EARTH RESISTIVITY MEASUREMENT AND INTERPRETATION-INGHAM COUNTY, MICHIGAN

Thesis for the Degree of M. S.

MICHIGAN STATE UNIVERSITY

Ralph F. Green

1962

ABSTRACT

EARTH RESISTIVITY MEASUREMENT AND
INTERPRETATION - INGHAM COUNTY,
MICHIGAN

by Ralph F. Green

Resistivity surveys involve the introduction of an electrical current to the ground. The measured resistivities vary with certain physical characteristics of the substrata of the earth. Porosity, percentage of pores filled with water and the conductivity of this water control the resistivity of non-metallic rocks. Various natural and artificial potentials can create difficulties in measuring earth resistivities, but these usually can be eliminated. After the field measurements have been obtained, proper interpretation may provide basic data (depths and lithologies) concerning the subsurface geology of an area.

Various means of interpreting resistivity data have been proposed. The present study compares several of these techniques by using the different interpretive methods on the same data to obtain depth predictions. Nearby wells provided geologic control for each station. The major goal of this thesis is to determine which interpretive method is best. It was also desired to test the usefullness of a low frequency AC instrument.

The resistivity curves from this instrument were compared to curves obtained with a DC instrument and were found to compare favorably.

Values of a depth coefficient were computed for each interpreted depth: depth coefficient equals resistivity depth divided by geological depth. The mean values of the depth coefficient were calculated for each interpretive method. Moore's cumulative method gave the best results and can be expected to give equally reliable results in areas of similar geology. The inflection method and the curve correlation method gave quite poor results. Barnes Layer method and Mooney and Wetzel's theoretical method of interpretation gave comparable results, but were not quite as good as Moore's method.

No unique or diagnostic resistivities were obtained for any formation by either of the two interpretive methods (Mooney and Wetzel's and Barnes) giving numerical resistivity values for the formations.

EARTH RESISTIVITY MEASUREMENT AND INTERPRETATION - INGHAM COUNTY, MICHIGAN

By

Ralph F. Green

A THESIS

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

MASTER OF SCIENCE

Department of Resource Development

1962

ACKNOWLEDGEMENTS

Special thanks in this thesis are due three persons. Dr. C. R. Humphrys, my major professor, was responsible for my initial introduction to earth resistivity work. In enjoyable and informative geophysics classes, Dr. W. J. Hinze of the Michigan State University Geology Department provided much of the necessary background for my study of resistivity. Helpful suggestions and criticisms were always available from Dr. Hinze. Finally, to my wife Sandra, I express my heartfelt thanks. Her patience and confidence provided the necessary stimulus to keep me working on each task till it was completed. In addition to being a wife and mother, she was family provider for several years. Her typing of the preliminary draft of this thesis was greatly appreciated.

TABLE OF CONTENTS

CONTENTS (continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (continued)

PART A

GENERAL INTRODUCTION TO EARTH RESISTIVITY

CHAPTER I

INTRODUCTION AND PURPOSE OF STUDY

Today earth resistivity studies are finding increased application in the fields of civil engineering and hydrology as well as in mining geology. In most cases it has been cheaper and faster to use a resistivity program correlated with a drilling program than to rely on information obtained from a few borings alone. This has proved to be a useful method in determining depth to bedrock, locating potential aquifers and delineating borrow material for road construction, among other uses. The resistivity curves obtained for these types of situations will show a variation depending on the geology involved.

In the type of resistivity survey used in this study, the depth of the formation of interest has to be determined. Since the turn of the century when resistivity surveying first was used, various workers have presented numerous different interpretive techniques to determine depths from resistivity curves. This immediately presents the problem of which technique should be used to obtain the best results. Various aspects of this problem include the determination of the one best interpretive method (if there is such a thing), or the determination of the techniques suited only to certain geologic situations.

In addition to the previously mentioned goals the adequacy of the instrument used in the survey was to be determined by checking field measurements obtained by this instrument against standard DC resistivity gear. The instrument used in this survey is slightly different from the type of equipment normally used in this type of work.

CHAPTER II

INTERFERENCE POTENTIALS

In conducting a resistivity survey the operator introduces an artificial current into the ground and measures the potential drop caused by the resistance of the earth at the area under investigation. Other potentials, some natural, some partially natural and some wholly resulting from cultural effects can create problems. All potentials other than that introduced into the ground by the operator may be termed "interference" or "noise." This noise detracts from the reliability of the measurements and often results in erroneous interpretations.

Cultural noise. Potