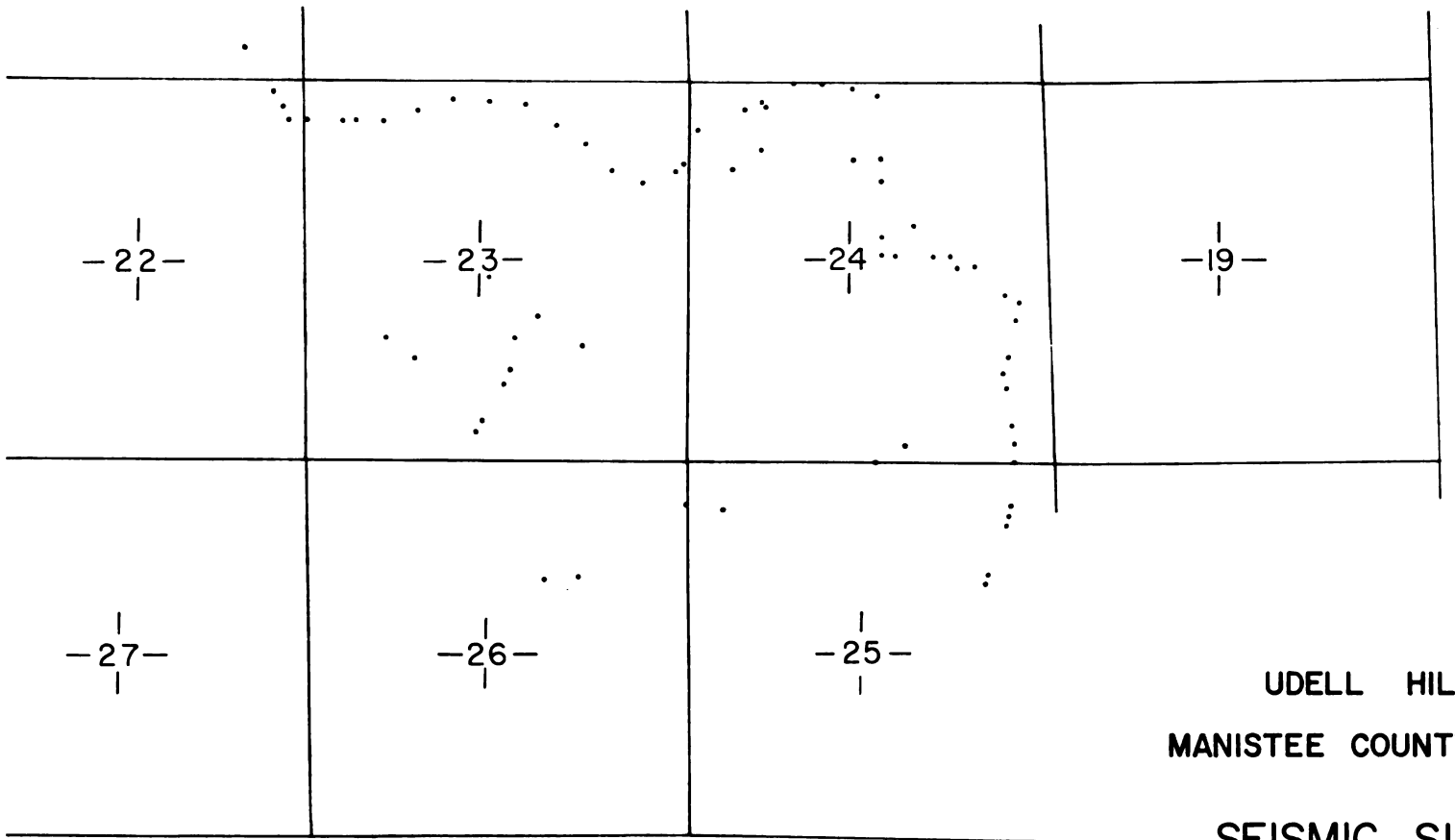
Introduction

The interpretation of the results of the seismic portion of this survey includes the determination of the number of layers, the velocity of these layers, and the depth to the interfaces, as determined from calculations performed on the observed data. The interpretation, which is considered in terms of the specific objectives of the survey, should be tempered by an understanding of the assumptions made in seismic refraction theory. These assumptions have been discussed and related to this study under the section "Seismic Method."

Velocities of Representative Glacial Drift Materials

The location of the seismic sites is shown on Figure 5.

Two layers generally were detected by the seismic method. This is illustrated in Figures 6 through 9 which are examples of typical time-distance graphs obtained in the area. The first linear segment of the graph represents travel times via the direct path through the surface layer. Beyond the critical distance, the second linear segment corresponds to travel times for the wave that has taken advantage of the higher velocity medium beneath the surface layer.



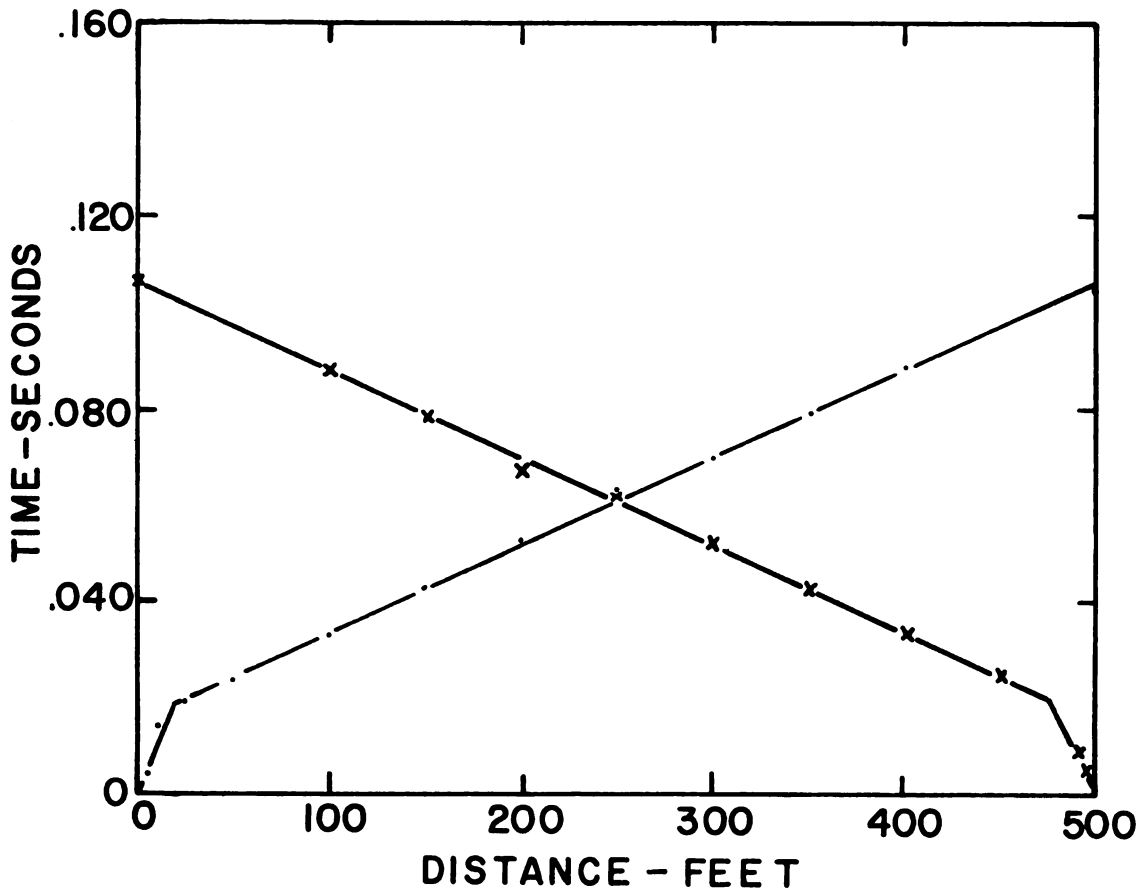
UDELL HILLS

MANISTEE COUNTY, MICH.

SEISMIC SITES

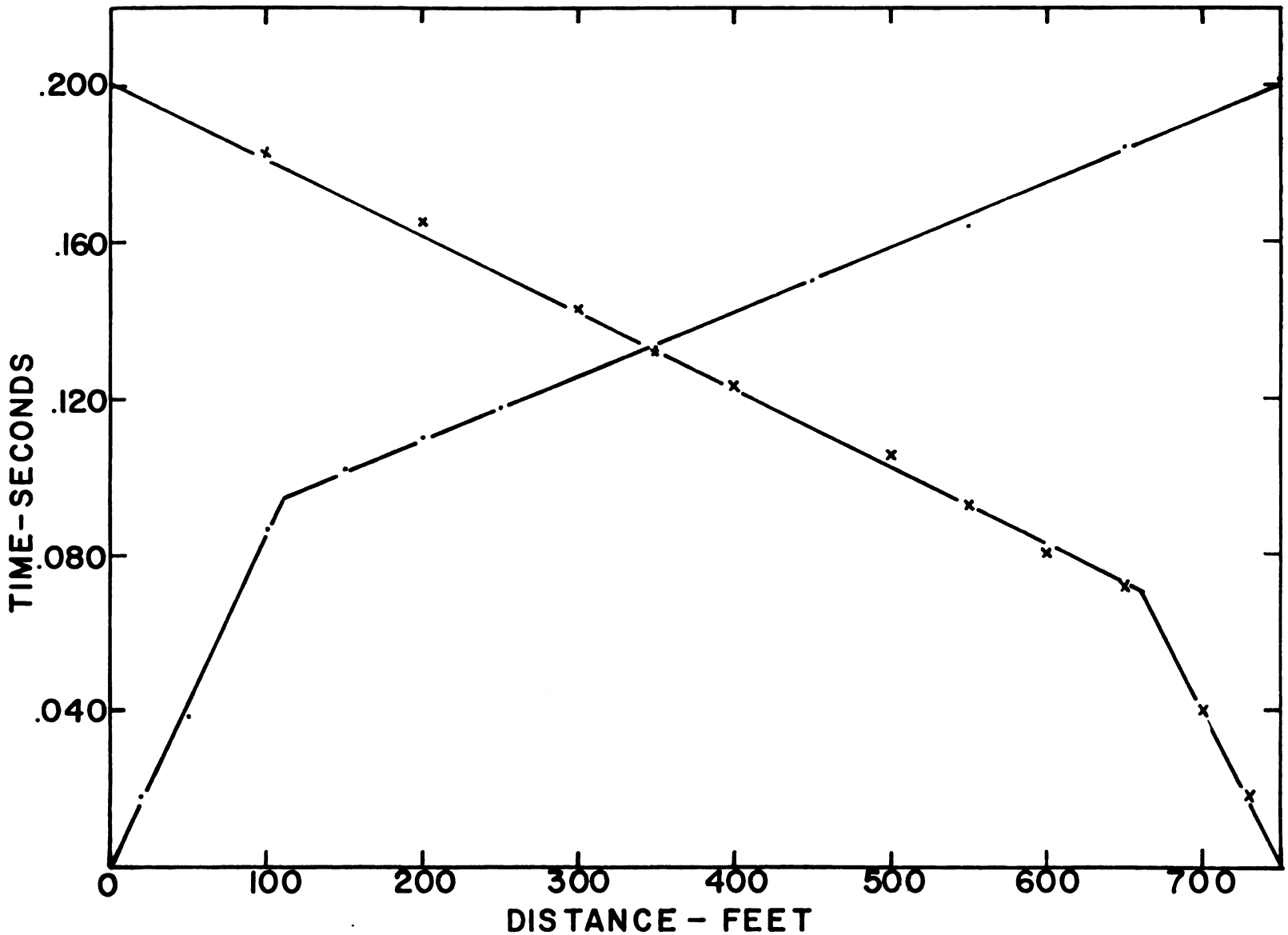
0 1000' 2000' 3000' 4000'

FIGURE 5



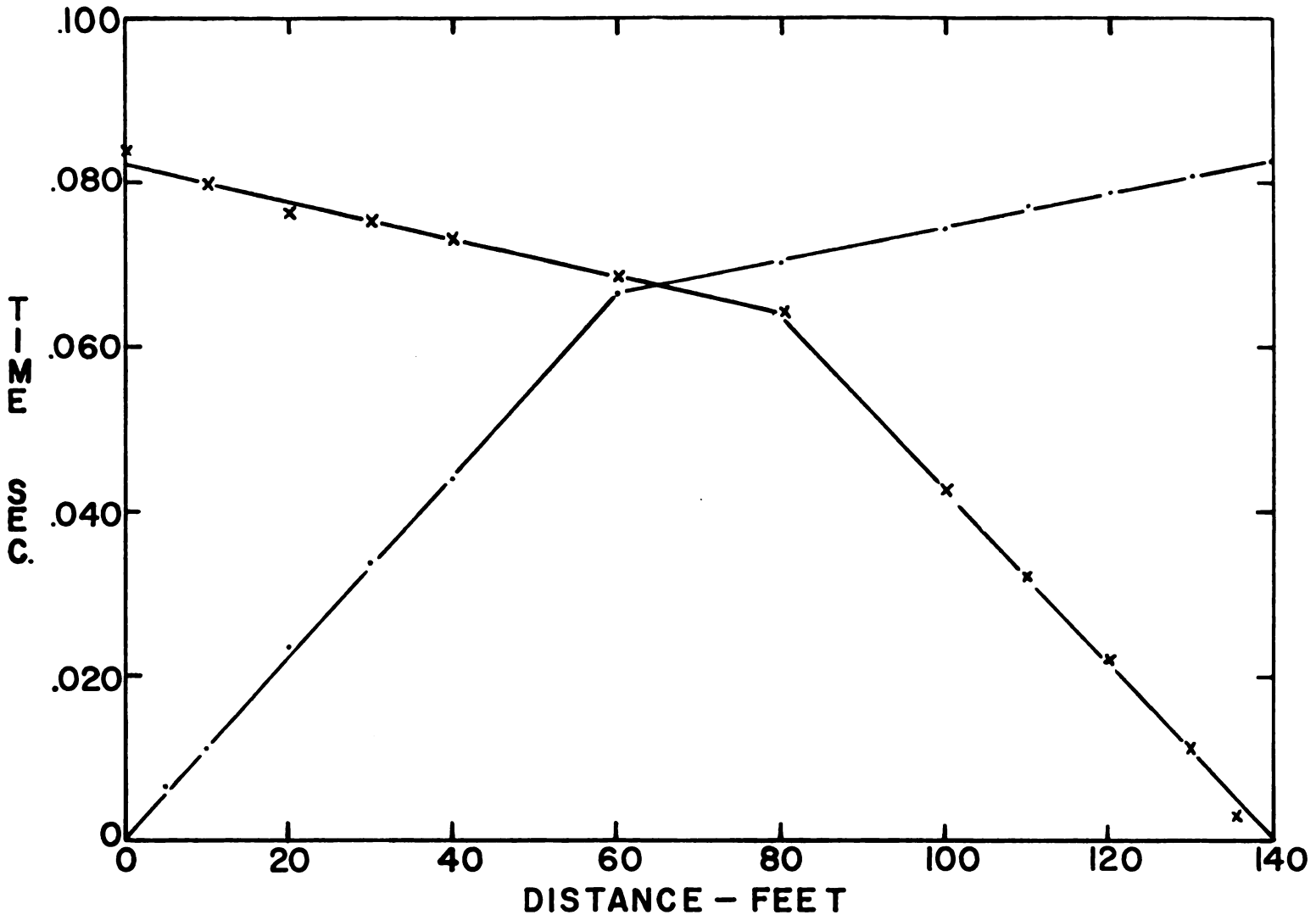
CORRECTED TIME VS. DISTANCE GRAPH

FIGURE 6



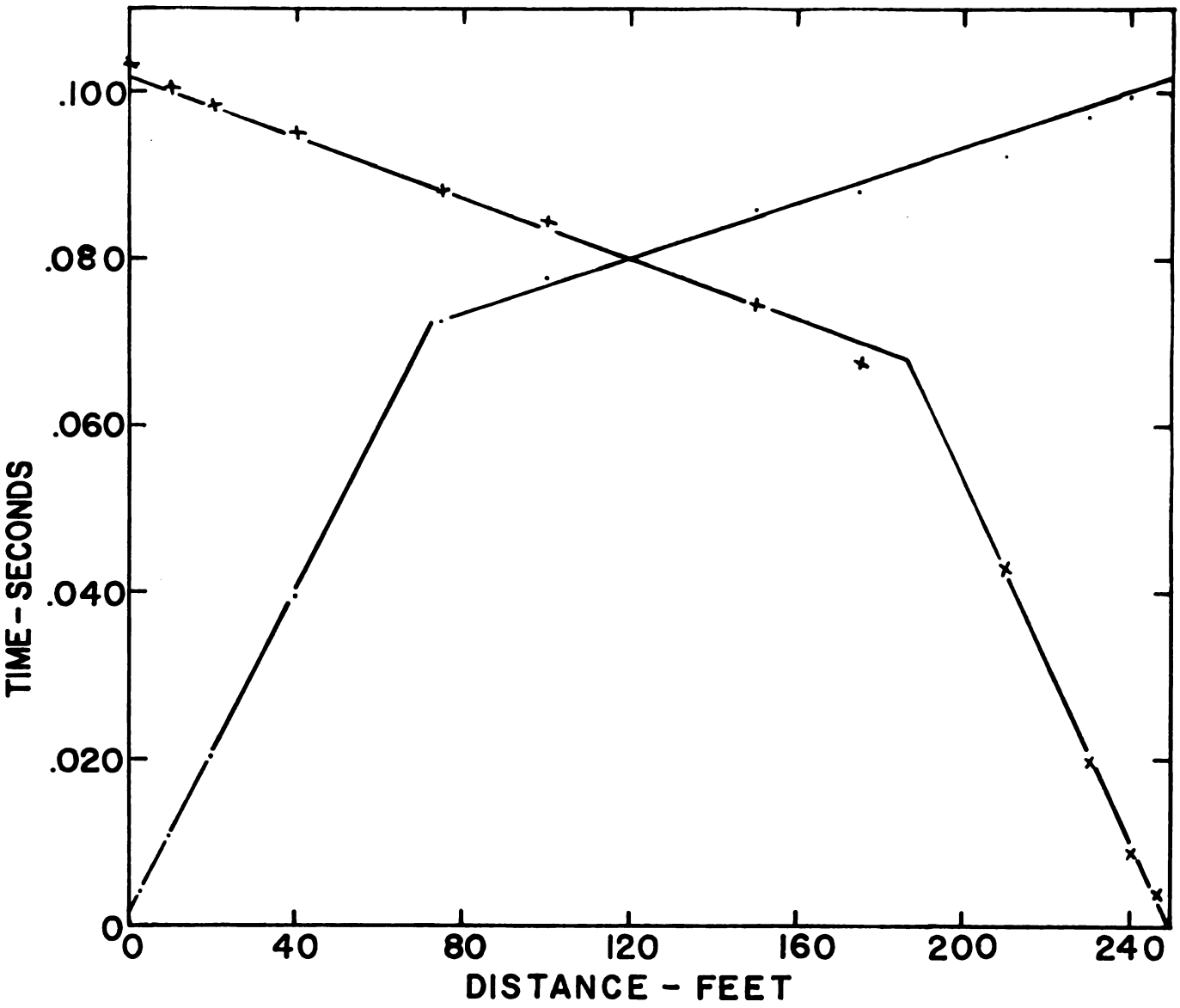
CORRECTED TIME VS. DISTANCE GRAPH

FIGURE 7



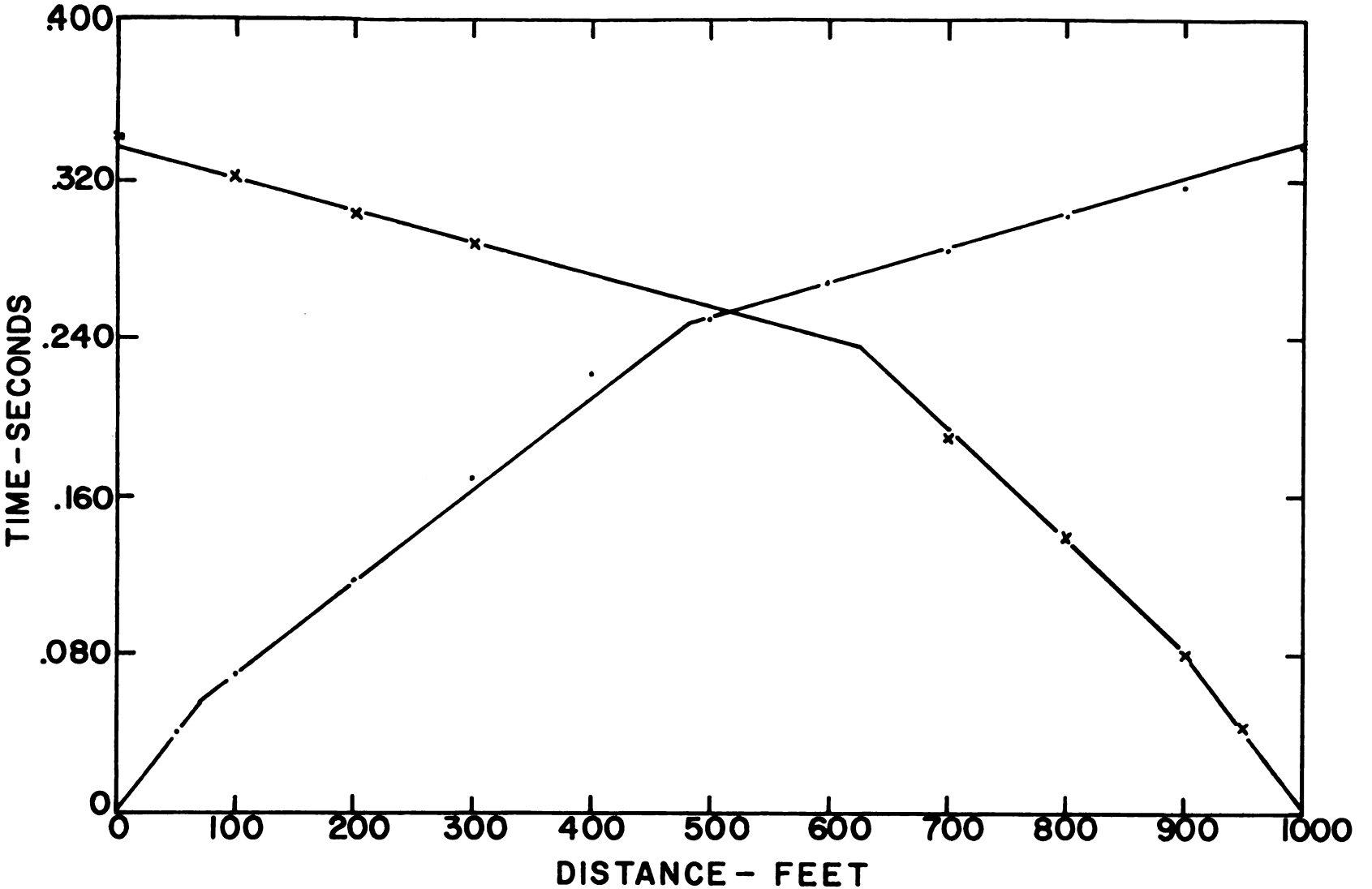
CORRECTED TIME VS. DISTANCE GRAPH

FIGURE 8



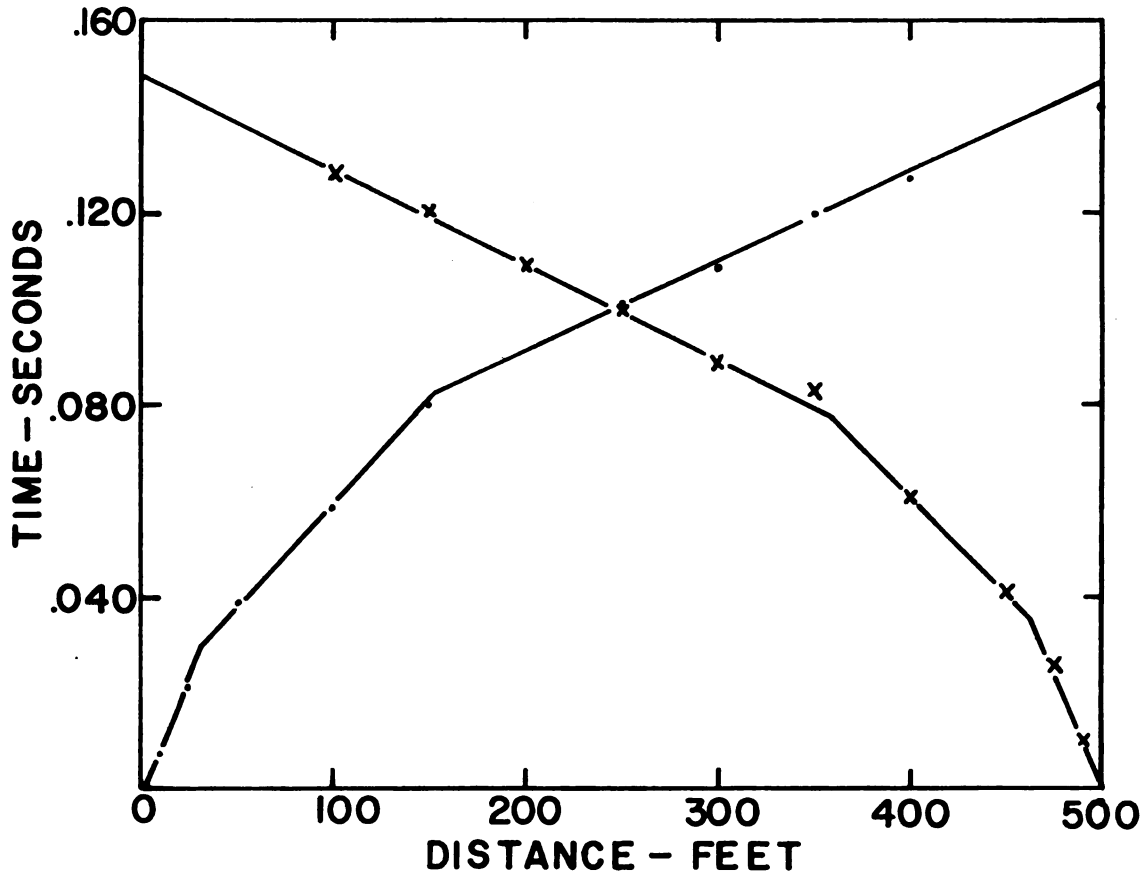
CORRECTED TIME VS. DISTANCE GRAPH

FIGURE 9



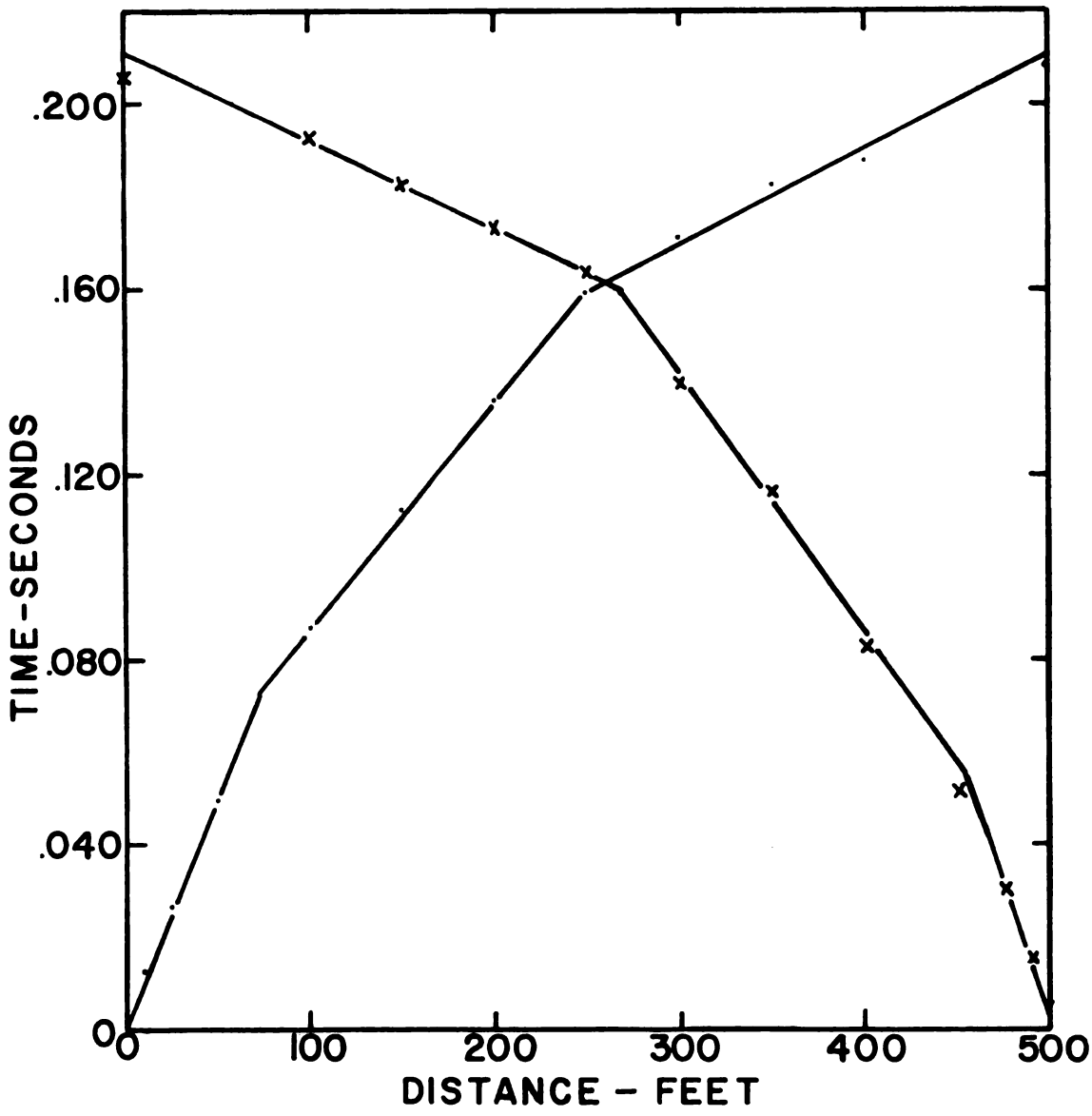
CORRECTED TIME VS. DISTANCE GRAPH

FIGURE 10



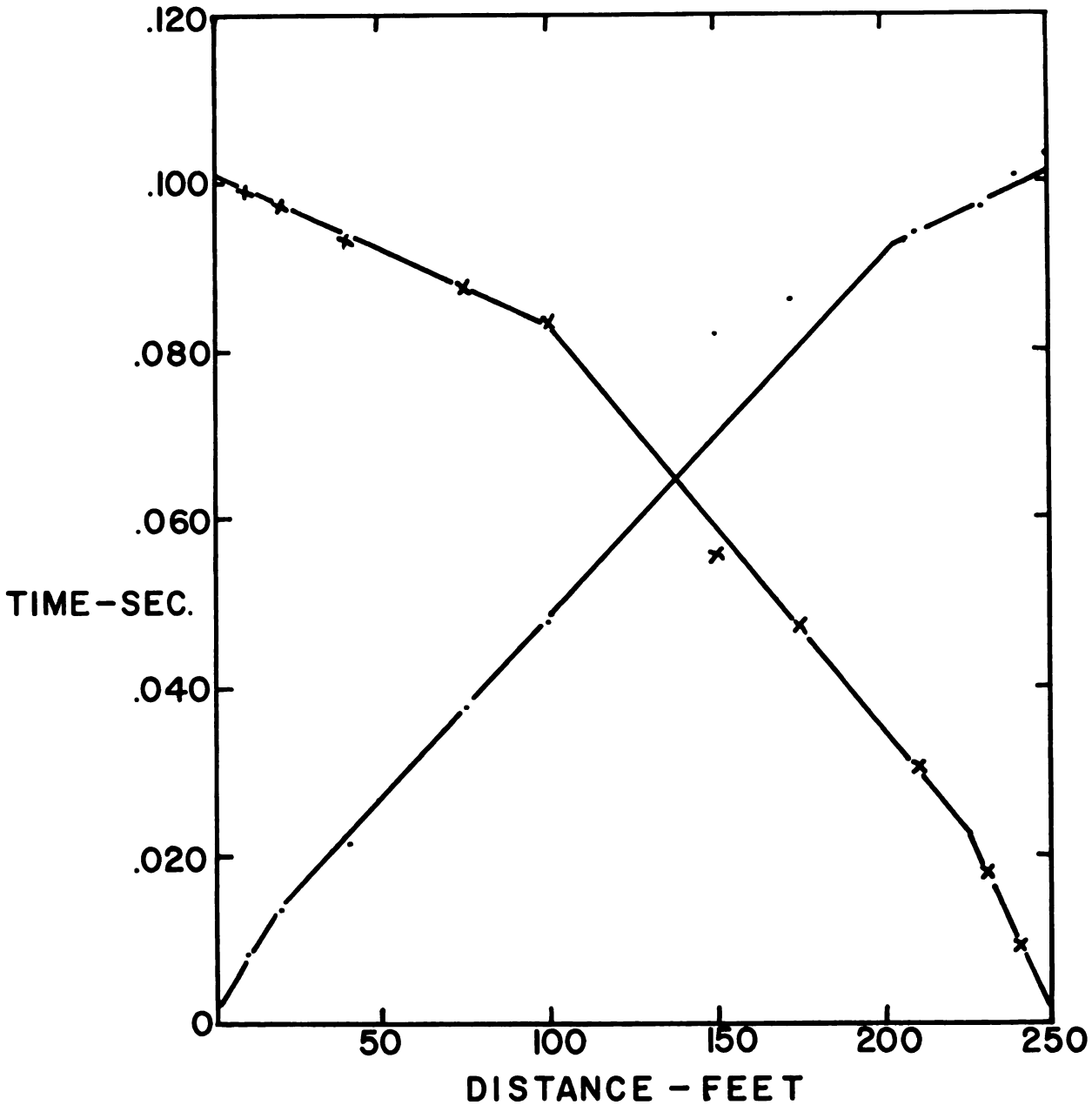
CORRECTED TIME VS. DISTANCE GRAPH

FIGURE 11



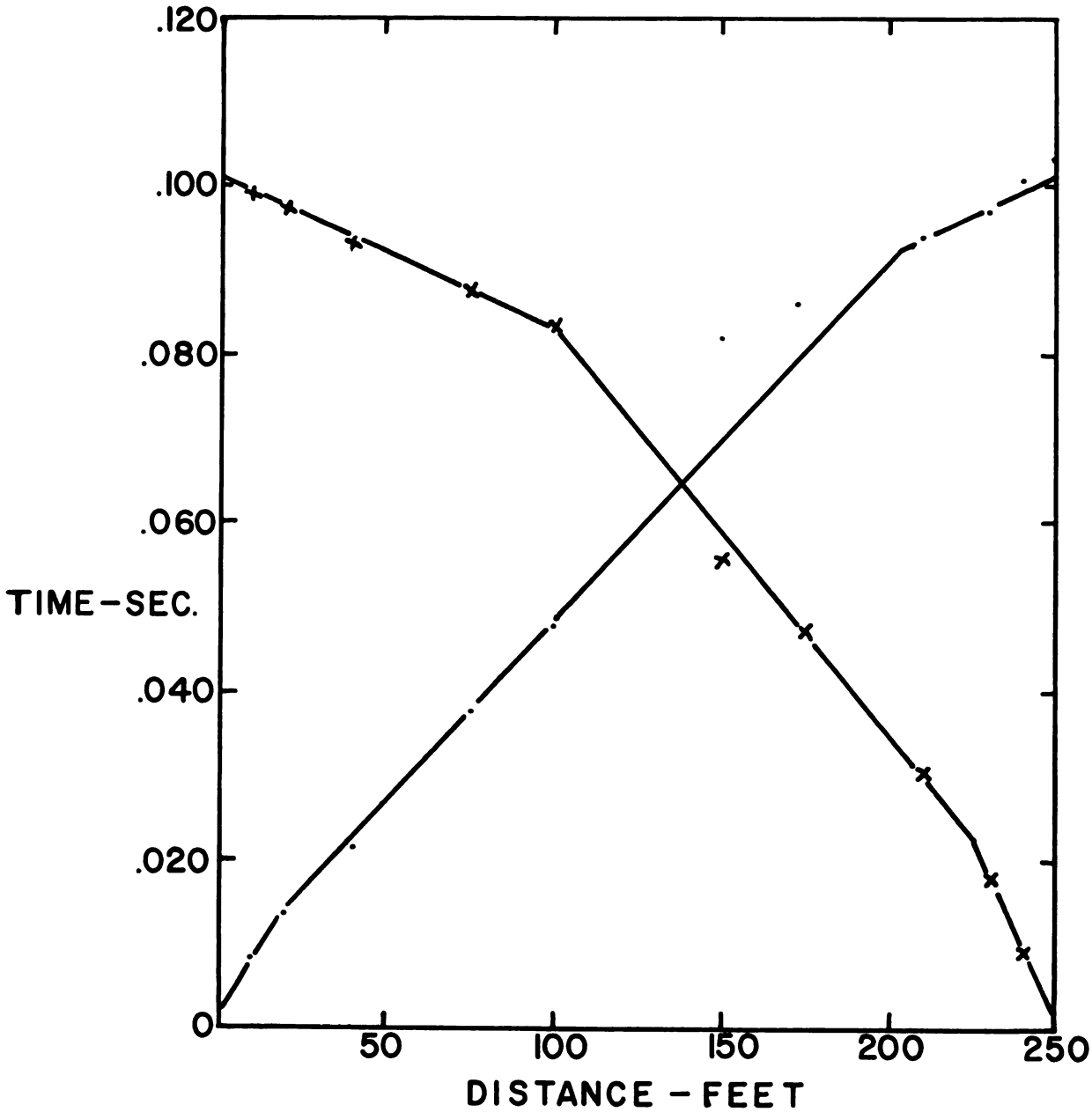
CORRECTED TIME VS. DISTANCE GRAPH

FIGURE 12



CORRECTED TIME VS. DISTANCE GRAPH

FIGURE 13



CORRECTED TIME VS. DISTANCE GRAPH
FIGURE 13

The surface layer consists of a dry, well sorted sand throughout most of the study area. The material beneath the surface layer is primarily saturated sand. In the interior basin and in the uplands, an intermediate layer was frequently detected by the seismic method. This layer is indicated on time-distance graphs (Figures 10 through 13) by the segment of intermediate slope between the direct arrivals and the refractions from the saturated layer. This zone of intermediate velocity probably is a result of lithologic variations in the unsaturated material.

The unsaturated layers excluding intermediate layers in this zone, have an average velocity of 1,141 feet per second, and a range of 600 to 2,000 feet per second (Figure 14). The average velocity of the intermediate velocity layers is 2,140 feet per second. The saturated sand shows a velocity range of 4,000 to 6,750 feet per second, with an average velocity of 5,461 feet per second (Figure 15).

Anomalously high velocities were occasionally recorded for both the unsaturated and saturated layers. These velocities may be due to an increase in the clay content of the layers.

Depth to Water Table

The indentification of the water table was made on the basis of the results of the seismic survey guided by

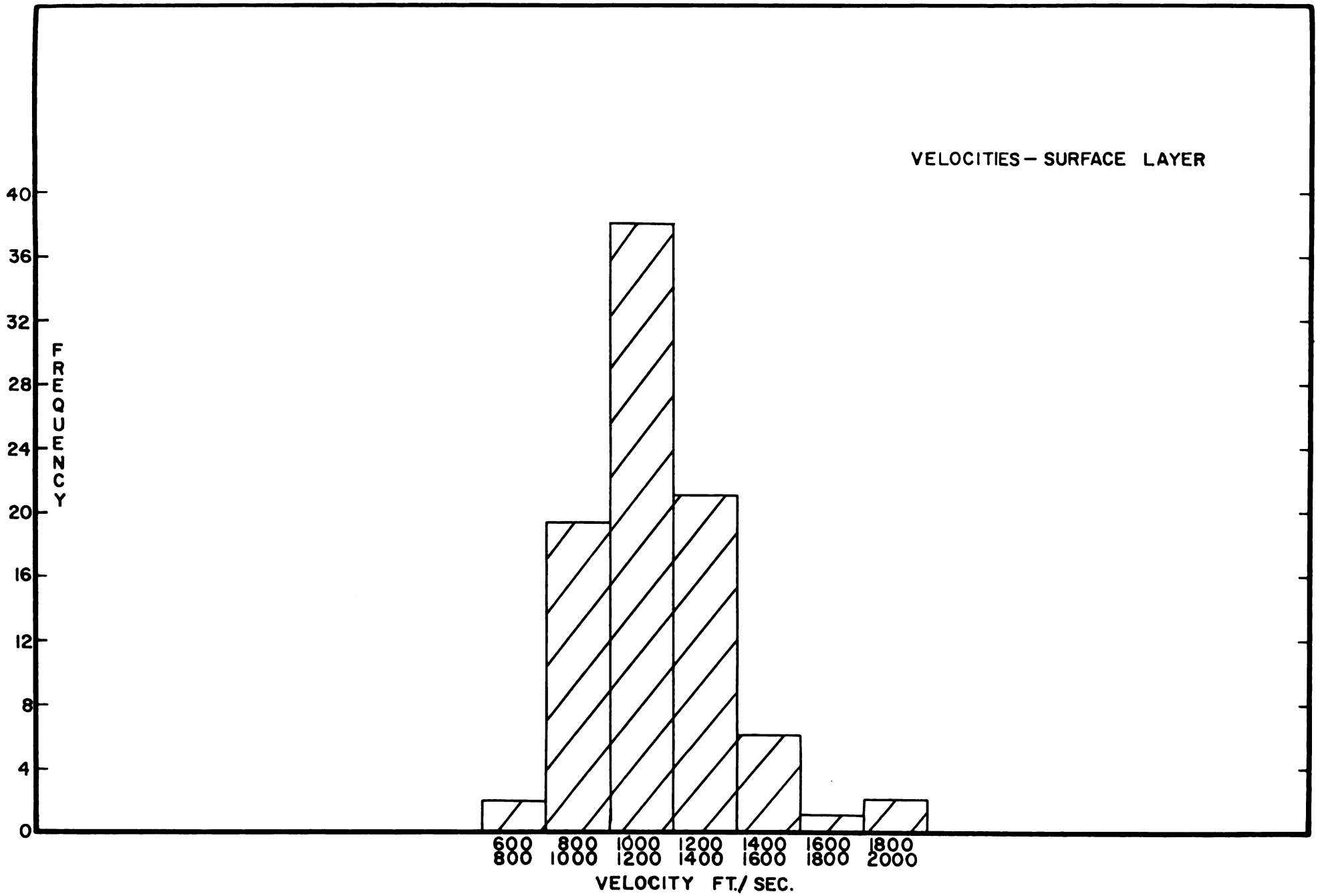
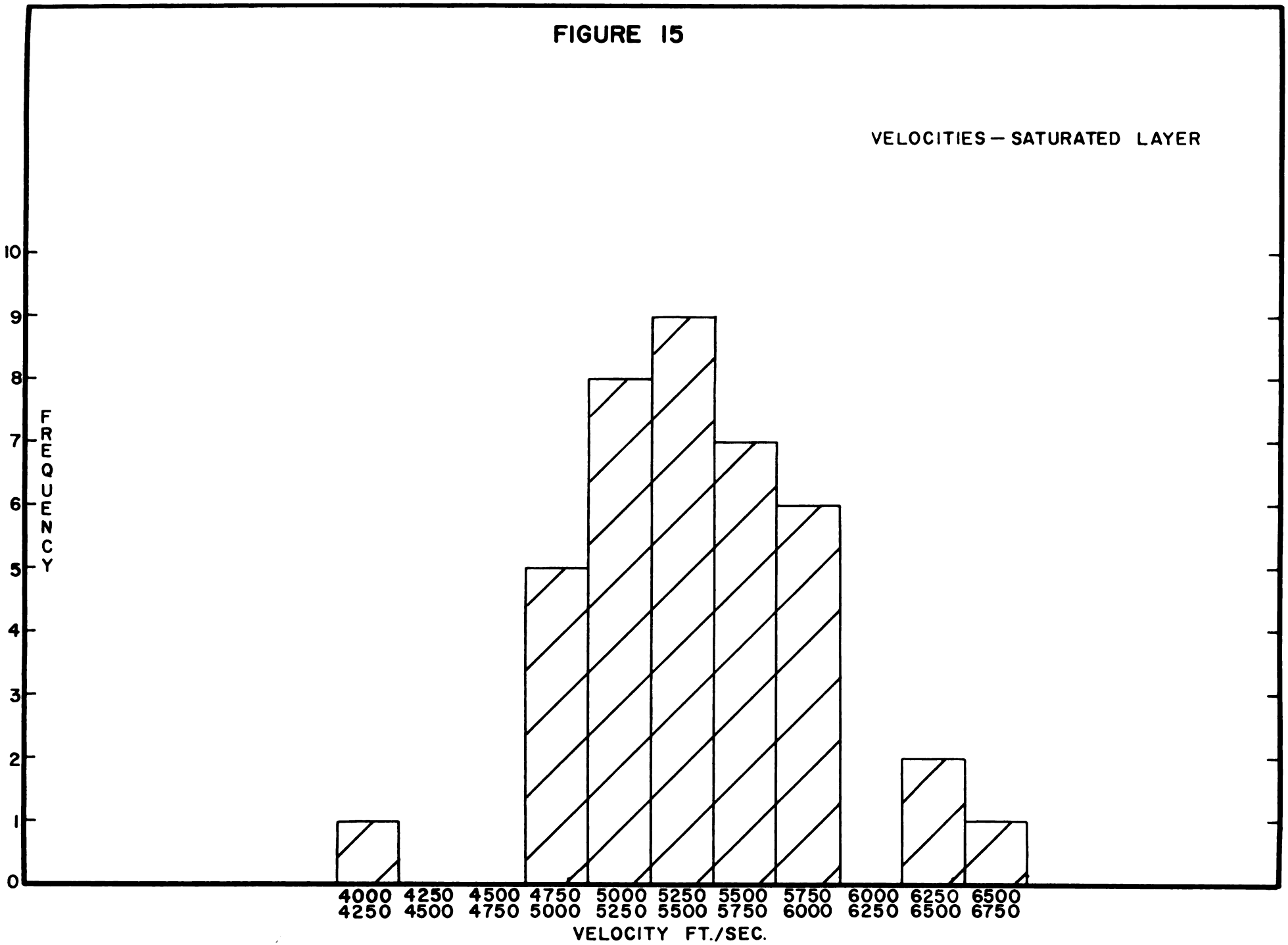

VELOCITIES – SURFACE LAYER
FREQUENCY
0
4
8
12
16
20
24
28
32
36
40
600 800
800 1000
1000 1200
1200 1400
1400 1600
1600 1800
1800 2000
VELOCITY FT./SEC.

FIGURE 14

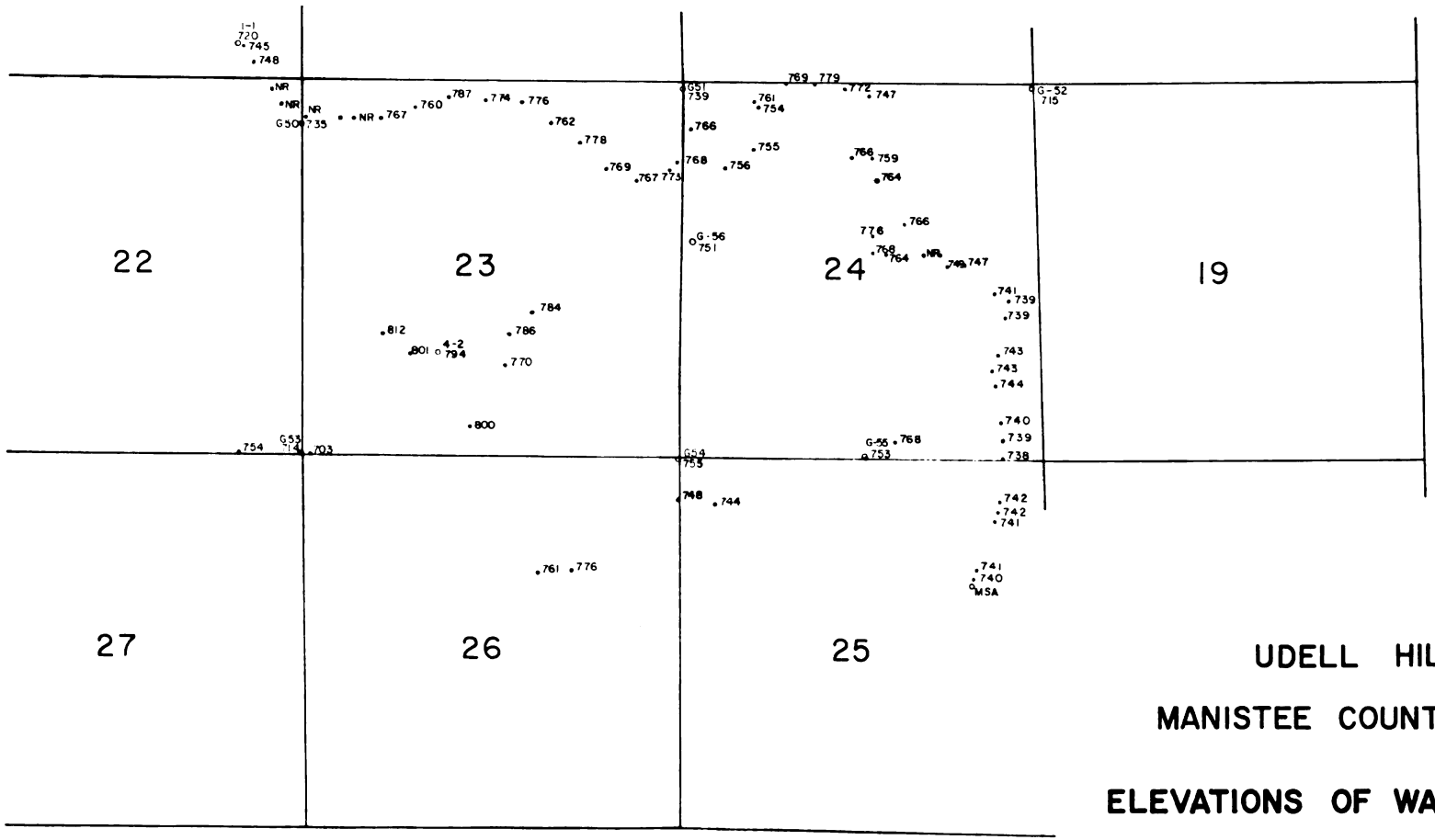
FIGURE 15


VELOCITIES — SATURATED LAYER
FREQUENCY
0
1
2
3
4
5
6
7
8
9
10
4000 4250
4250 4500
4500 4750
4750 5000
5000 5250
5250 5500
5500 5750
5750 6000
6000 6250
6250 6500
6500 6750
VELOCITY FT./SEC.

water table depths from well data. Figure 16 shows the elevations of the water table obtained from the results of the seismic method, together with the elevations of the water table in each control well. The water table map prepared from the results of the seismic method and drilling data indicates a ground water mound associated with the Udell Hills centered in section 23 (Figure 17). This mound displays a total relief of about 100 feet over the area of investigation. A minor water table depression is indicated in the northwestern quarter of section 24.

A fence diagram (Figure 18) isometrically projected N 45° W is useful for observing the spatial relationships of the results of the seismic study. In particular, the relationship between the surface topography and the water table surface is evident from an examination of the diagram. The solid black line represents the horizontal datum from which elevations were measured. Surface elevations are shown as dashed lines, while the water table is represented as alternating dots and dashes. Individual layers in the unsaturated zone have been omitted from the diagram. Each of the columns of the diagram represents a point of seismic depth determination.

The ground water mound, previously noted, is evident from the diagram. In other areas, the water table generally follows the surface topography.



UDELL HILLS

MANISTEE COUNTY, MICH.

ELEVATIONS OF WATER TABLE

BY THE SEISMIC METHOD

0 1000' 2000' 3000' 4000'

FIGURE 16

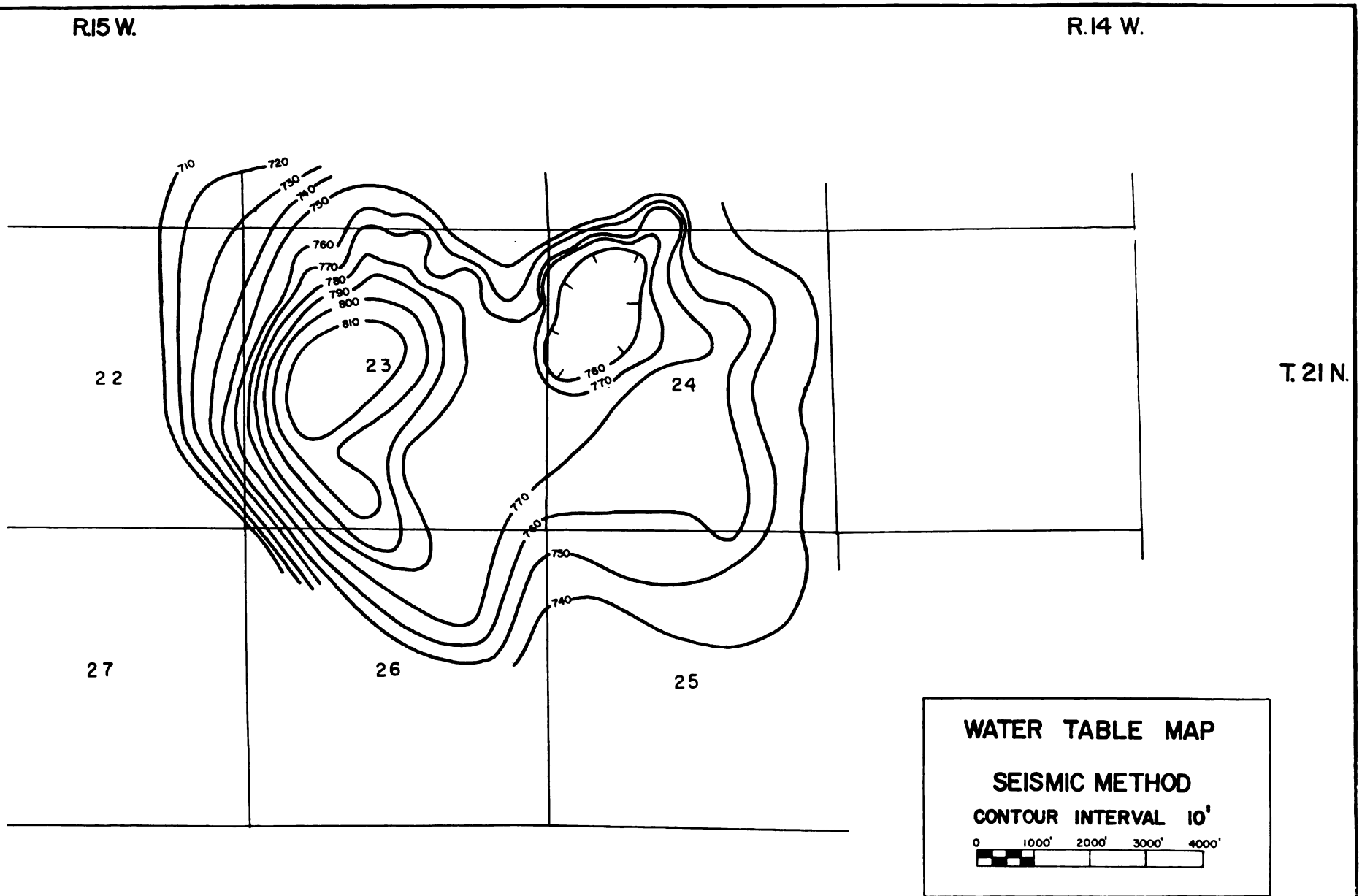

R.15 W.
R.14 W.
T. 21 N.
710
720
730
740
750
760
770
780
790
800
810
22
23
24
25
26
27
WATER TABLE MAP
SEISMIC METHOD
CONTOUR INTERVAL 10'
0
1000'
2000'
3000'
4000'

FIGURE 17

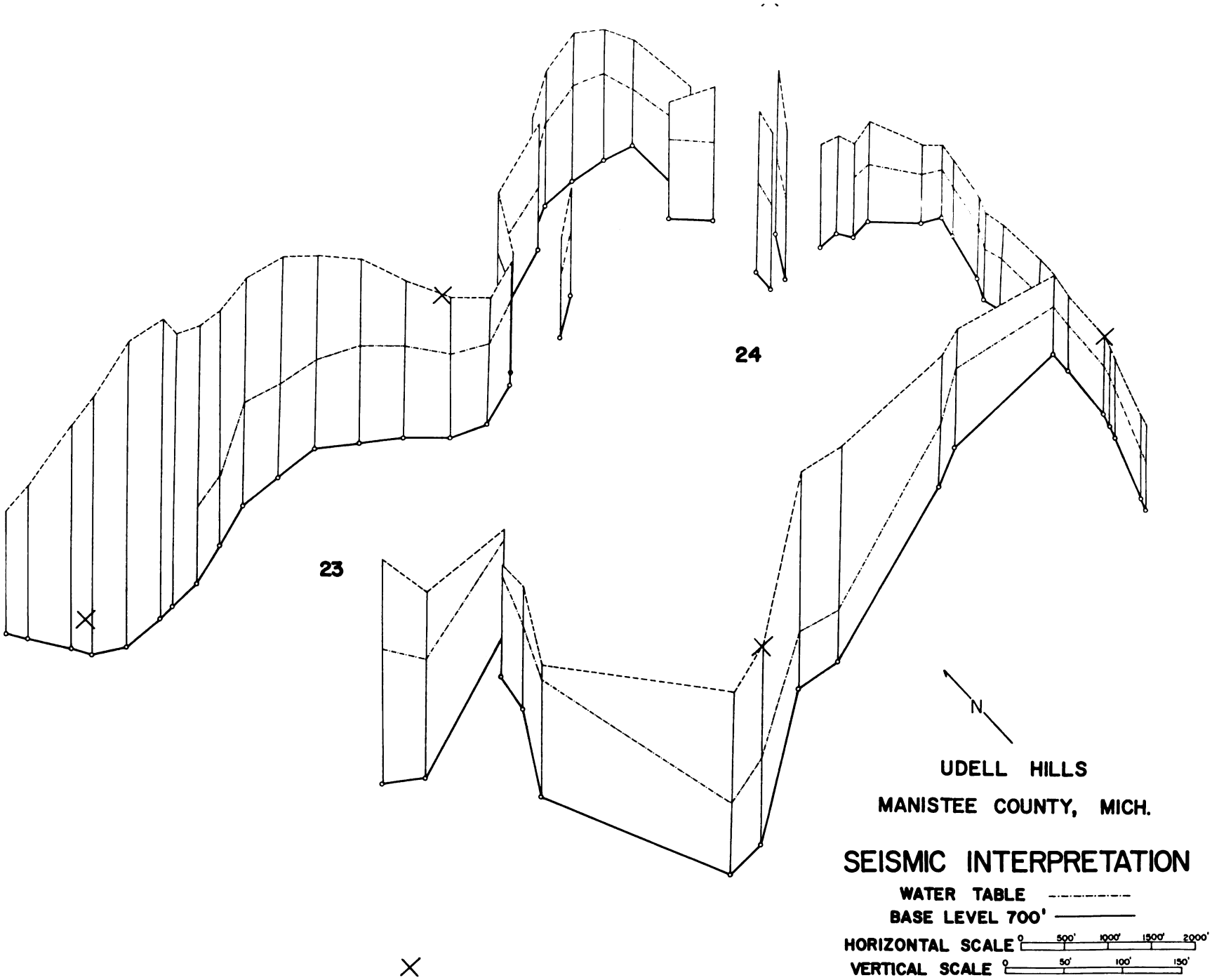

24
23
N
UDELL HILLS
MANISTEE COUNTY, MICH.
SEISMIC INTERPRETATION
WATER TABLE
BASE LEVEL 700'
HORIZONTAL SCALE 0 500' 1000' 1500' 2000'
VERTICAL SCALE 0 50' 100' 150'
SECTION CORNERS +

FIGURE 18

Analysis of Errors

An analysis of the error between the interpolated and calculated depth to the water table for spreads adjacent to seven control wells is given in Table 1. Linear interpolation between two wells was used to obtain the projected water table elevation at the position of the geophysical measurement (third column). The per cent error for the seismic observations is given in the final column.

The average per cent error for the five cases in which seismic and geological conditions were amenable to the detection of the water table is 10%. The remaining two cases failed to detect the water table. This is probably due either to insufficient spread length or to the existence of a low velocity zone.

Several factors contribute to the percentage of error. First, the control wells are located a minimum of 100 feet, and a maximum of 740 feet from the points of seismic observation. Secondly, the linear interpolation process used to obtain the water table elevation of the seismic site may be in error. In addition, errors may arise because of the departure of the subsurface conditions from the assumptions which are made in seismic theory.

TABLE I

ANALYSIS OF ERRORS

Well Designation	Distance Between Geo-physical Measurement and well	Surface Elevation of Well	Water Table Elevation From Well Data	Seismic Water Table Elevation	Resistivity Water Table Elevation	Surface Elevation of Geophysical Measurement	% Error Seismic	% Error Resistivity
MSA Well No. 1	667	763	740	741	733	764	4	23
G-51	740	855	748	762	756	806	24	14
G-50	605	968	730	NR	720	952	--	1
Well 1-1	600	786	726	NR	733	863	--	5
G-53	300	904	714	722	767	900	4	29
G-54	710	862	758	746	736	886	9	17
G-55	100-S 540-R	815	757-S 748-R	753	752	812-S 802-R	7	7
						Average Error	10%	14%

RESISTIVITY INTERPRETATION

Introduction

The interpretation of the resistivity portion of this survey includes locating the depths of the interfaces between layers of contrasting resistivities, determining the number of layers, and obtaining resistivity values for these layers. All pertinent well data were integrated into the interpretation, which is considered in terms of the specific objectives of this study.

Various interpretive procedures have been developed for mapping lithologic and structural variations from resistivity data. Interpretative methods employed in this study were of two basic types; theoretical and empirical.

Theoretical Methods

Theoretical methods employ some form of master curve computed from theoretical considerations. The field curve is superimposed on families of theoretical curves until a match is found. From the matched curves, resistivities and depths may be obtained.

Only the Mooney and Wetzel theoretical curves were employed in this study (Mooney and Wetzel, 1956), because the various theoretical curve matching methods will give approximately equivalent results.

Empirical Methods

Empirical methods used in this study include Moore's Cumulative method and Barnes' Layer method.

Moore's Cumulative method.--Moore's Cumulative method, which has no theoretical basis, involves plotting a summation of resistivities at equal electrode intervals, against electrode separations. Straight lines are then drawn through as many points of accumulated resistivity as possible. Because earth materials usually consist of layers having different resistivities, two or more straight line segments ordinarily will be required to connect these points. The electrode separation at the point of intersection of two adjacent segments may be interpreted as the depth to an interface between materials of contrasting resistivities.

The Moore's Cumulative method is essentially a graphical integration of the apparent resistivity curve. The method does not give layer resistivity values. It was applied in this study through separate interpretations with electrode intervals of 10 and 20 feet. Figure 19 is an example of a Moore's curve with an indicated depth of 94 feet.

Barnes Layer method.--The Barnes Layer method assumes that layers of earth material are analogous in behavior to a number of parallel connected resistors. Each resistor represents a specific layer of earth material equivalent

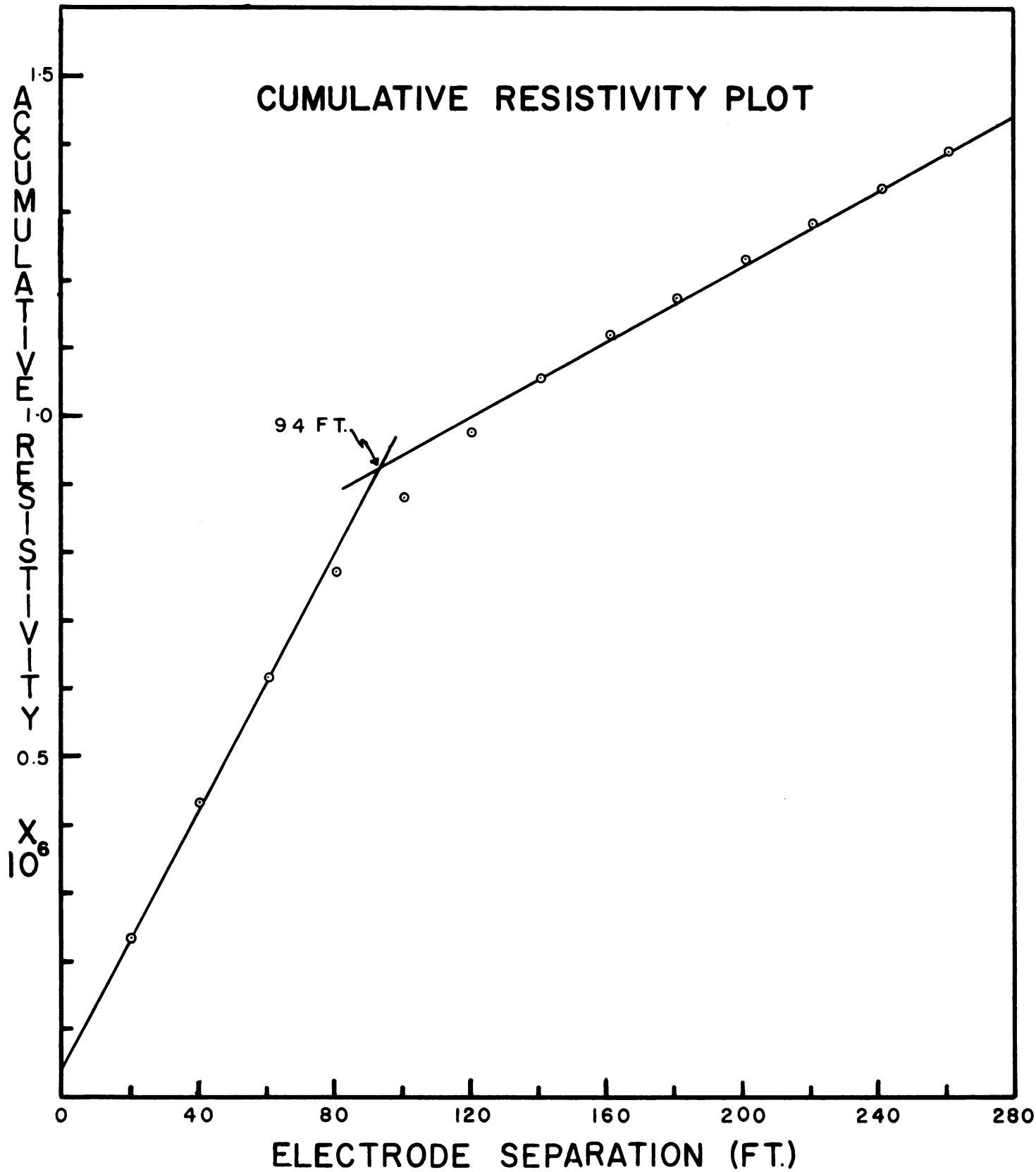

CUMULATIVE RESISTIVITY PLOT
ACCUMULATIVE RESISTIVITY
X 10^6
1.5
1.0
0.5
94 FT.
0
40
80
120
160
200
240
280
ELECTRODE SEPARATION (FT.)

FIGURE 19

in thickness to the separation of adjacent electrodes. The method essentially modifies the Wenner formula to remove the effect of the current flowing through the layers above. Values of resistivity obtained from the Barnes' method are relative to the true resistivity of each horizon. The resistivity of a specific layer may be obtained from the following relationship (Barnes, 1954):

$$\rho_L = 2\pi A \left(\frac{V_n}{I_n - \frac{V_n}{\bar{R}_{n-1}}} \right)$$

Where:

ρ_L = resistivity in ohm-centimeters of any individual layer,

A = separation of adjacent electrodes or thickness of layer in centimeters,

I_n = current in amperes through the outer or current electrodes,

V_n = potential in volts measured across the inner or potential electrodes,

$\bar{R}_{n-1}$ = average resistance in ohms of the layers lying between the surface of the earth and the bottom of the layer just above the layer being investigated,

N = number of any individual layer.

The interpretation of the Barnes' resistivities was based on the detection of significant trends in the data. The values of $\frac{V}{I}$ used in calculating the Barnes' data were obtained from Wenner curves smoothed to minimize the effects from near surface variations in resistivity.

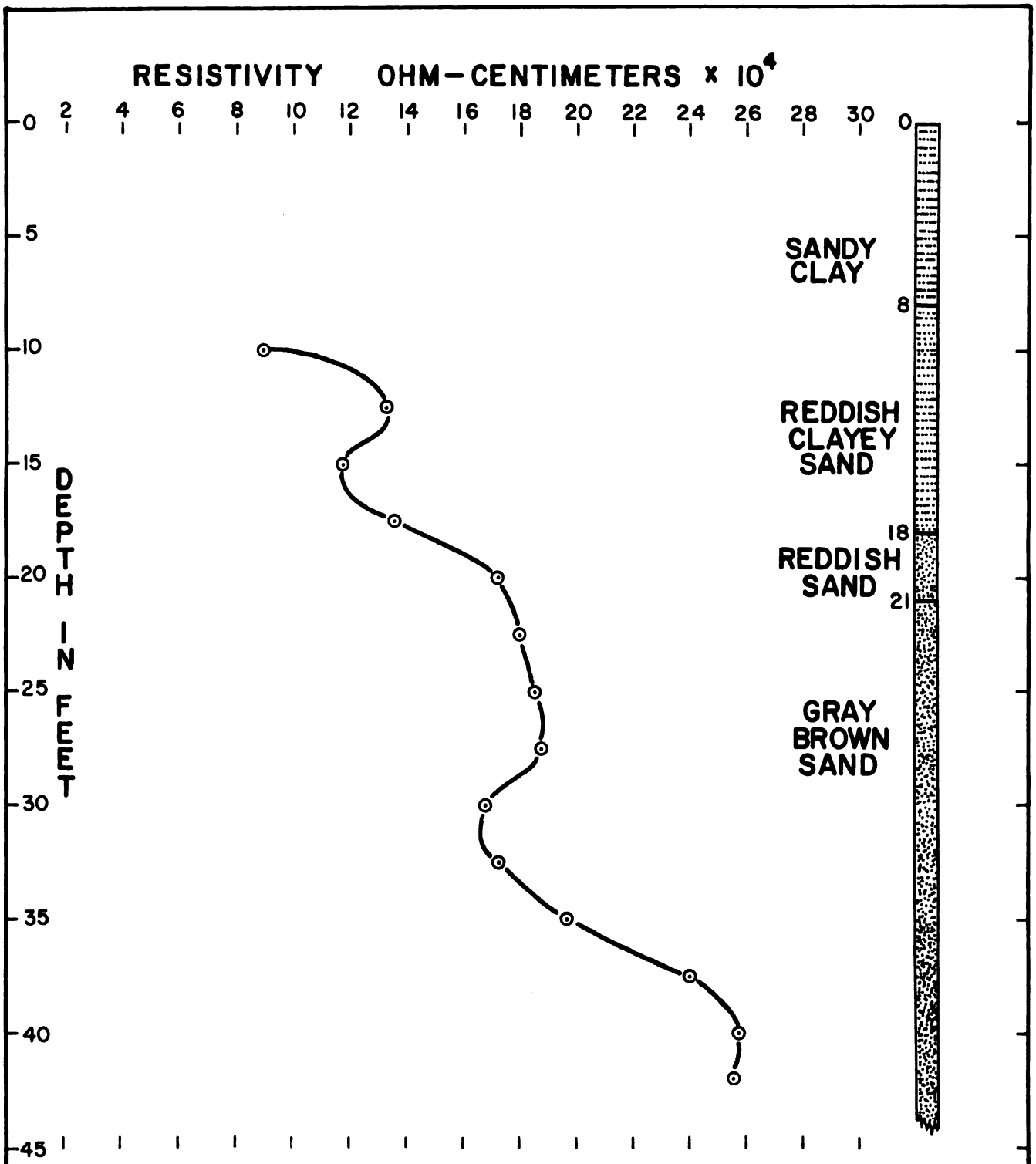
Resistivities of Representative Glacial Drift Materials

Electrical resistivity well-log measurements were attempted at several wells that had not reached the water table. However, the very high surface resistivities and limited current capacity of the instrument prevented usable data from being obtained except at well G-50 where the surface material is clay. Figure 20 is the electrical resistivity and lithologic log of well G-50 from a depth of 10 to 42 feet. The resistivities range from 80,000 to 260,000 ohm-centimeters.

The geographic location of the resistivity spreads is shown in Figure 21. Profiles of apparent resistivity versus electrode separation are shown in Figures 22 through 28. In general, the curves show high surface resistivities, and as the water table is encountered or the percentage of clay minerals increases, the apparent resistivity decreases.

Electrical resistivities obtained by the Barnes' and Mooney and Wetzel methods of interpretation varied from a few thousand ohm-centimeters to values in excess of 2,500,000 ohm-centimeters. The higher values are associated with dry near surface sand, deficient in moisture. Lower resistivities are related to materials containing a greater percentage of moisture and/or clay minerals.

The results of this portion of the study are presented in the form of a series of histograms. Figures 29 and 30 show



WELL G-50

ELECTRICAL & LITHOLOGIC LOGS

FIGURE 20

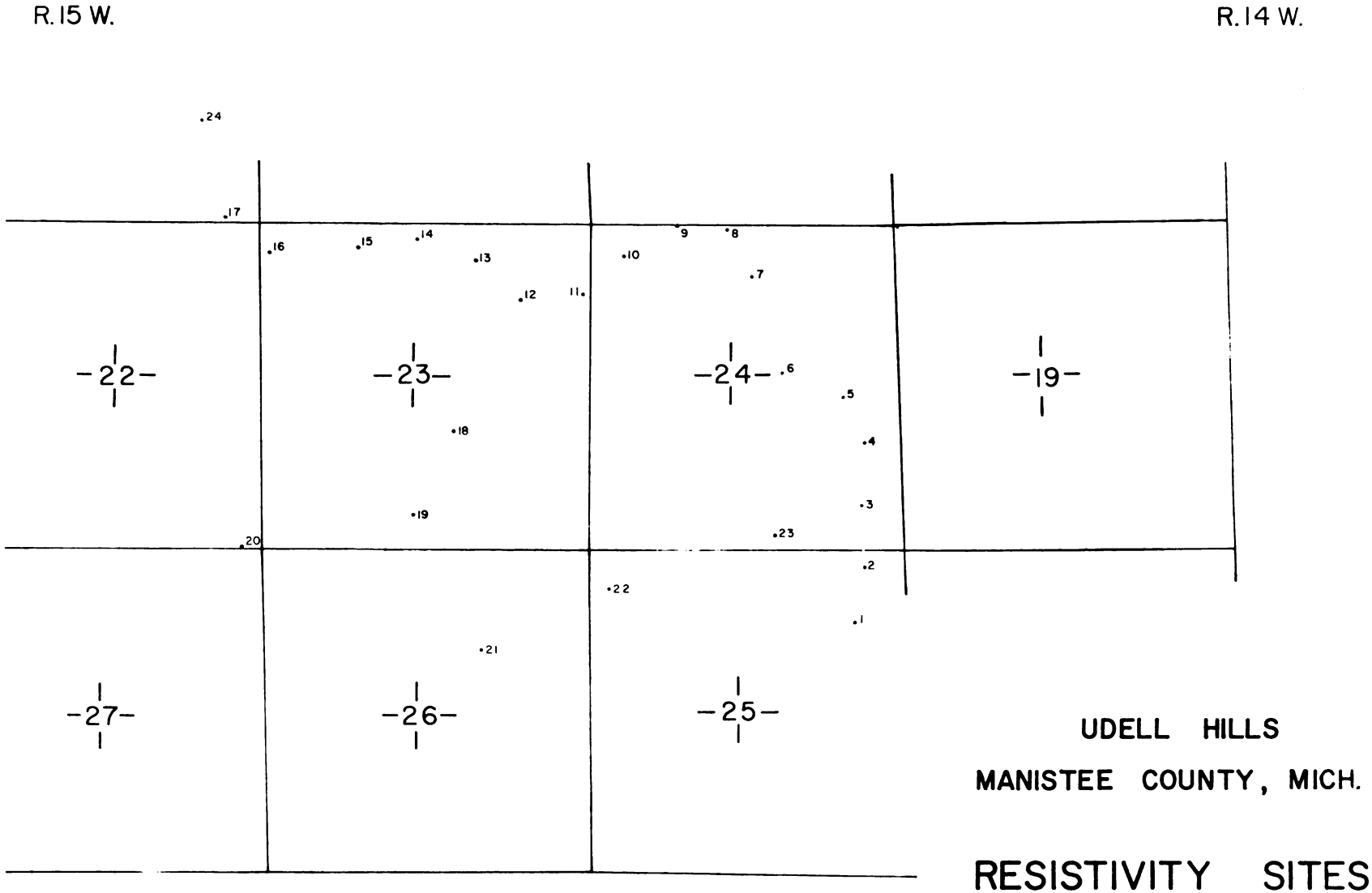

R.15 W.
R.14 W.
T.21 N.
-22-
-23-
-24-
-19-
-27-
-26-
-25-
.24
.17
.16
.15
.14
.13
.12
.11
.10
.9
.8
.7
.6
.5
.4
.3
.2
.1
.18
.19
.20
.21
.22
.23
UDELL HILLS
MANISTEE COUNTY, MICH.
RESISTIVITY SITES
0
1000'
2000'
3000'
4000'

FIGURE 21

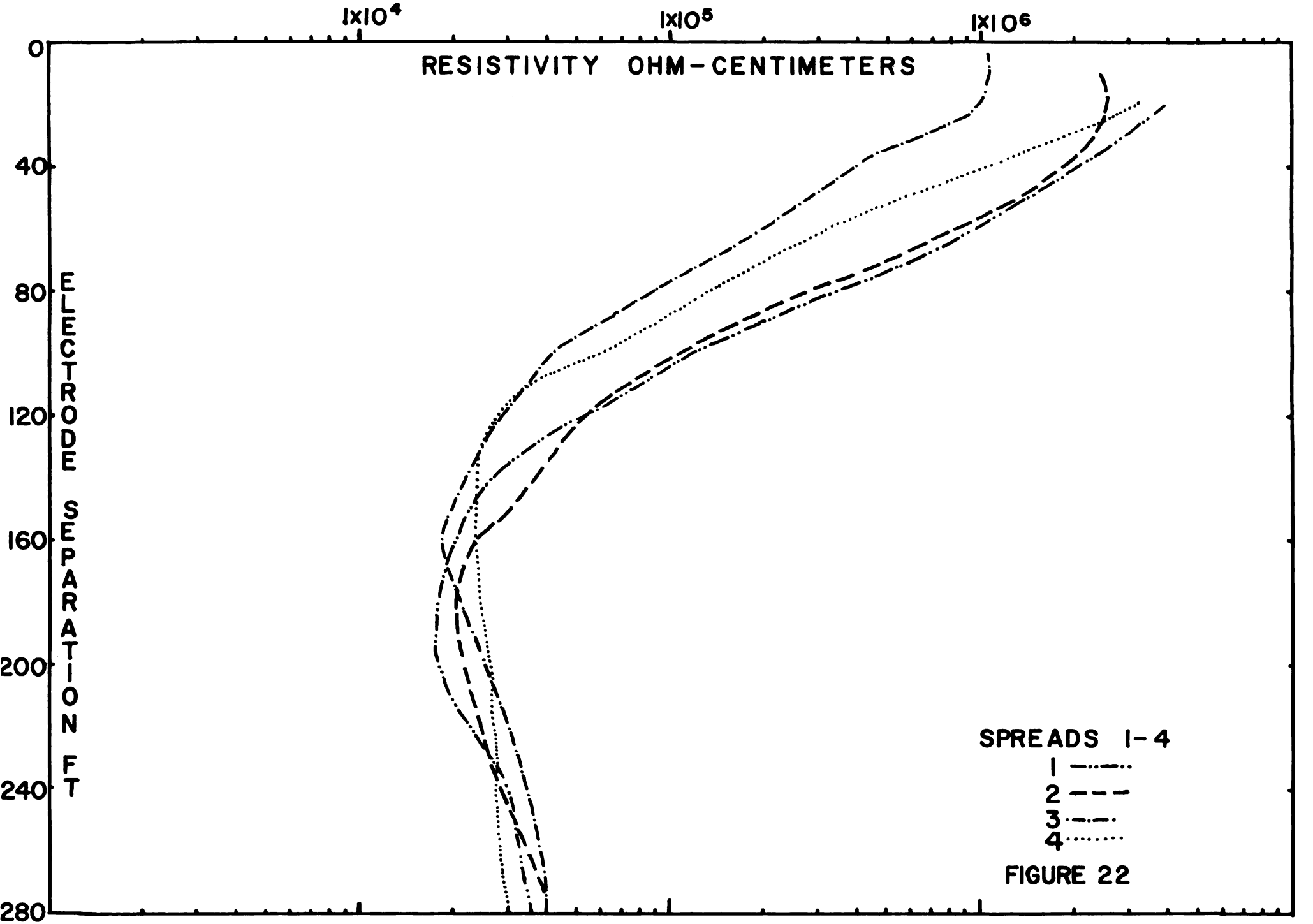


FIGURE 22

p 47

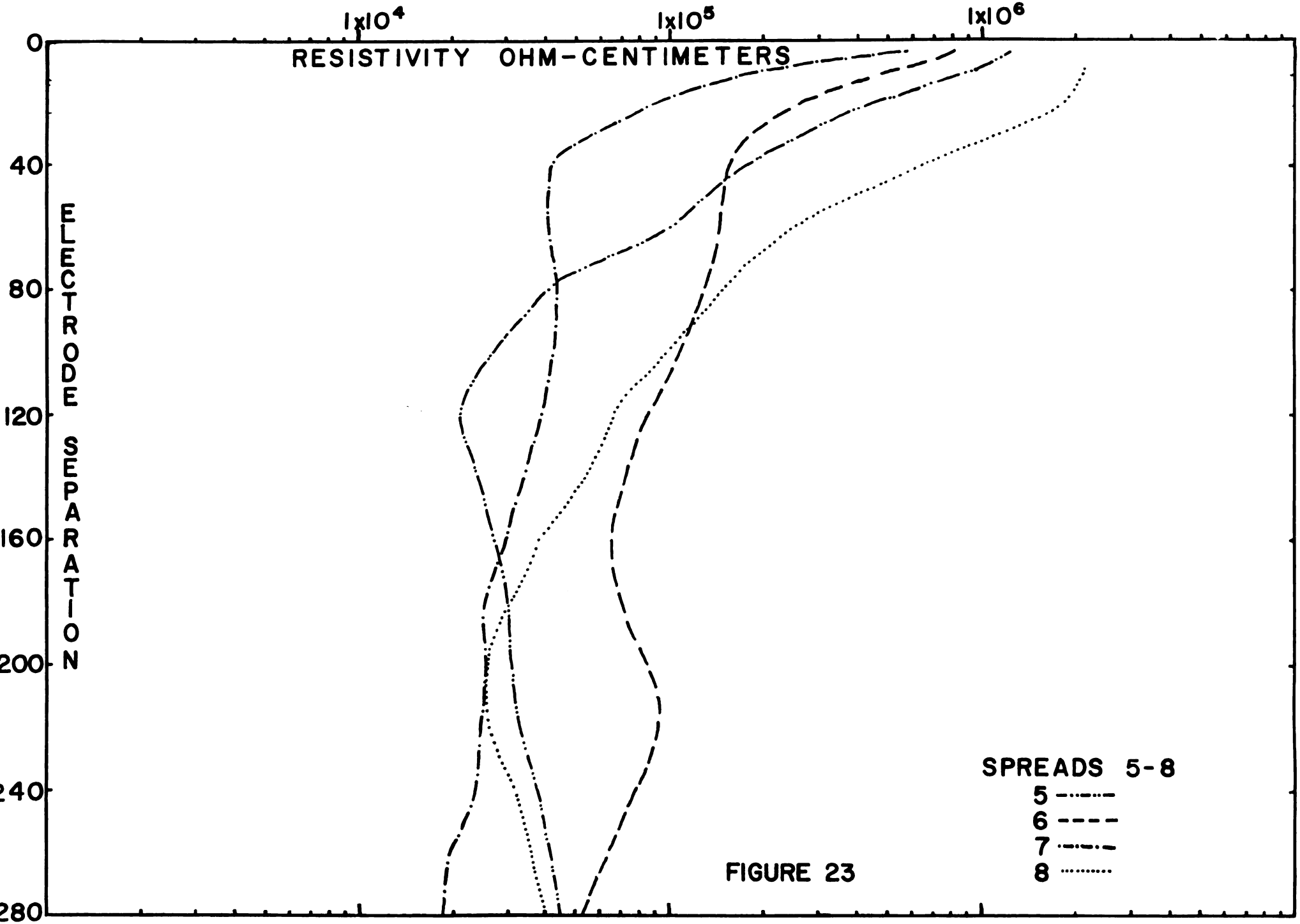

1x10⁴
1x10⁵
1x10⁶
RESISTIVITY OHM-CENTIMETERS
0
40
80
120
160
200
240
280
ELECTRODE SEPARATION
SPREADS 5-8
5
6
7
8

FIGURE 23

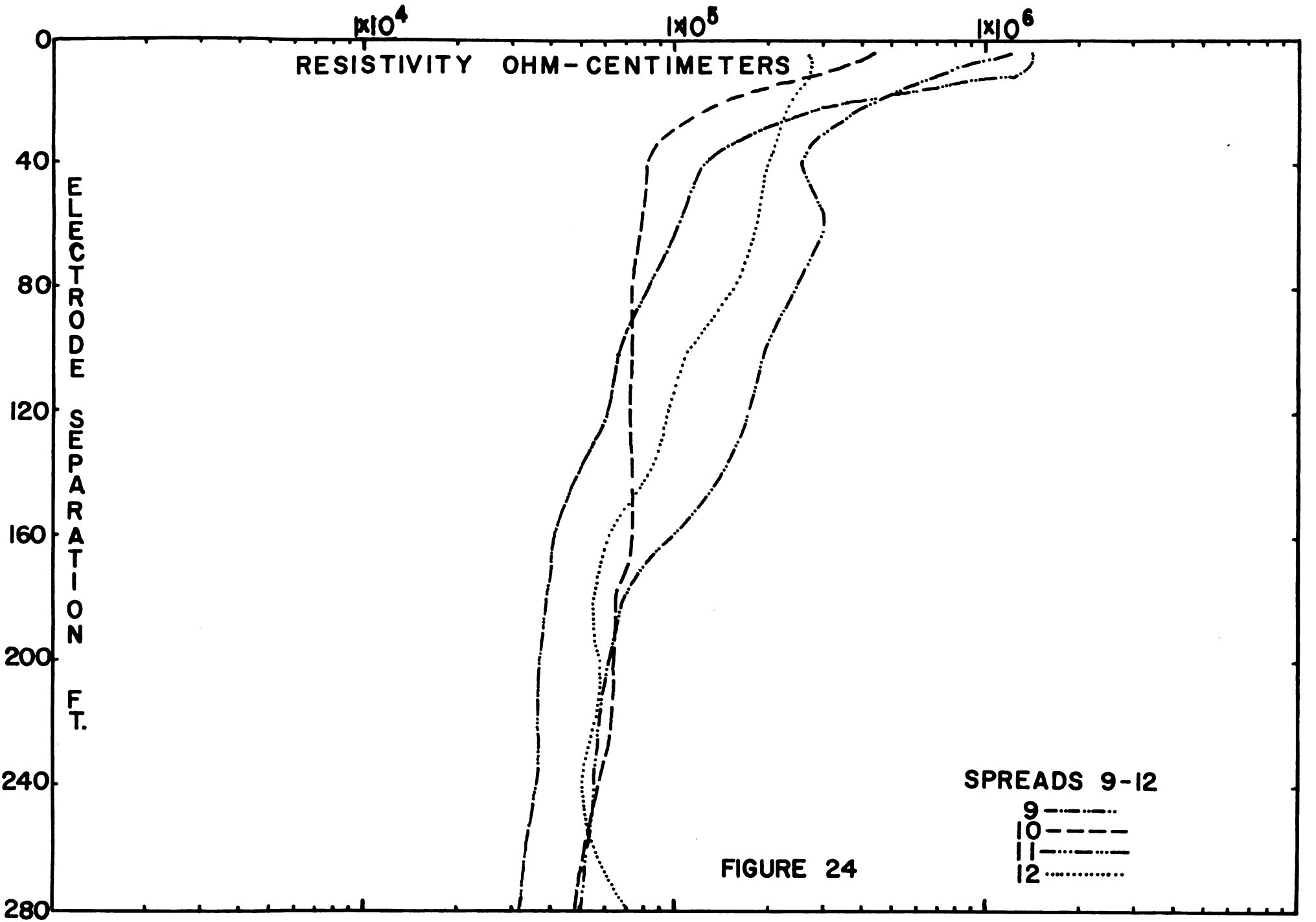

1×10⁴
1×10⁵
1×10⁶
RESISTIVITY OHM-CENTIMETERS
0
40
80
120
160
200
240
280
ELECTRODE SEPARATION FT.
SPREADS 9-12
9
10
11
12

FIGURE 24

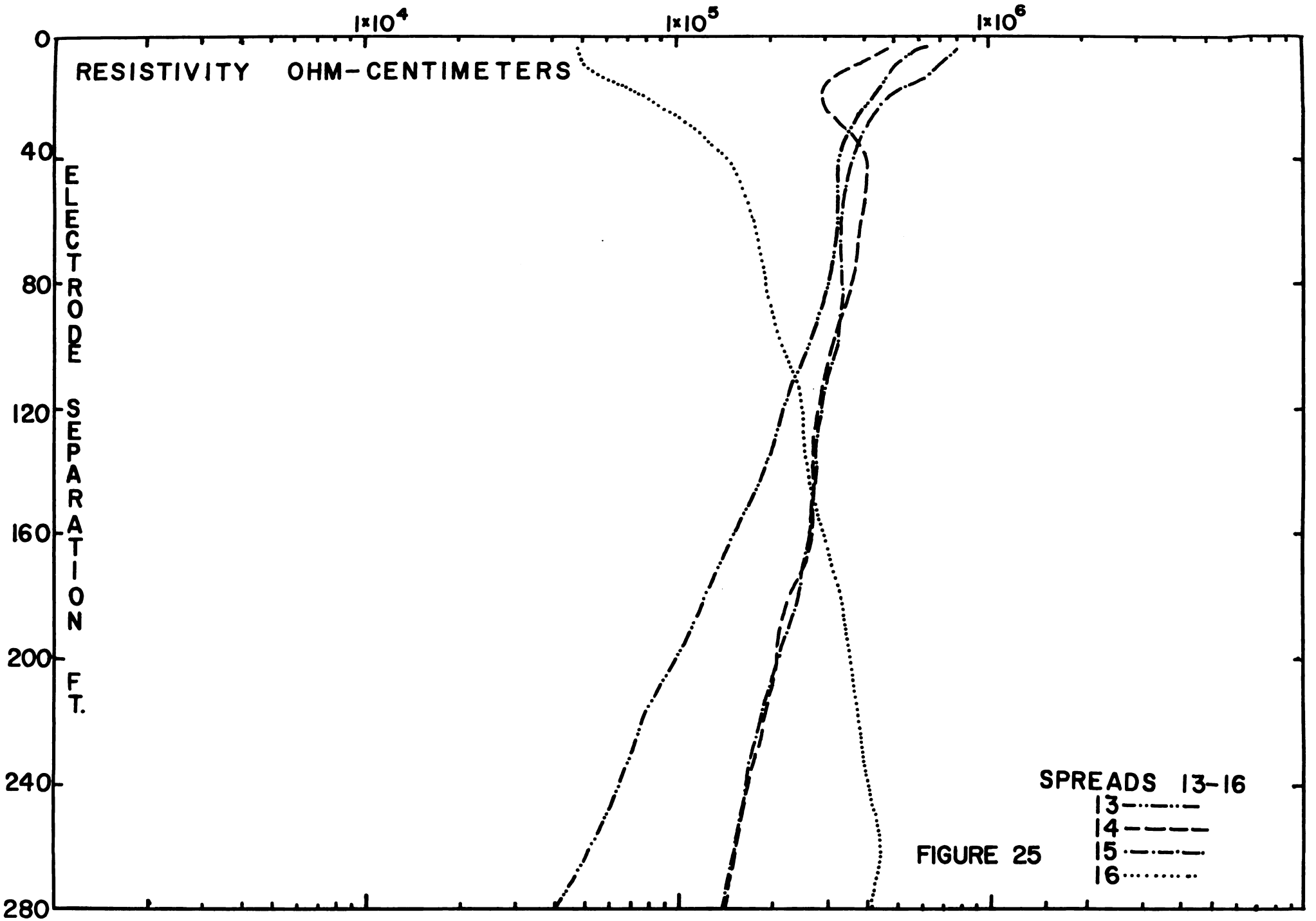

RESISTIVITY OHM-CENTIMETERS
1×10^4
1×10^5
1×10^6
ELECTRODE SEPARATION FT.
0
40
80
120
160
200
240
280
SPREADS 13-16
13
14
15
16

FIGURE 25

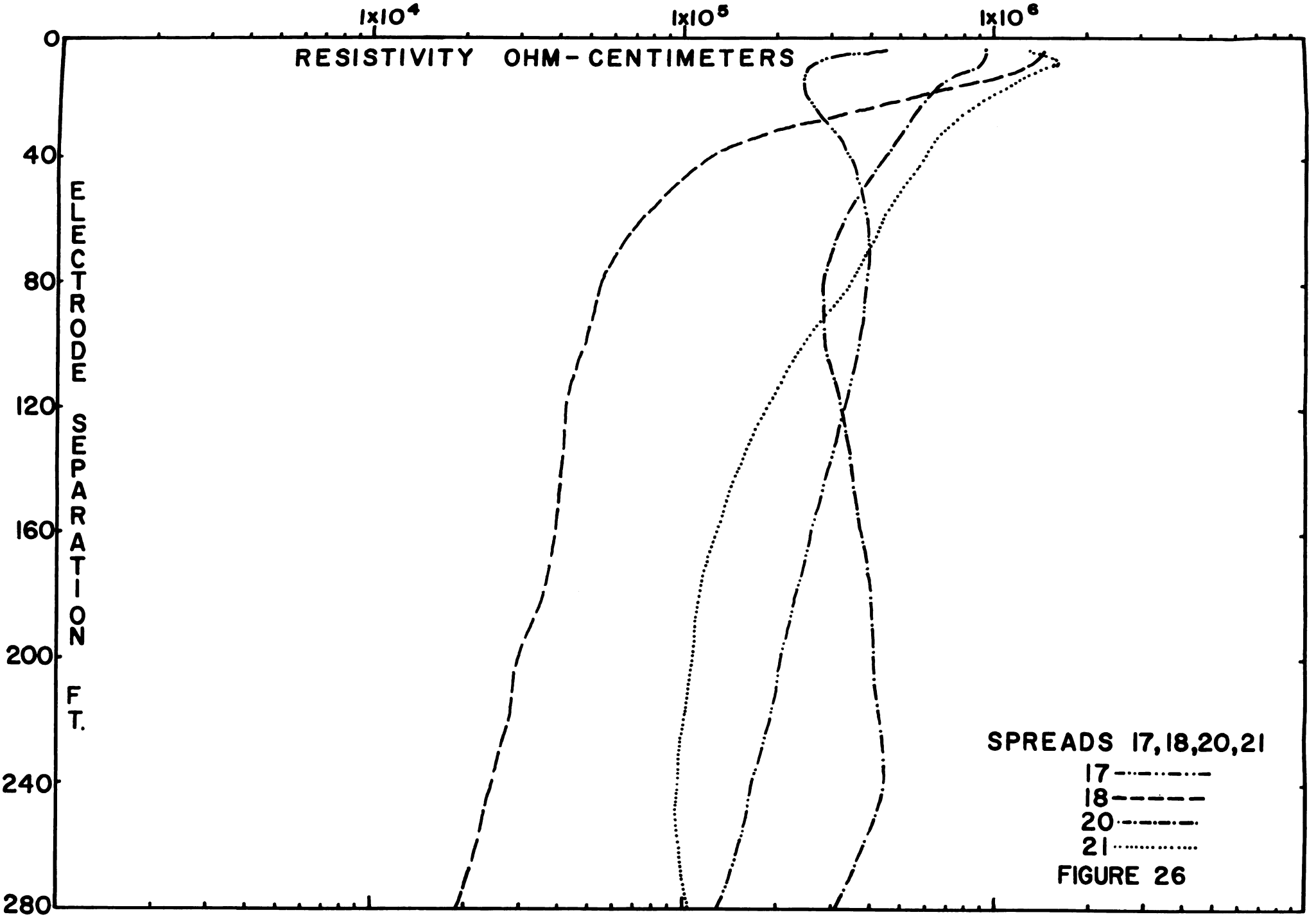

1x10⁴
1x10⁵
1x10⁶
RESISTIVITY OHM-CENTIMETERS
0
40
80
120
160
200
240
280
ELECTRODE SEPARATION FT.
SPREADS 17,18,20,21
17
18
20
21

FIGURE 26

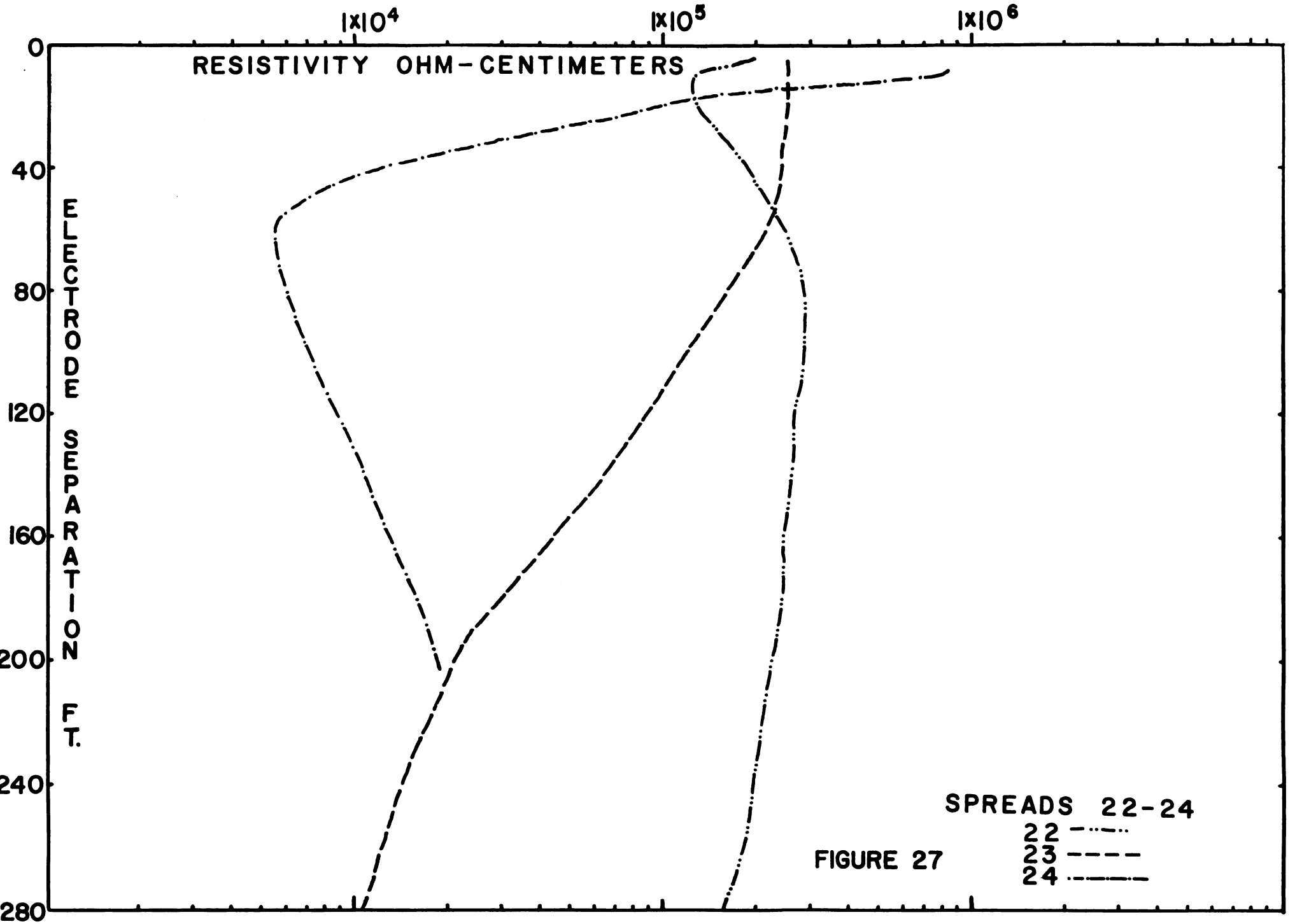
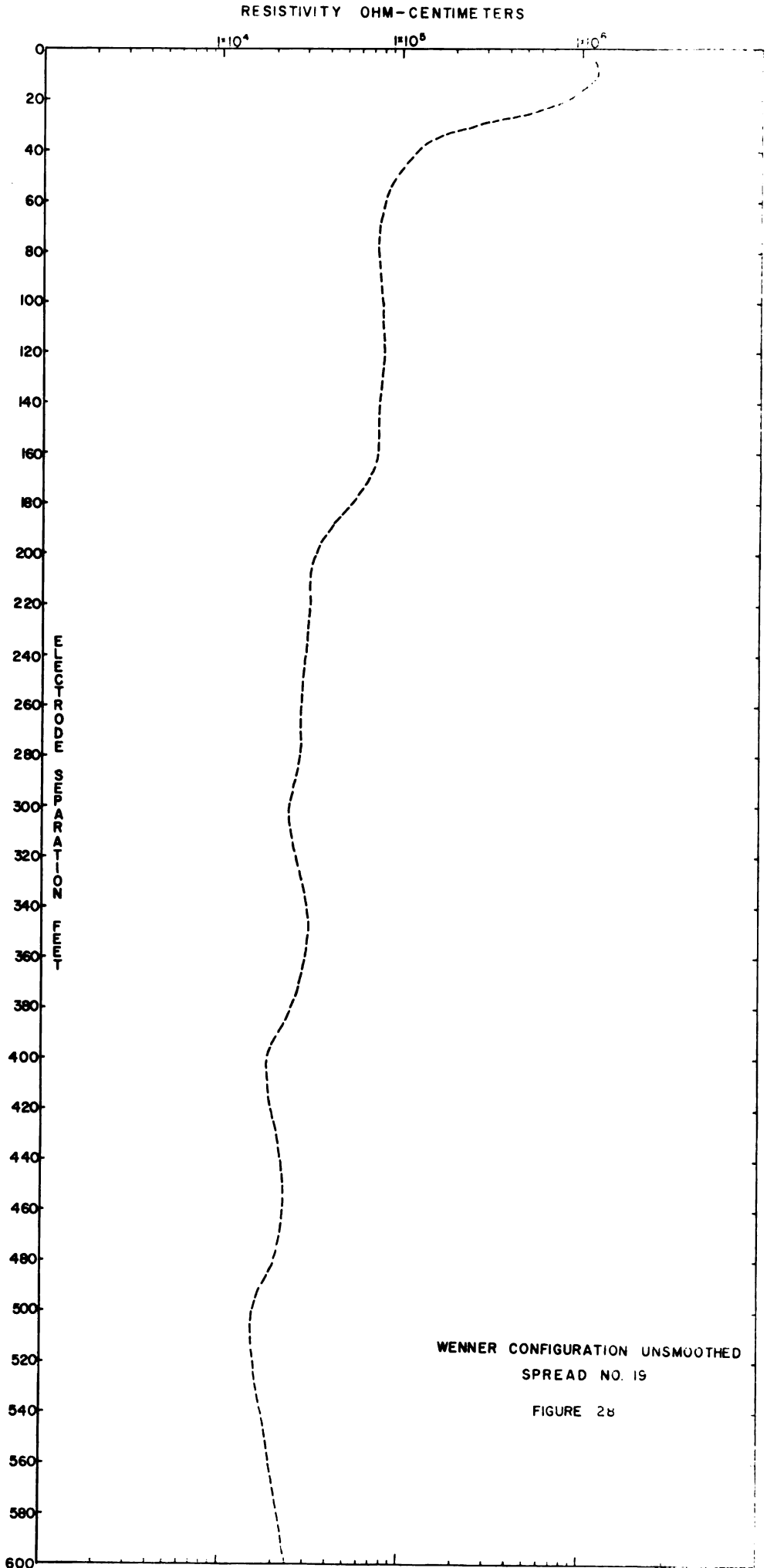

1x10^4
1x10^5
1x10^6
RESISTIVITY OHM-CENTIMETERS
0
40
80
120
160
200
240
280
ELECTRODE SEPARATION FT.
SPREADS 22-24
22
23
24

FIGURE 27



WENNER CONFIGURATION UNSMOOTHED
SPREAD NO. 19

FIGURE 28

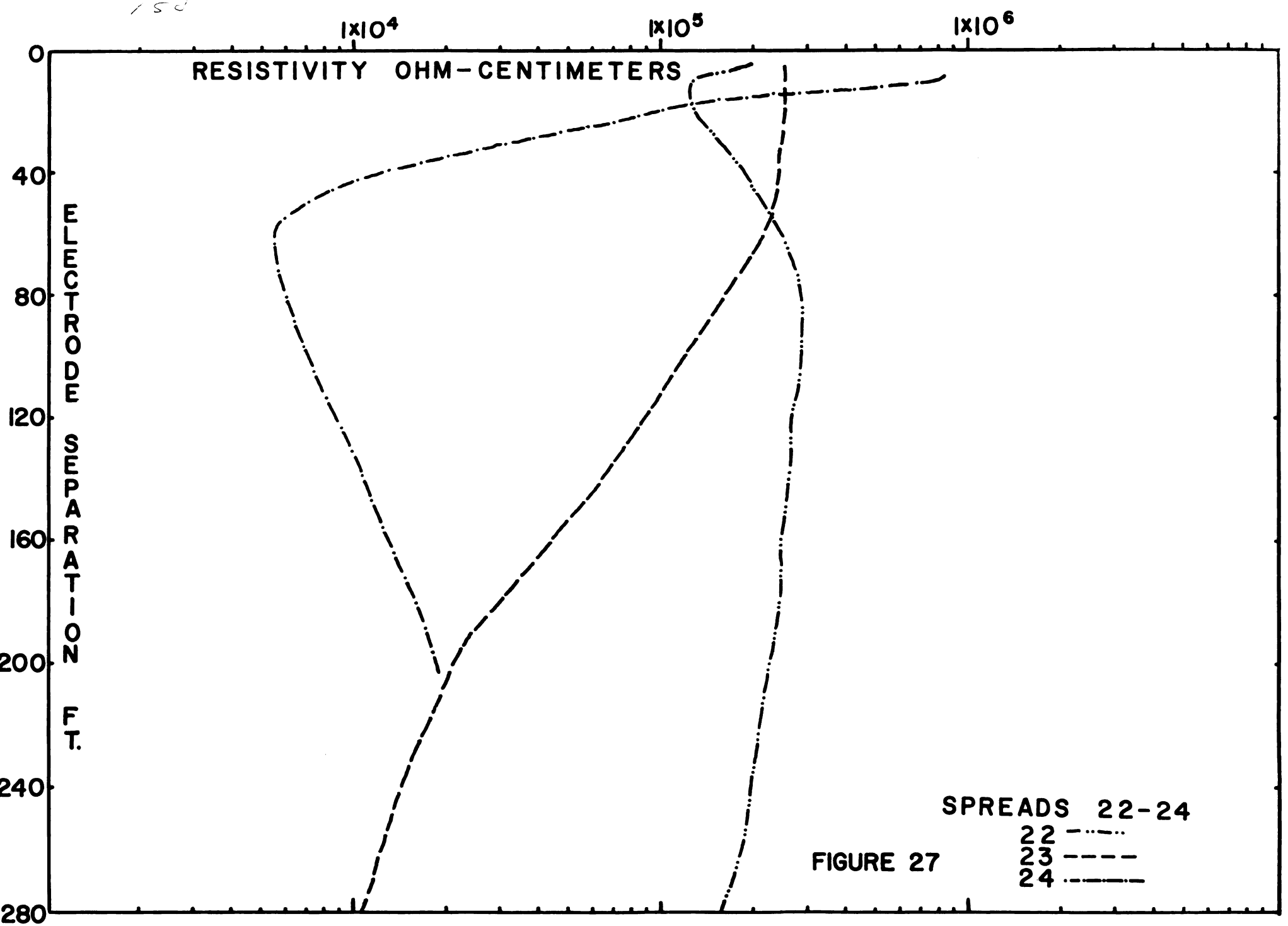

1×10⁴
1×10⁵
1×10⁶
RESISTIVITY OHM-CENTIMETERS
0
40
80
120
160
200
240
280
ELECTRODE SEPARATION FT.
SPREADS 22-24
22
23
24

FIGURE 27

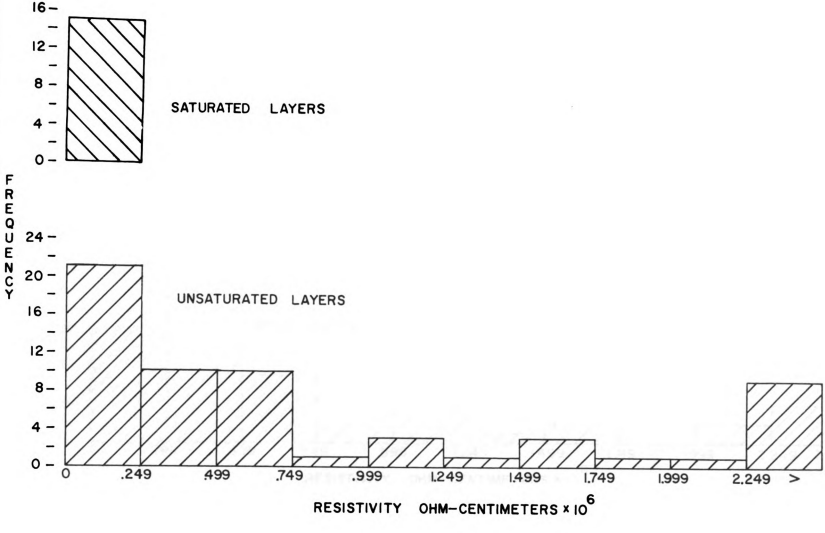


FIGURE 29 LAYER RESISTIVITIES BY MOONEY & WETZEL CURVES

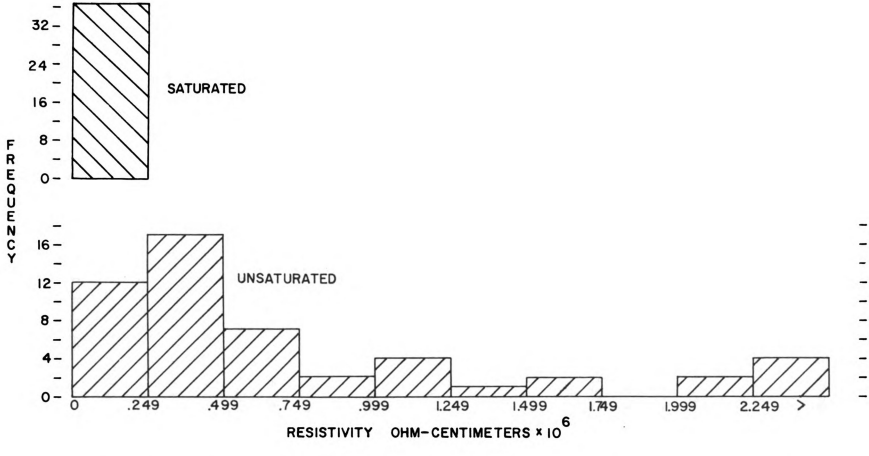


FIGURE 30 LAYER RESISTIVITIES BY BARNES LAYER METHOD

layer resistivities obtained with the Mooney and Wetzel theoretical curves and the Barnes' Layer method respectively. In both cases, saturated layers have resistivities of less than 250,000 ohm-centimeters. The unsaturated layers display a considerably greater range.

The differentiation of the saturated and unsaturated resistivities was based upon the interpretation of the data guided by results from the seismic method and well data.

Figure 31 is a histogram of layer resistivities constructed by dividing the first interval of Figure 29 into subintervals of 25,000 ohm-centimeters. All of the saturated resistivities except one zone are confined to an interval of 75,000 ohm-centimeters or less. A significant portion of the unsaturated layers also have a resistivity of less than 75,000 ohm-centimeters.

A similar situation pertains to the layer resistivities obtained with the Barnes' Layer method. The result of dividing the first interval of Figure 30 into subintervals of 25,000 ohm-centimeters is shown in Figure 32. The majority of the saturated resistivities are less than 75,000 ohm-centimeters. All of the resistivities less than 25,000 ohm-centimeters fall in this category.

The detection of the clay layers, and hence the determination of characteristic electrical resistivities of these layers, generally was not possible. The limited thickness in relation to the depth of these layers is believed to be responsible for this condition.

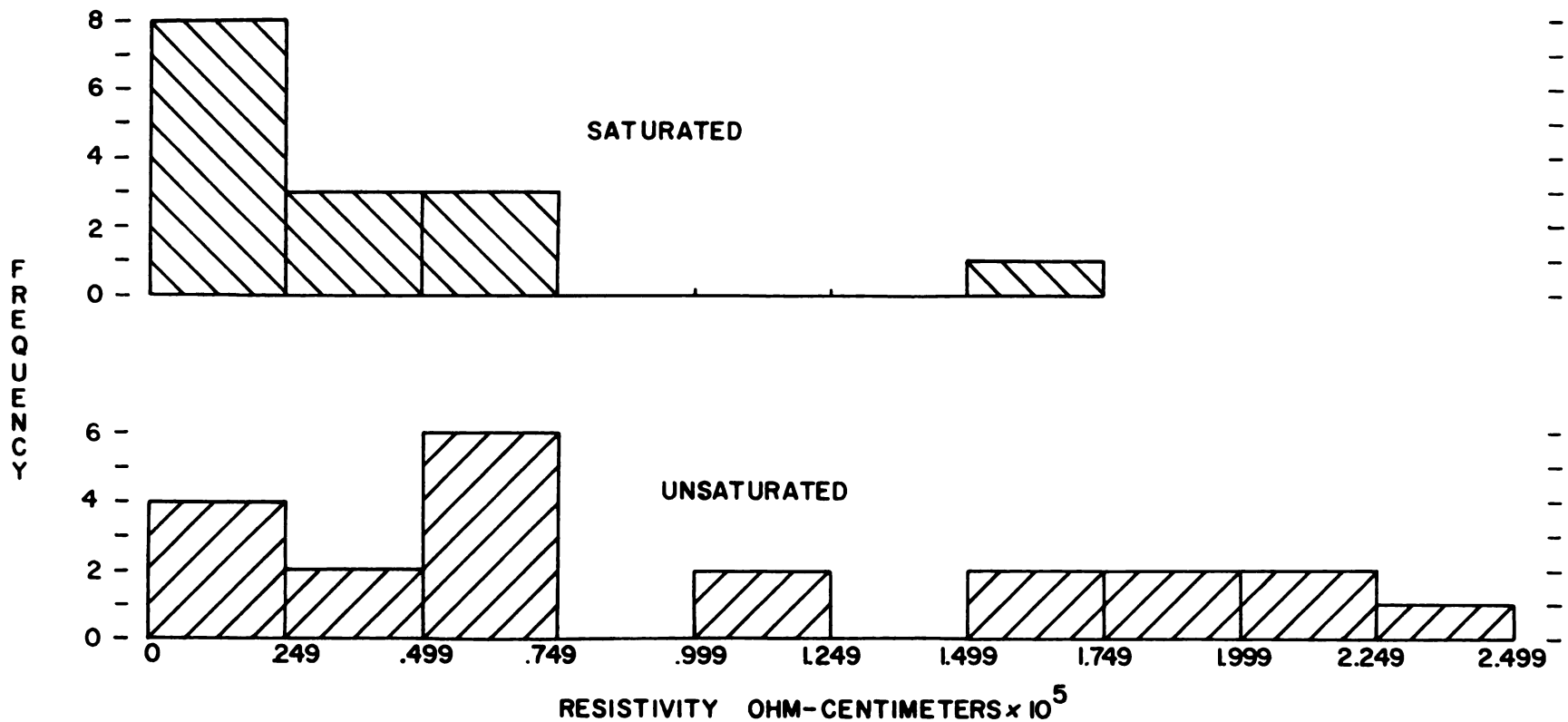


FIGURE 31 LAYER RESISTIVITIES BY MOONEY & WETZEL CURVES

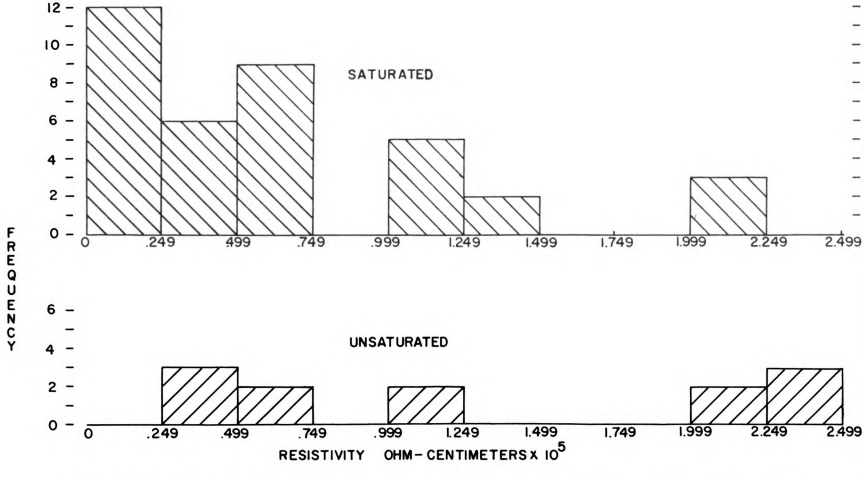


FIGURE 32 LAYER RESISTIVITIES BY BARNES LAYER METHOD

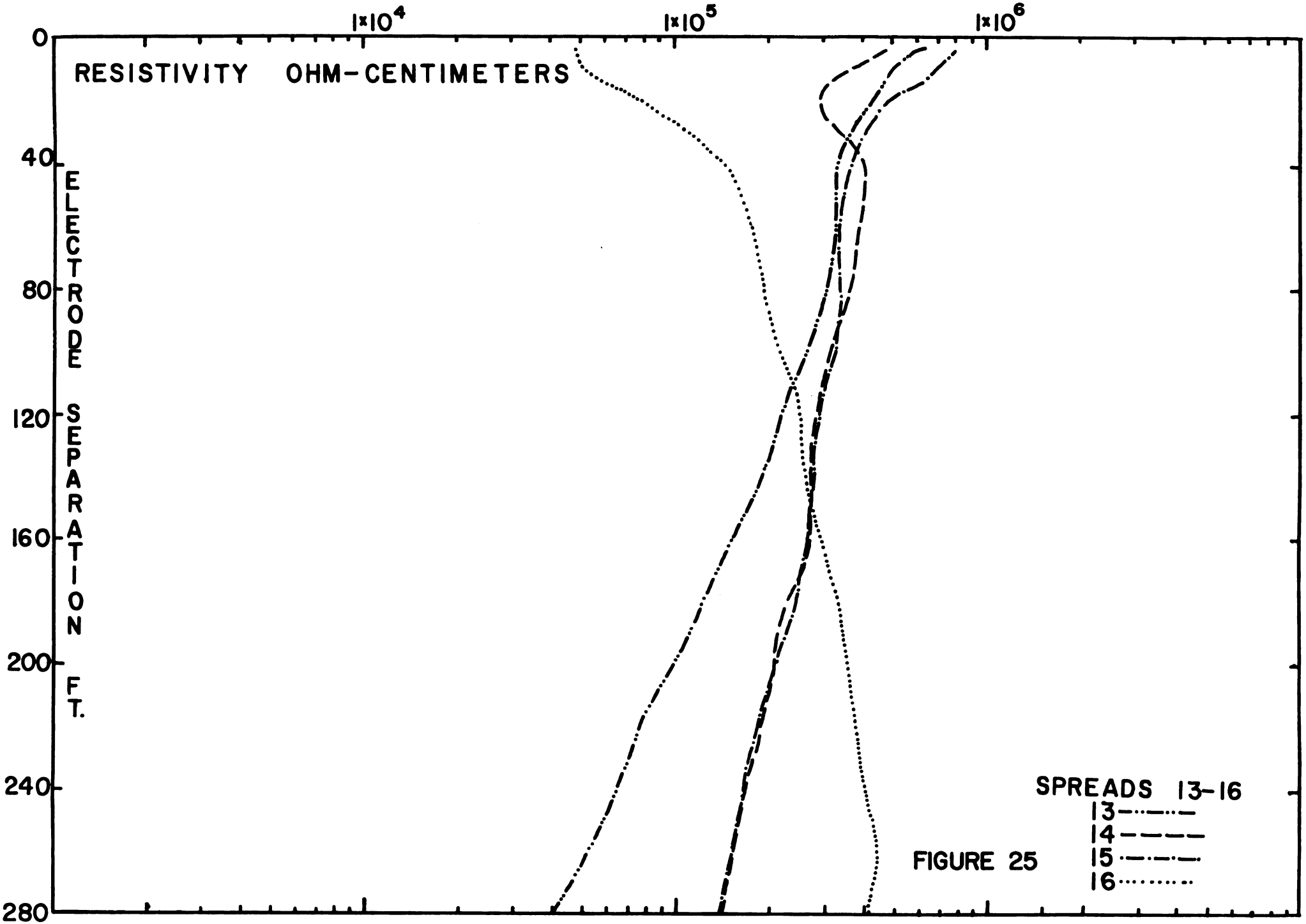

RESISTIVITY OHM-CENTIMETERS
1×10^4
1×10^5
1×10^6
ELECTRODE SEPARATION FT.
0
40
80
120
160
200
240
280
SPREADS 13-16
13
14
15
16

FIGURE 25

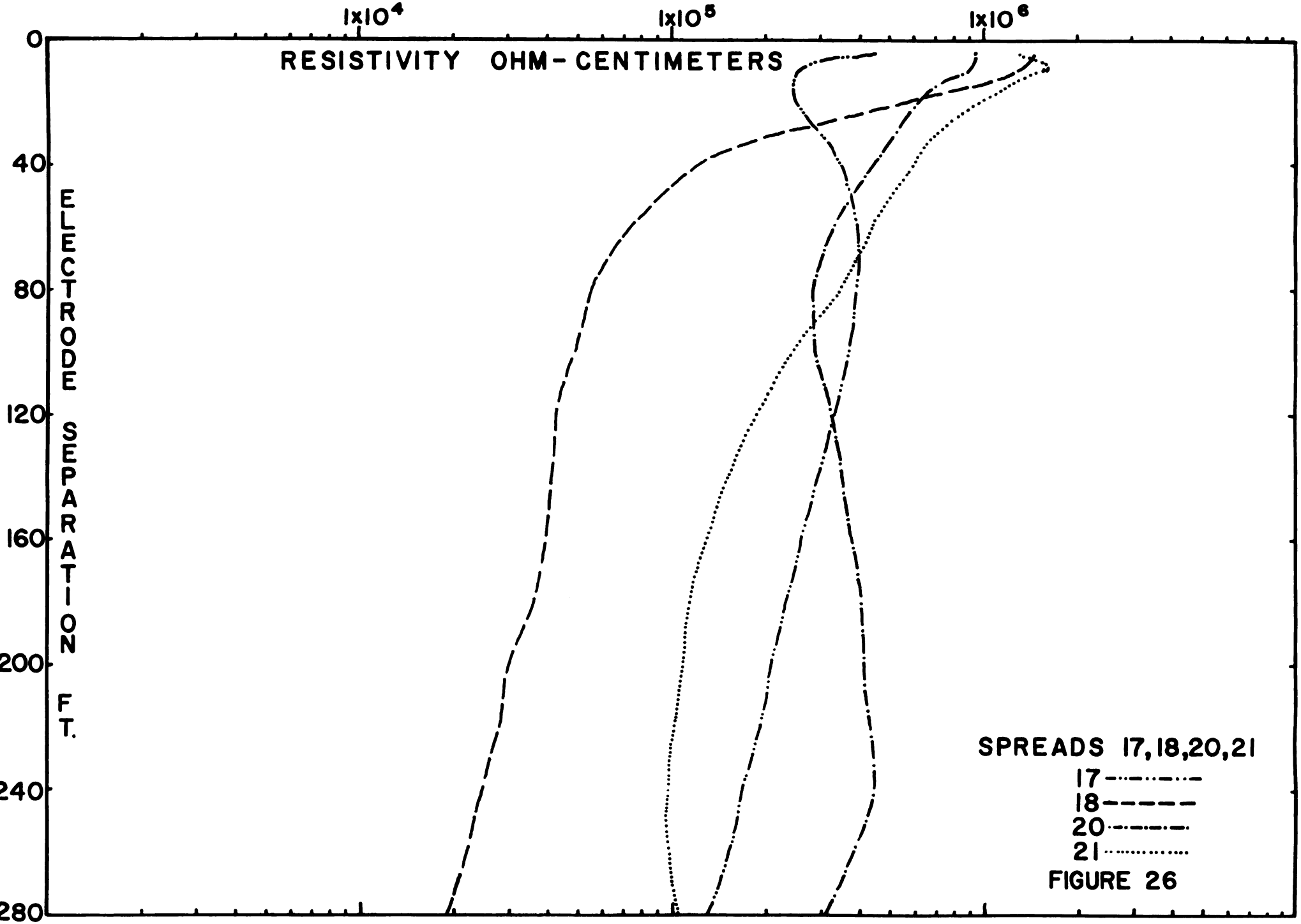

1x10⁴
1x10⁵
1x10⁶
RESISTIVITY OHM-CENTIMETERS
ELECTRODE SEPARATION FT.
0
40
80
120
160
200
240
280
SPREADS 17,18,20,21
17
18
20
21

FIGURE 26

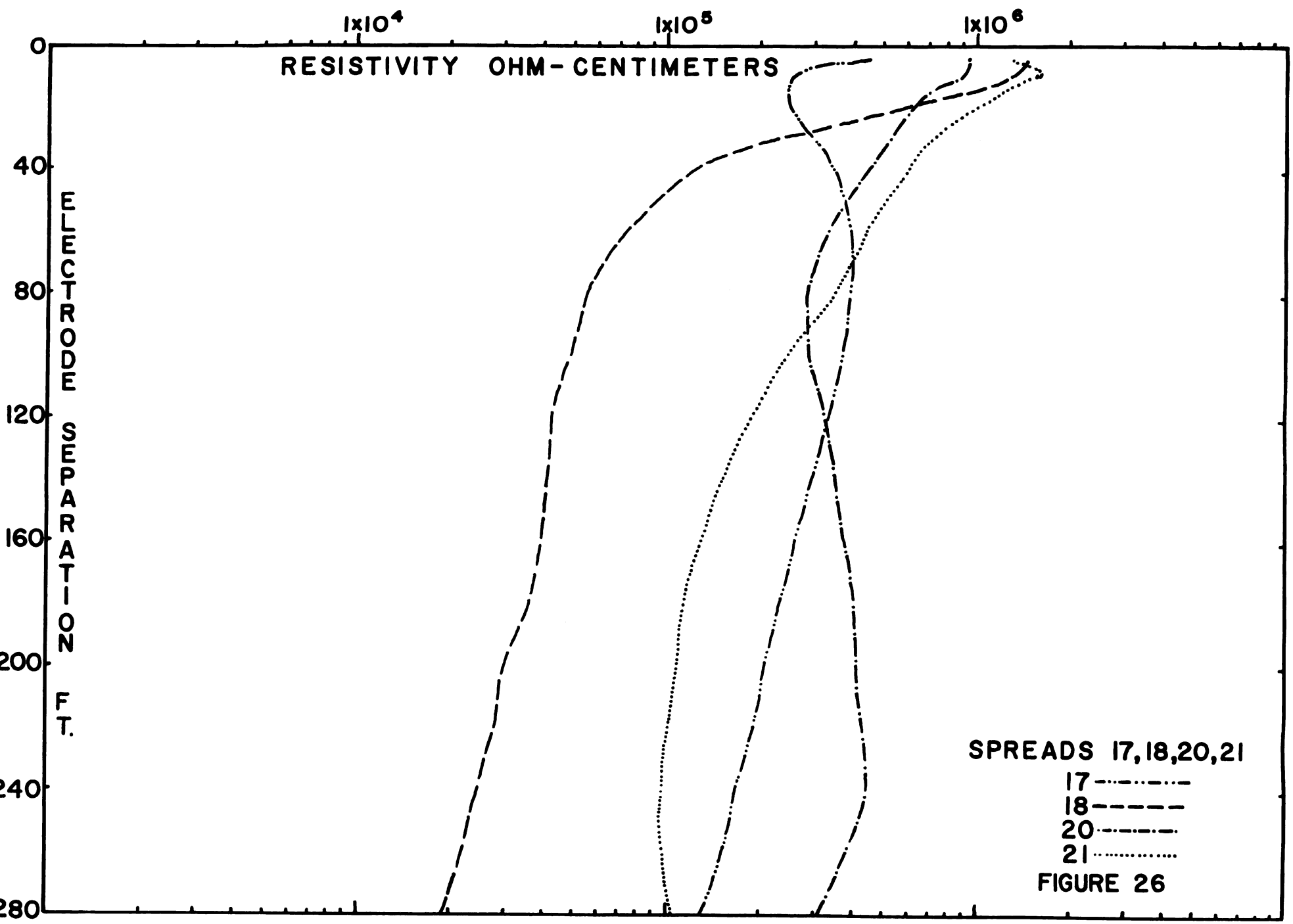

1x10⁴
1x10⁵
1x10⁶
RESISTIVITY OHM-CENTIMETERS
0
40
80
120
160
200
240
280
ELECTRODE SEPARATION FT.
SPREADS 17,18,20,21
17
18
20
21

FIGURE 26

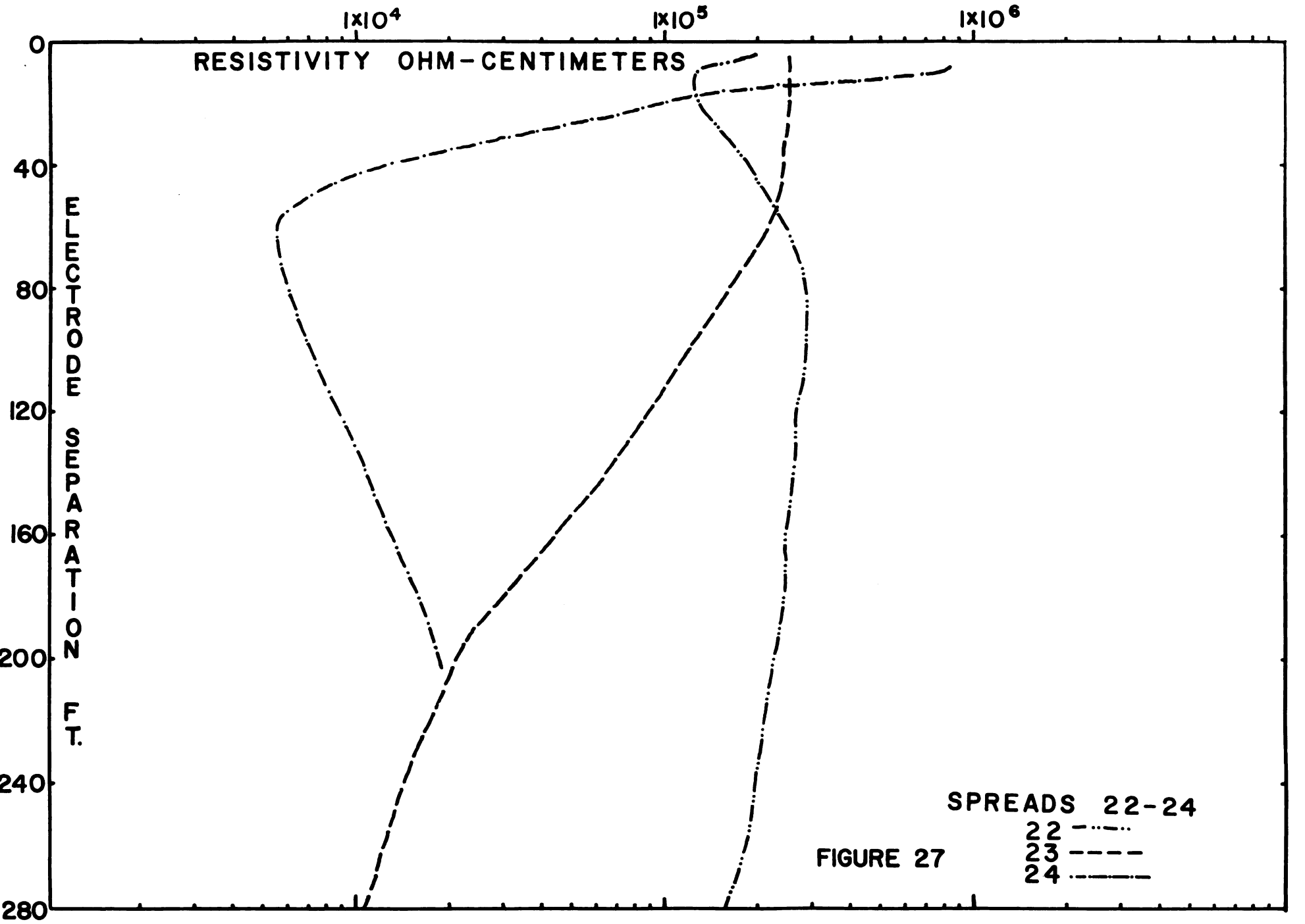
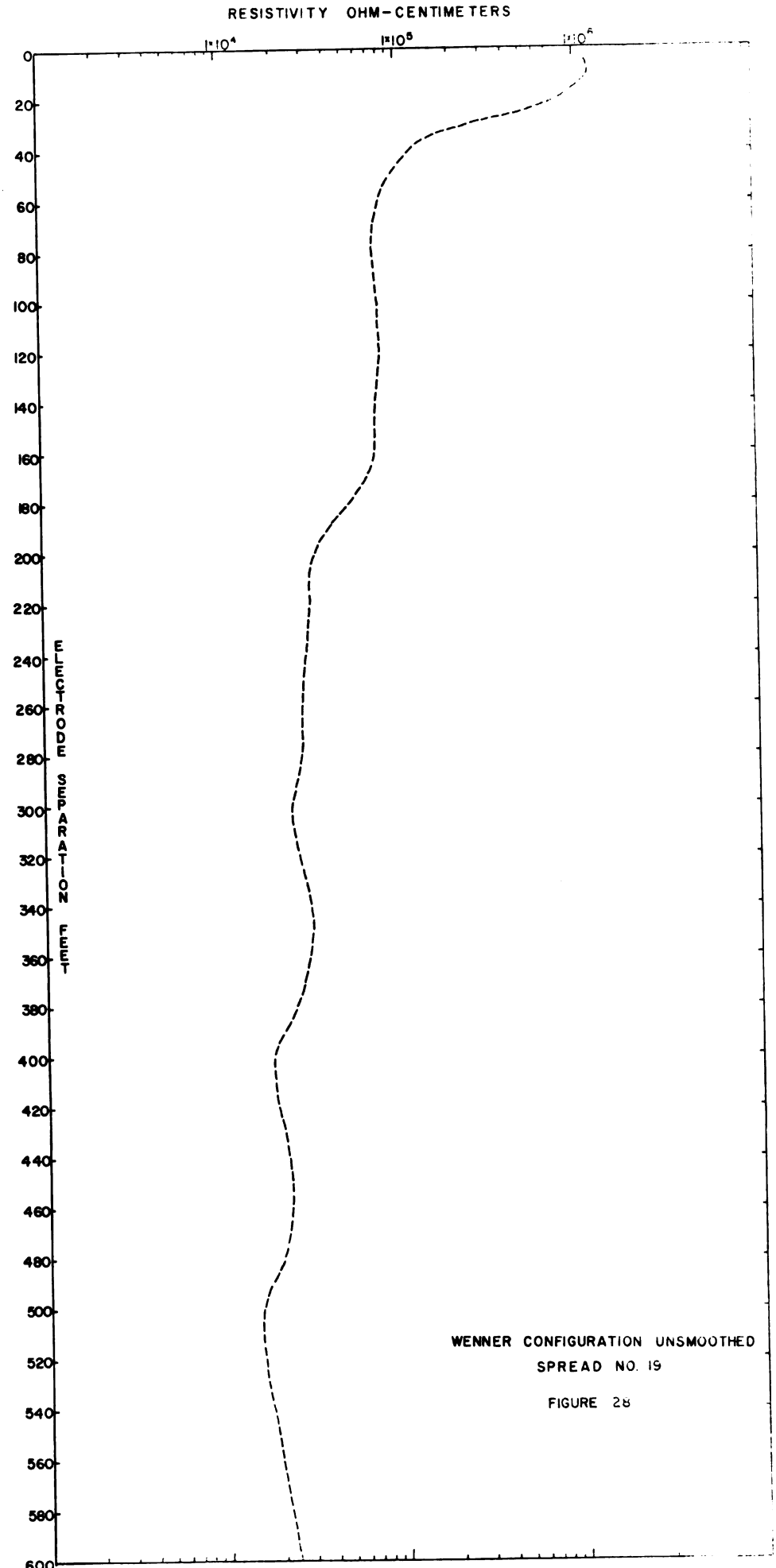

1x10^4
1x10^5
1x10^6
RESISTIVITY OHM-CENTIMETERS
0
40
80
120
160
200
240
280
ELECTRODE SEPARATION FT.
SPREADS 22-24
22
23
24

FIGURE 27



WENNER CONFIGURATION UNSMOOTHED
SPREAD NO. 19

FIGURE 28

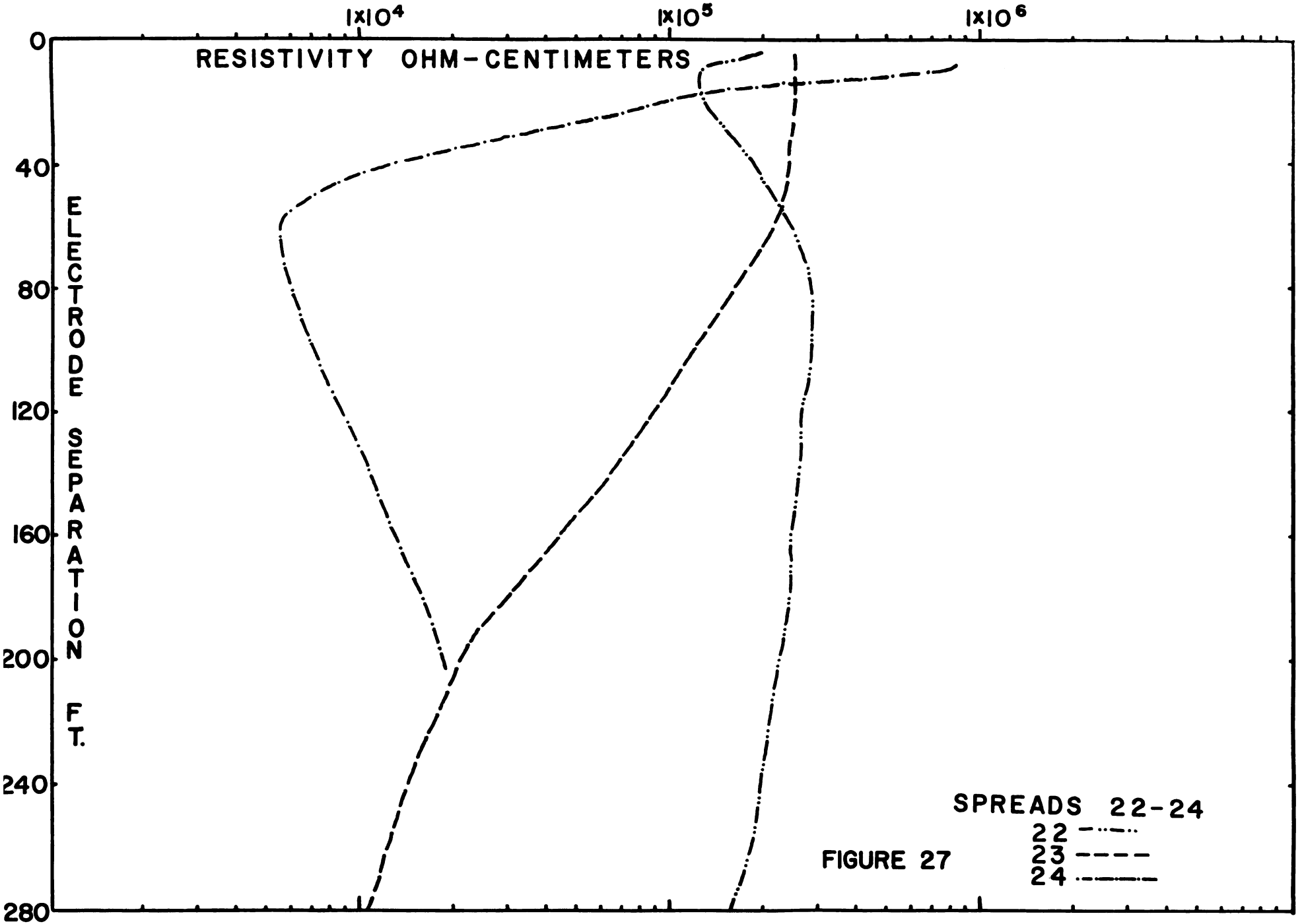


FIGURE 27

p 52 Fig 28 p 53.

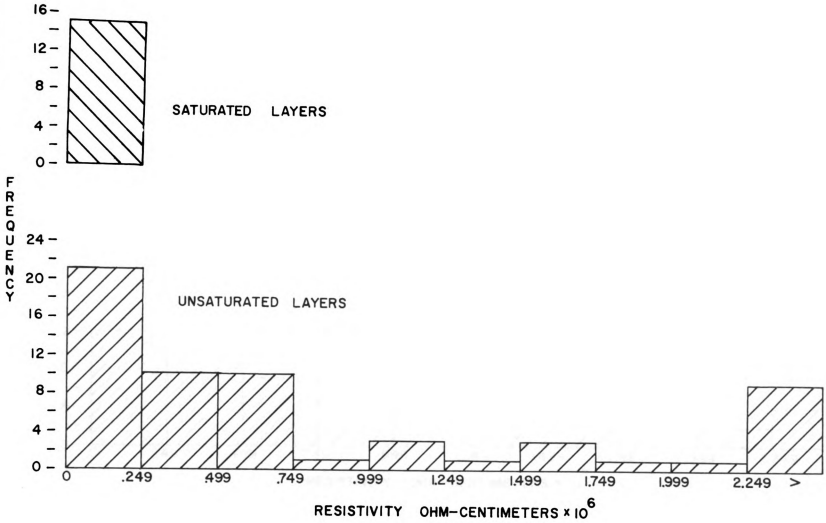


FIGURE 29 LAYER RESISTIVITIES BY MOONEY & WETZEL CURVES

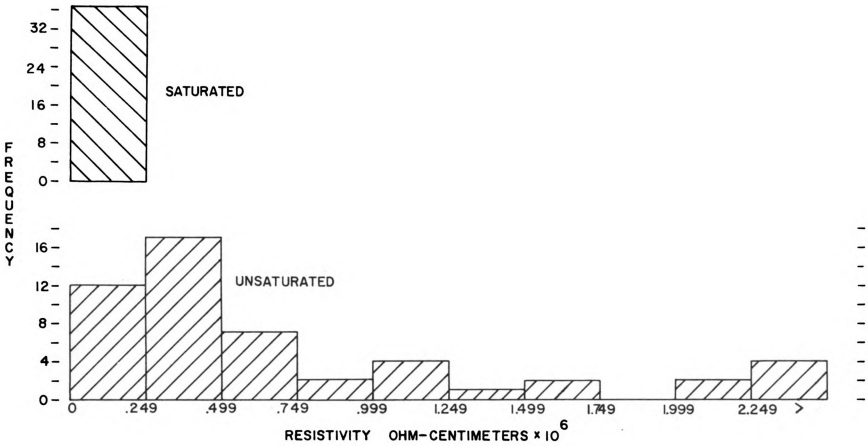


FIGURE 30 LAYER RESISTIVITIES BY BARNES LAYER METHOD

layer resistivities obtained with the Mooney and Wetzel theoretical curves and the Barnes' Layer method respectively. In both cases, saturated layers have resistivities of less than 250,000 ohm-centimeters. The unsaturated layers display a considerably greater range.

The differentiation of the saturated and unsaturated resistivities was based upon the interpretation of the data guided by results from the seismic method and well data.

Figure 31 is a histogram of layer resistivities constructed by dividing the first interval of Figure 29 into subintervals of 25,000 ohm-centimeters. All of the saturated resistivities except one zone are confined to an interval of 75,000 ohm-centimeters or less. A significant portion of the unsaturated layers also have a resistivity of less than 75,000 ohm-centimeters.

A similar situation pertains to the layer resistivities obtained with the Barnes' Layer method. The result of dividing the first interval of Figure 30 into subintervals of 25,000 ohm-centimeters is shown in Figure 32. The majority of the saturated resistivities are less than 75,000 ohm-centimeters. All of the resistivities less than 25,000 ohm-centimeters fall in this category.

The detection of the clay layers, and hence the determination of characteristic electrical resistivities of these layers, generally was not possible. The limited thickness in relation to the depth of these layers is believed to be responsible for this condition.

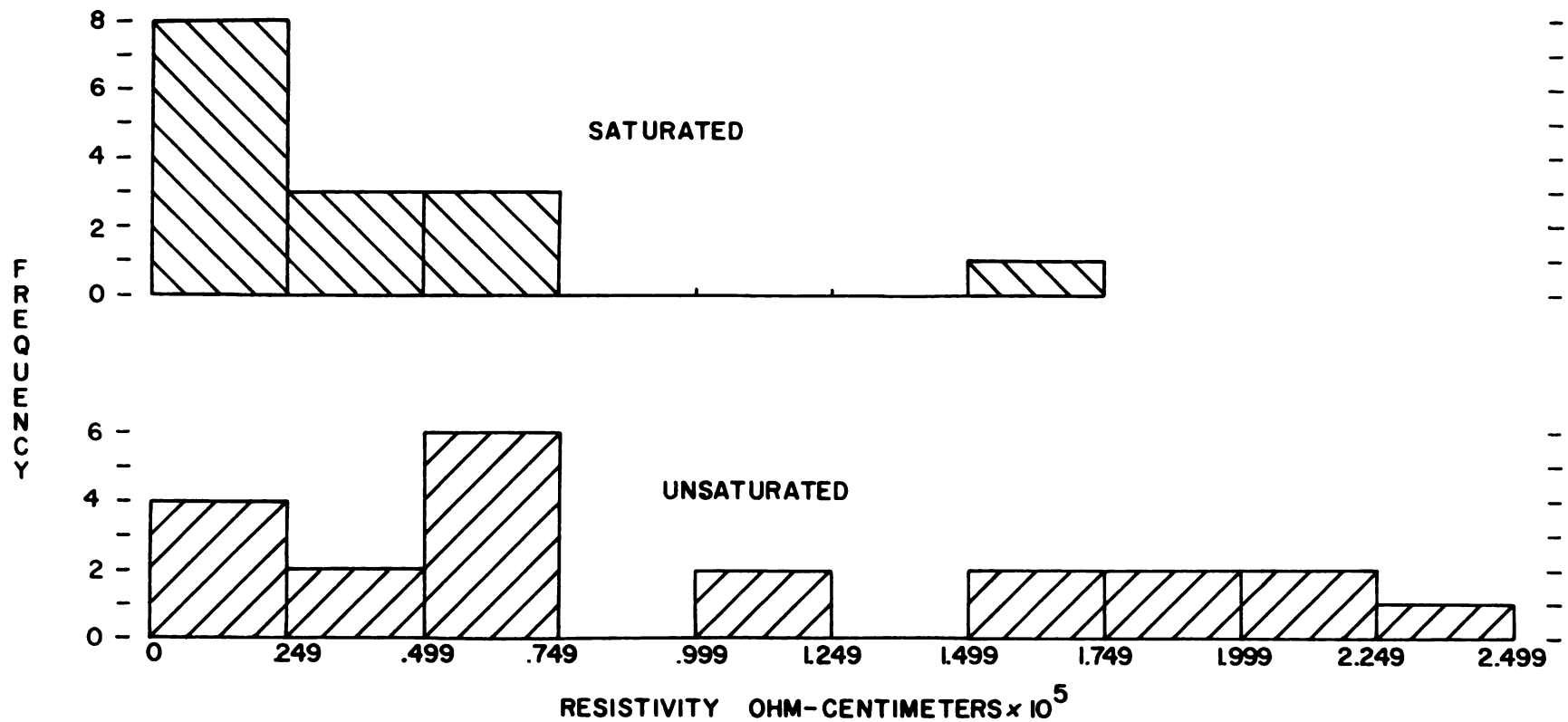


FIGURE 31 LAYER RESISTIVITIES BY MOONEY & WETZEL CURVES

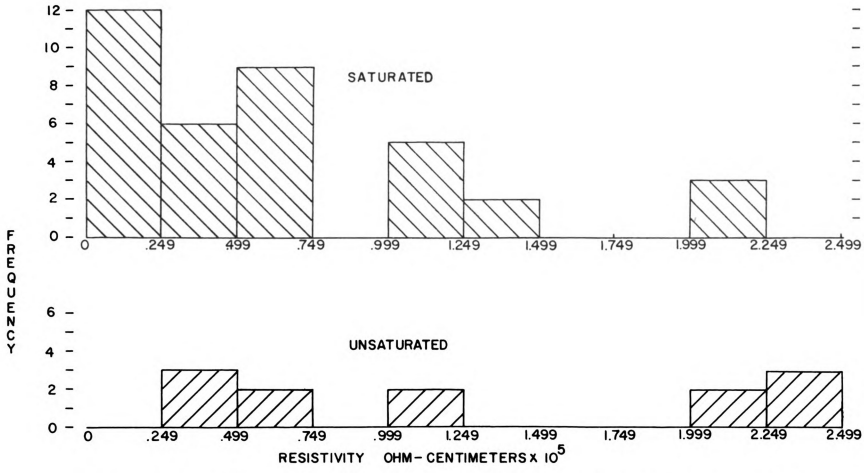


FIGURE 32 LAYER RESISTIVITIES BY BARNES LAYER METHOD

Depth to Water Table

Figure 33 is a contour map of the water table prepared from the results of the resistivity method, together with well data. The map is constructed on the basis of the interpretation of the data as guided by the results of the seismic method and well control information. All of the methods of interpretation were used in preparing this map. However, the Barnes' Layer method was used most frequently because the results from this method were more compatible with seismic and well control data.

A ground water mound is centered in section 23. This mound and the small depression in the western portion of section 24 are similar to features previously noted on the seismic map. The ground water mound has a total relief of about 80 feet over the area of study.

Figure 34 is a fence diagram, isometrically projected N 45° W and constructed from the same results as those used for the contour map of the water table. The datum and symbols used in this figure are the same as those employed in the seismic fence diagram.

The ground water mound is apparent from an examination of the diagram. In other areas, the water table generally follows the relief of the surface elevation.

Analysis of Errors

An analysis of the error between the predicted and calculated depths obtained from resistivity mapping is

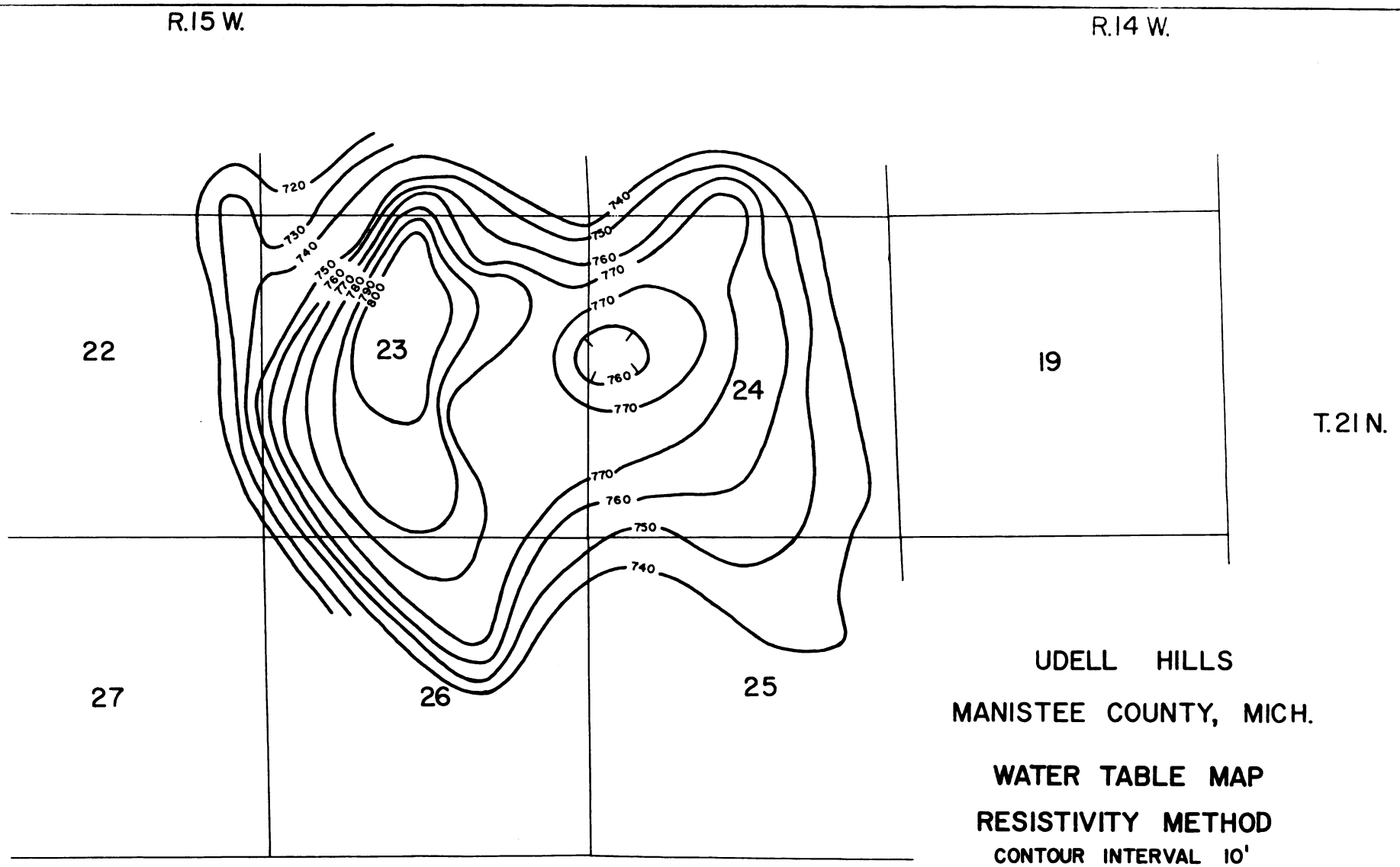

R.15 W.
R.14 W.
T.21 N.
22
23
24
19
27
26
25
720
730
740
750
760
770
780
790
800
740
750
760
770
770
760
770
770
760
750
740
UDELL HILLS
MANISTEE COUNTY, MICH.
WATER TABLE MAP
RESISTIVITY METHOD
CONTOUR INTERVAL 10'
0
1000'
2000'
3000'
4000'

FIGURE 33

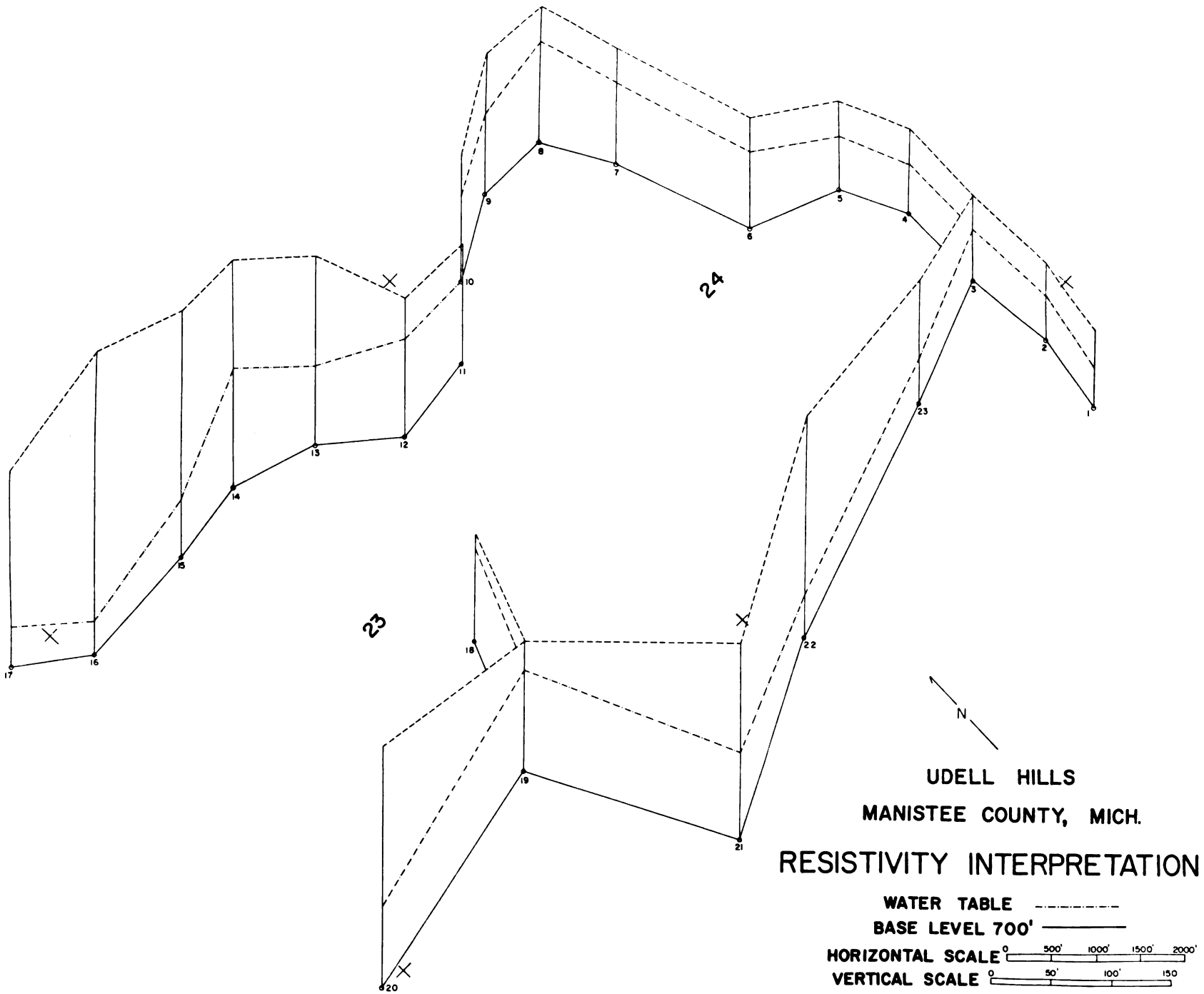

24
23
N
UDELL HILLS
MANISTEE COUNTY, MICH.
RESISTIVITY INTERPRETATION
WATER TABLE
BASE LEVEL 700'
HORIZONTAL SCALE 0 500' 1000' 1500' 2000'
VERTICAL SCALE 0 50' 100' 150
SECTION CORNERS

FIGURE 34

given in Table 1, for seven profiles adjacent to control wells. The average per cent error for the resistivity determinations is 14%. This compares favorably with the average per cent error of 10% obtained for the seismic depth determinations.

Depths obtained in resistivity surveying may be affected by a number of factors which should be considered in evaluating the accuracy of the method. First, the resistivity data are subject to uncertainties which are inherent in the subjective nature of the interpretation process. Further, as explained previously, the depth of current penetration is dependent upon the relative conductivities of the materials included in the zone of measurement. Therefore, the relationship may not be one to one between the depth of current penetration and the electrode separation. Finally, lateral variations in the conductivity near the surface may produce changes in the apparent resistivities which may be mistaken for major resistivity variations at depth.

SUMMARY OF THE INTERPRETATION

Representative Seismic Velocities and Electrical Resistivities

The seismic refraction method generally detected a two layer earth. The surface layer is composed of dry, well sorted sand, while the material beneath the surface layer is believed to consist of the same material in a water saturated state. The seismic study frequently detected a third layer in the uplands and the interior basin. This layer may be attributed to minor lithologic variations in the unsaturated layer.

Seismic velocities of the unsaturated layer, excluding intermediate velocity materials in this layer, range from 600 to 2,000 feet per second with an average velocity of 1,140 feet per second. The average velocity of the intermediate layers is 2,140 feet per second. The saturated materials range from 4,000 to 6,750 feet per second with an average velocity of 5,460 feet per second.

Three methods of interpretation were employed in the resistivity study. These included the Mooney and Wetzel curve matching method, the Moore's Cumulative method employing both 10 and 20 foot increments, and the Barnes' Layer method.

Electrical resistivities obtained from the Mooney and Wetzel and Barnes' methods of interpretation vary from

a few thousand to several million ohm-centimeters. The Mooney and Wetzel method of interpretation indicated all of the saturated layers except one have resistivities of less than 75,000 ohm-centimeters. A significant number of unsaturated layers also have resistivities confined to this range.

The Barnes' method of interpretation yielded results that are more definitive than the Mooney and Wetzel method. All resistivities less than 25,000 ohm-centimeters fall within the saturated zone. The majority of resistivities less than 75,000 ohm-centimeters also fall within this zone. Resistivities in excess of 250,000 ohm-centimeters as determined by both methods of interpretation occur within the unsaturated zone.

Thickness of the Unsaturated Overburden

The interpretation of both the seismic and resistivity data indicates a ground water mound associated with the Udell Hills. The mound is centered in section 23 and has a maximum relief of about 100 feet over the area of study. A minor depression is indicated in the northwestern quarter of section 24.

In the resistivity study, all three methods of interpretation were employed to obtain the final map. However, the Barnes' Layer method was emphasized in the final interpretation, because the results from this interpretational technique were in better agreement with the seismic results

and well control data. A series of comparison charts are presented in Figures 35 through 40, which show the results of each method of interpretation together with the seismic results in the final column.

The seismic results were found to be 10% in error when compared to well control information at five sites. The average per cent error for the resistivity interpretation at seven control well sites was 14%.

Configuration of Impermeable Clay Layers

The geophysical methods employed in this study were unsuccessful in detecting the clay layers that are known to exist in this area from drill hole information. This failure can be attributed to the limited resolving power of the seismic and resistivity methods in detecting layers of limited thickness. The resolving power of these methods is a function of the ratio of the thickness of the layer to its depth beneath the surface. In the Udell Hills, this ratio is too small to permit detection of the clay layers.

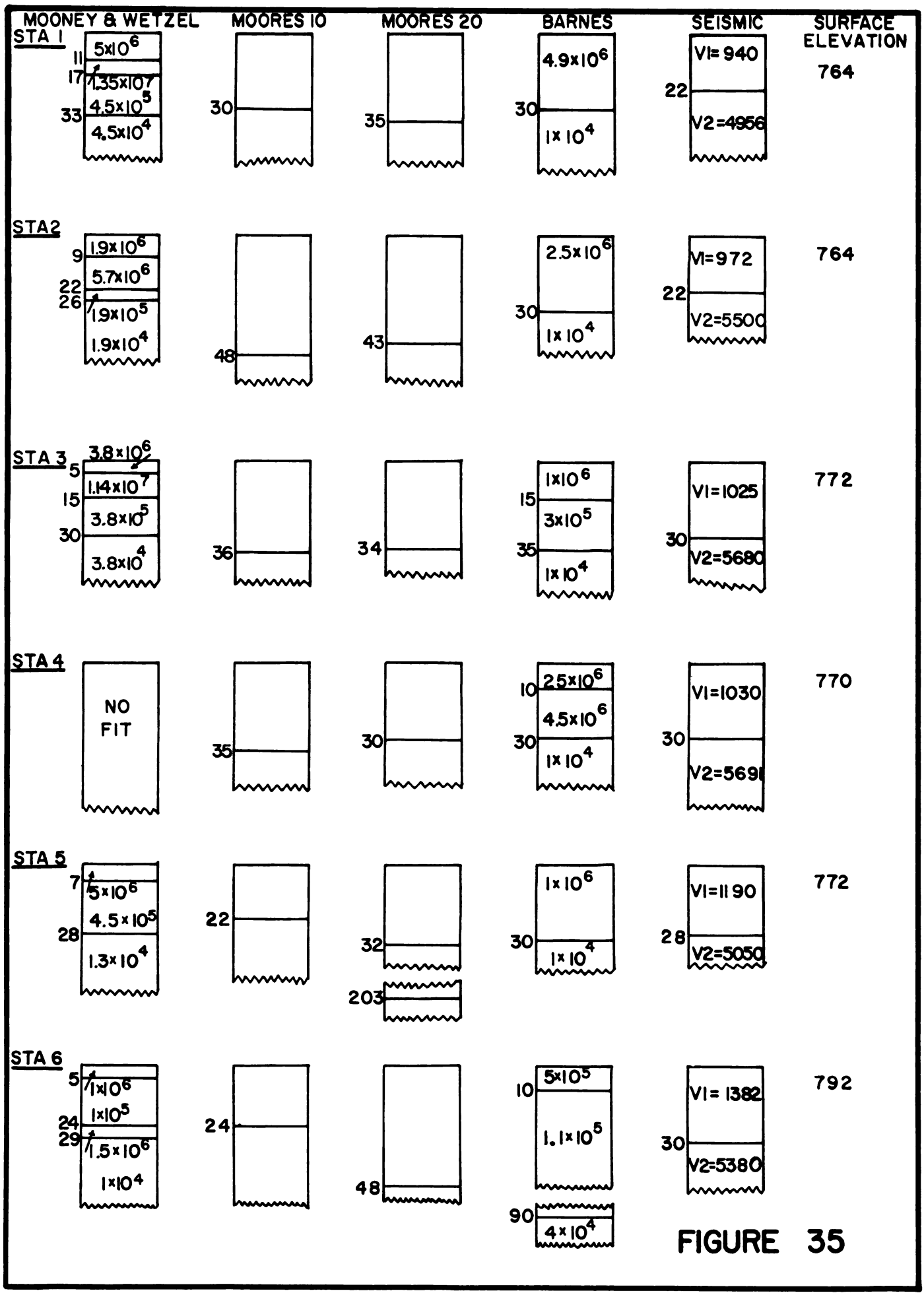

MOONEY & WETZEL
MOORES 10
MOORES 20
BARNES
SEISMIC
SURFACE ELEVATION
STA 1
11
17
33
5x10^6
1.35x10^7
4.5x10^5
4.5x10^4
30
35
4.9x10^6
30
1x10^4
22
V1= 940
V2=4956
764
STA 2
9
22
26
1.9x10^6
5.7x10^6
1.9x10^5
1.9x10^4
48
43
2.5x10^6
30
1x10^4
22
V1=972
V2=5500
764
STA 3
5
15
30
3.8x10^6
1.14x10^7
3.8x10^5
3.8x10^4
36
34
15
1x10^6
3x10^5
35
1x10^4
30
V1=1025
V2=5680
772
STA 4
NO FIT
35
30
10
2.5x10^6
4.5x10^6
30
1x10^4
30
V1=1030
V2=5691
770
STA 5
7
28
5x10^6
4.5x10^5
1.3x10^4
22
32
203
1x10^6
30
1x10^4
28
V1=1190
V2=5050
772
STA 6
5
24
29
1x10^6
1x10^5
1.5x10^6
1x10^4
24
48
10
5x10^5
1.1x10^5
90
4x10^4
30
V1= 1382
V2=5380
792

FIGURE 35

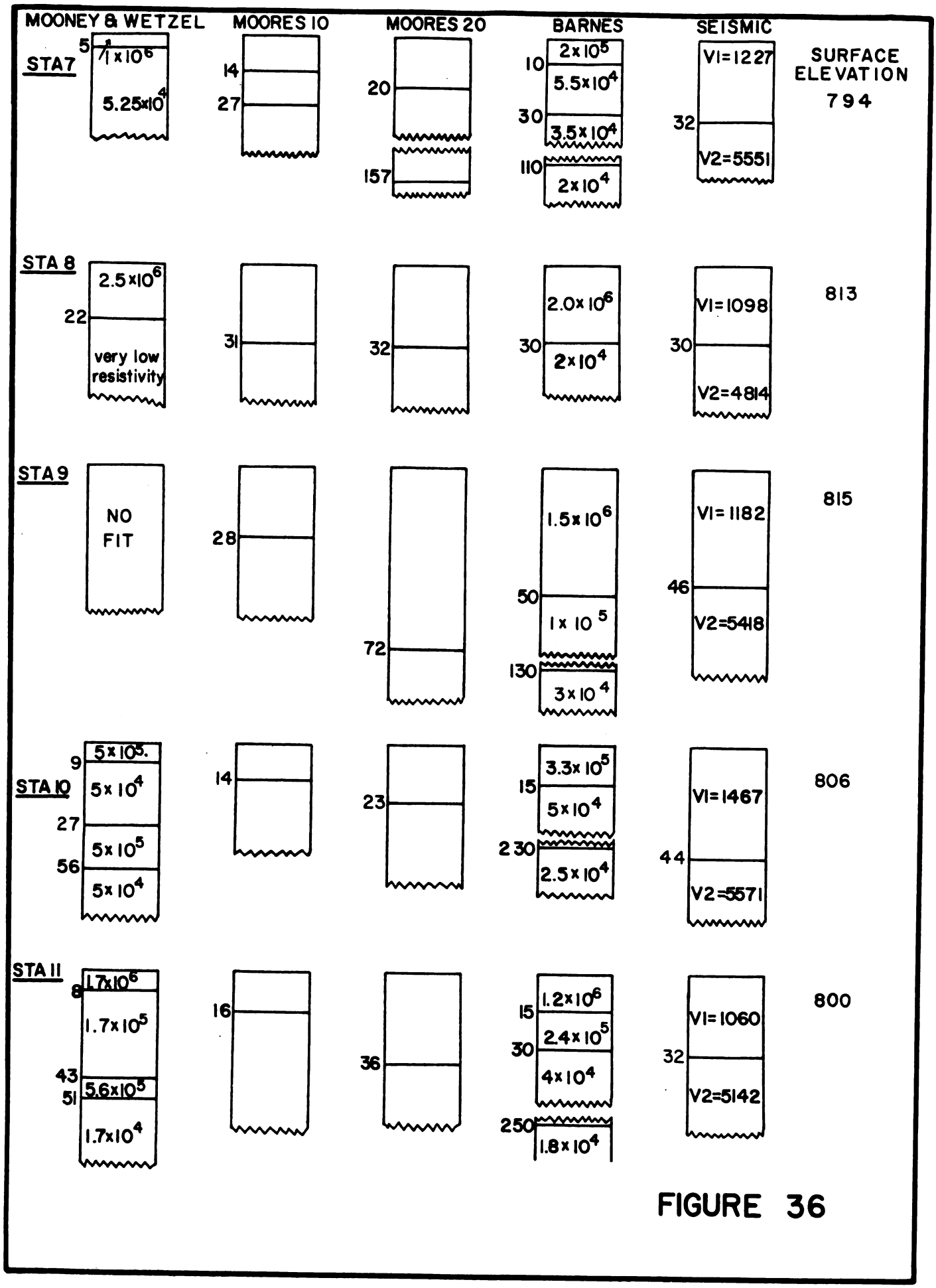

MOONEY & WETZEL
MOORES 10
MOORES 20
BARNES
SEISMIC
SURFACE ELEVATION
STA 7
5
1 x 10^6
5.25x10^4
14
27
20
157
10
2x10^5
5.5x10^4
30
3.5x10^4
110
2x10^4
V1=1227
32
V2=5551
794
STA 8
2.5x10^6
22
very low resistivity
31
32
2.0x10^6
30
2x10^4
V1=1098
30
V2=4814
813
STA 9
NO FIT
28
72
1.5x10^6
50
1x10^5
130
3x10^4
V1=1182
46
V2=5418
815
STA 10
9
5x10^5.
5x10^4
27
5x10^5
56
5x10^4
14
23
15
3.3x10^5
5x10^4
230
2.5x10^4
V1=1467
44
V2=5571
806
STA 11
8
1.7x10^6
1.7x10^5
43
51
5.6x10^5
1.7x10^4
16
36
15
1.2x10^6
30
2.4x10^5
4x10^4
250
1.8x10^4
V1=1060
32
V2=5142
800

FIGURE 36

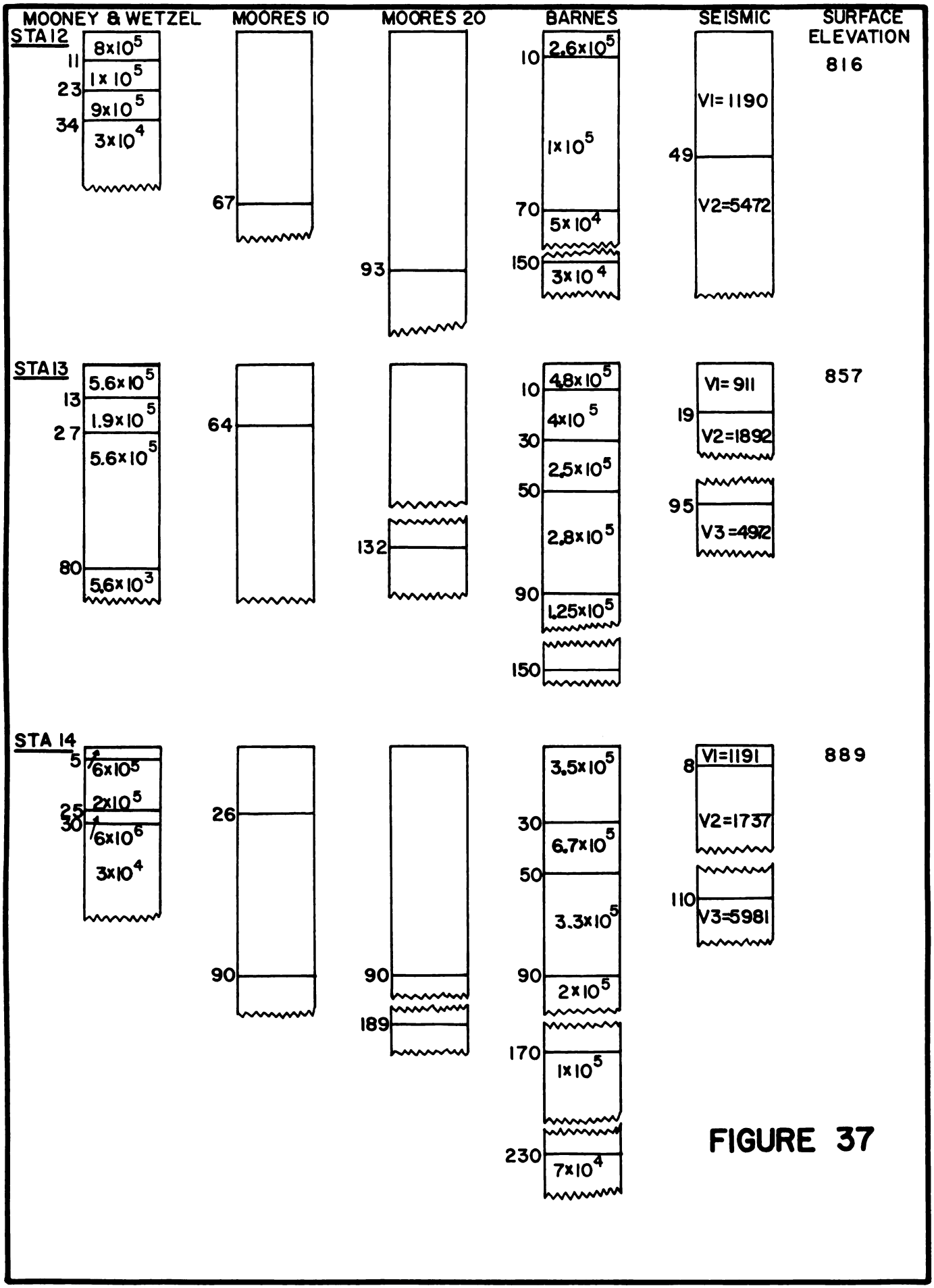

MOONEY & WETZEL
MOORES 10
MOORES 20
BARNES
SEISMIC
SURFACE ELEVATION
STA 12
8x10^5
11
1x10^5
23
9x10^5
34
3x10^4
67
93
2.6x10^5
10
1x10^5
70
5x10^4
150
3x10^4
V1= 1190
49
V2=5472
816
STA 13
5.6x10^5
13
1.9x10^5
27
5.6x10^5
80
5.6x10^3
64
132
4.8x10^5
10
4x10^5
30
2.5x10^5
50
2.8x10^5
90
1.25x10^5
150
V1= 911
19
V2=1892
95
V3=4972
857
STA 14
5
6x10^5
25
2x10^5
30
6x10^6
3x10^4
26
90
90
189
3.5x10^5
30
6.7x10^5
50
3.3x10^5
90
2x10^5
170
1x10^5
230
7x10^4
V1=1191
8
V2=1737
110
V3=5981
889

FIGURE 37

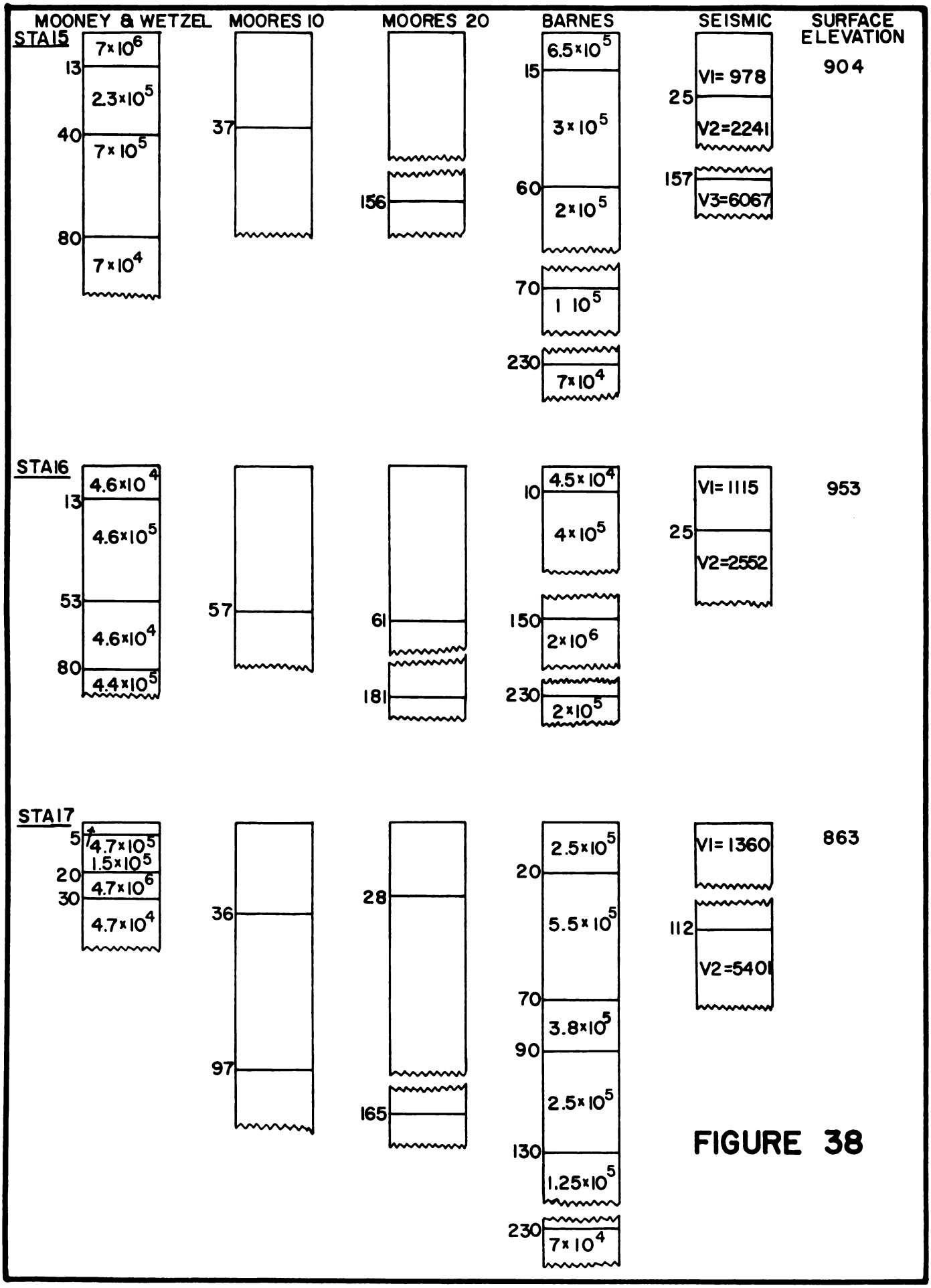

MOONEY & WETZEL
MOORES 10
MOORES 20
BARNES
SEISMIC
SURFACE ELEVATION
STA15
7×10^6
13
2.3×10^5
40
7×10^5
80
7×10^4
37
156
6.5×10^5
15
3×10^5
60
2×10^5
70
1 10^5
230
7×10^4
V1= 978
25
V2=2241
157
V3=6067
904
STA16
4.6×10^4
13
4.6×10^5
53
4.6×10^4
80
4.4×10^5
57
61
181
4.5×10^4
10
4×10^5
150
2×10^6
230
2×10^5
V1= 1115
25
V2=2552
953
STA17
5
4.7×10^5
1.5×10^5
20
4.7×10^6
30
4.7×10^4
36
97
28
165
2.5×10^5
20
5.5×10^5
70
3.8×10^5
90
2.5×10^5
130
1.25×10^5
230
7×10^4
V1= 1360
112
V2=5401
863

FIGURE 38

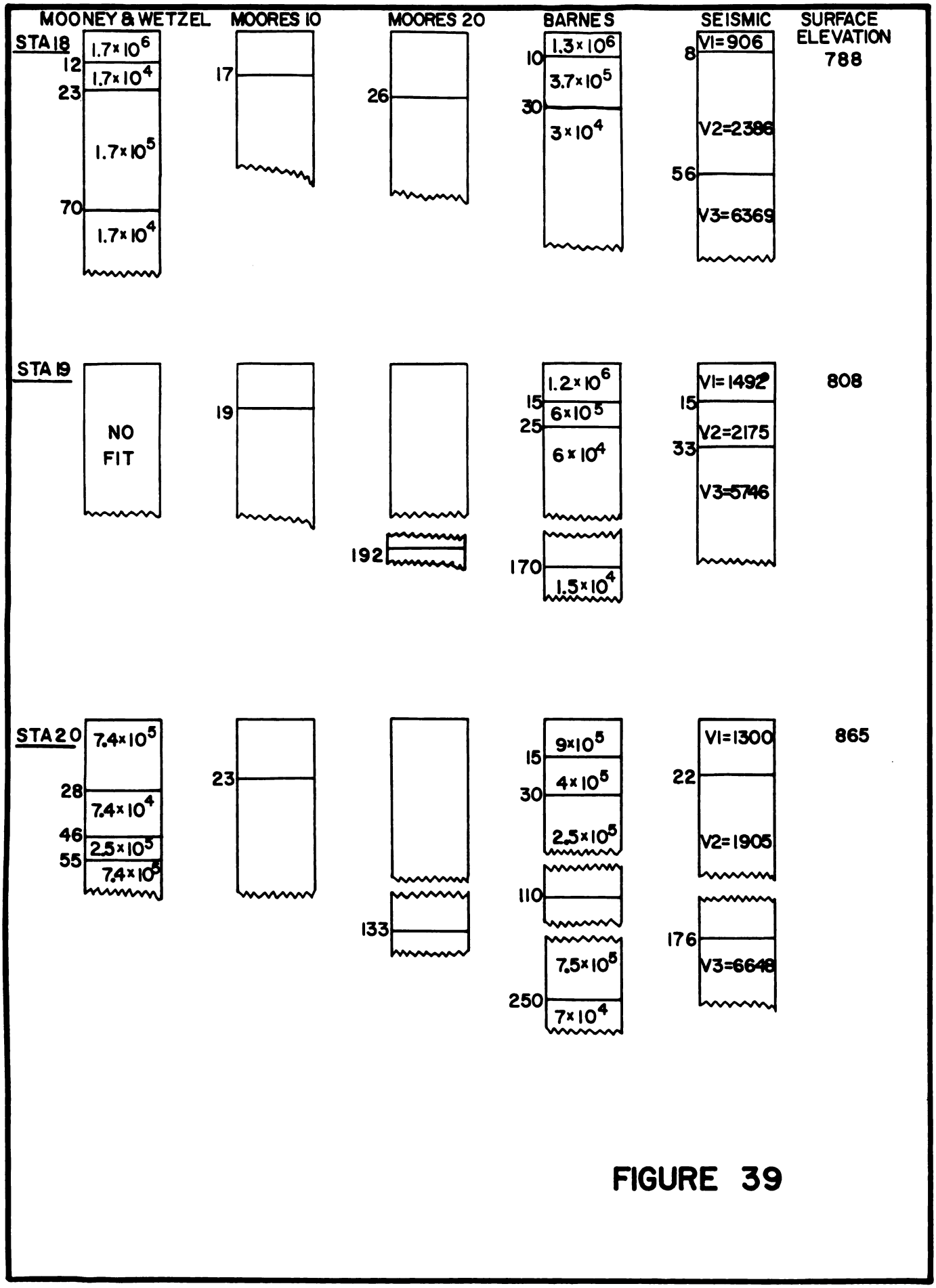

MOONEY & WETZEL
MOORES 10
MOORES 20
BARNES
SEISMIC
SURFACE ELEVATION
STA 18
1.7×10^6
12
1.7×10^4
23
1.7×10^5
70
1.7×10^4
17
26
1.3×10^6
10
3.7×10^5
30
3×10^4
8
V1=906
V2=2386
56
V3=6369
788
STA 19
NO FIT
19
192
1.2×10^6
15
6×10^5
25
6×10^4
170
1.5×10^4
V1=1492
15
V2=2175
33
V3=5746
808
STA 20
7.4×10^5
28
7.4×10^4
46
2.5×10^5
55
7.4×10^5
23
133
9×10^5
15
4×10^5
30
2.5×10^5
110
7.5×10^5
250
7×10^4
V1=1300
22
V2=1905
176
V3=6648
865

FIGURE 39

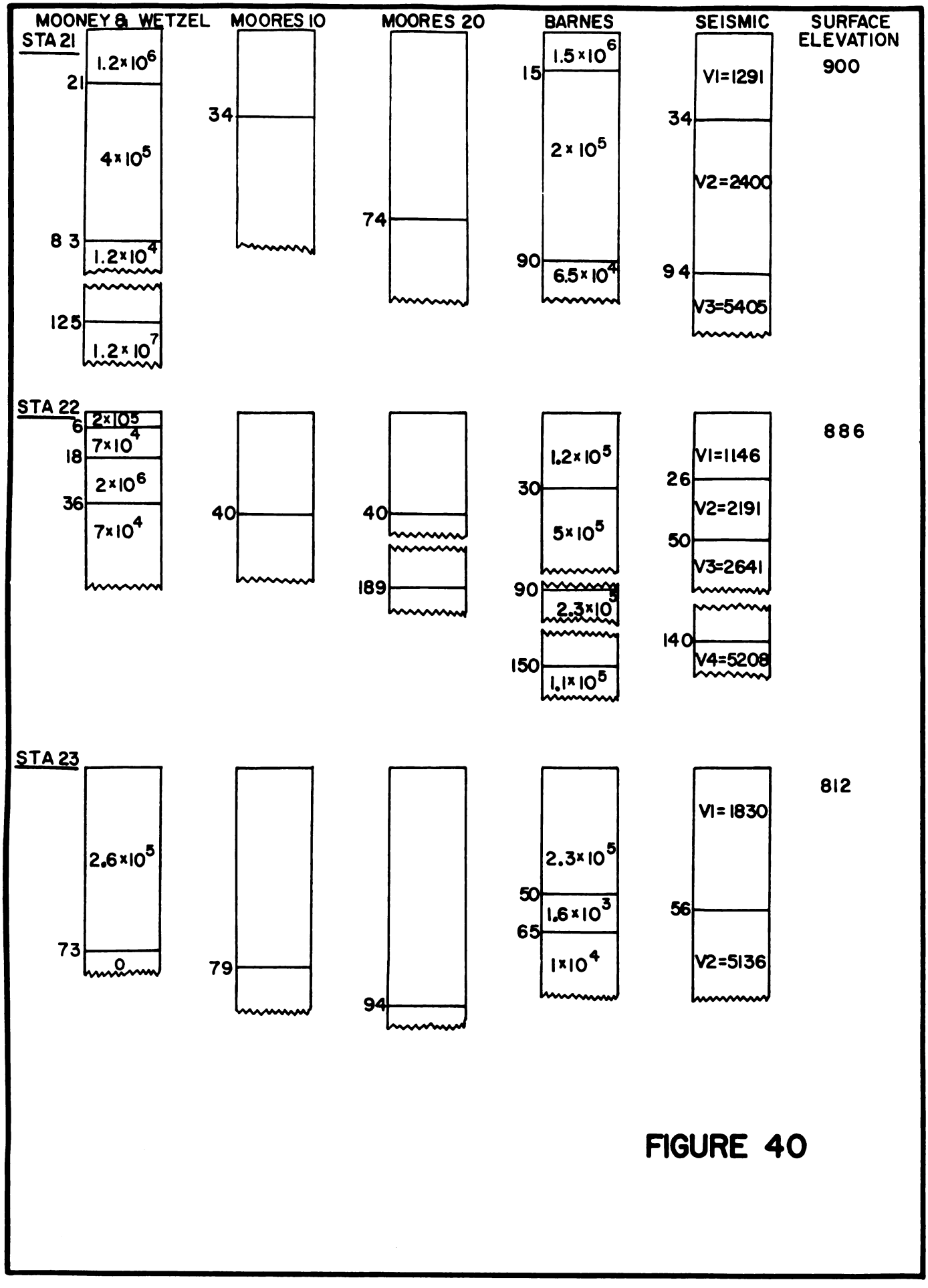

MOONEY & WETZEL
MOORES 10
MOORES 20
BARNES
SEISMIC
SURFACE ELEVATION
STA 21
1.2×10^6
21
4×10^5
8 3
1.2×10^4
125
1.2×10^7
34
74
1.5×10^6
15
2×10^5
90
6.5×10^4
V1=1291
34
V2=2400
94
V3=5405
900
STA 22
6
2×10^5
7×10^4
18
2×10^6
36
7×10^4
40
40
189
1.2×10^5
30
5×10^5
90
2.3×10^5
150
1.1×10^5
V1=1146
26
V2=2191
50
V3=2641
140
V4=5208
886
STA 23
2.6×10^5
73
0
79
94
2.3×10^5
50
1.6×10^3
65
1×10^4
V1=1830
56
V2=5136
812

FIGURE 40

CONCLUSIONS

The seismic refraction and electrical resistivity geophysical methods were successfully applied to the determination of representative seismic velocities and electrical resistivities, and to the depth of the unsaturated overburden. The methods failed to detect the impermeable clay layers.

The results of the seismic velocity study indicate a marked difference between the velocities of unsaturated and saturated layers. The electrical resistivities of saturated materials differ from the unsaturated layer values, but their ranges show considerable overlap.

A ground water mound with approximately 100 feet of relief was found associated with the Udell Hills. The peak of the mound is centered in section 23 and a minor depression is located in the northwest quarter of section 24.

In this area, the seismic method gave the most precise results when interpreted in conjunction with control well information. The resistivity method, the interpretation of which is generally more subjective than the seismic method, nevertheless contributed to the study and supplemented the seismic observations.

The seismic and resistivity geophysical methods in conjunction with control well information, was an effective tool for determining the thickness of the unsaturated overburden and delineating the ground water divides in the Udell Experimental Forest.

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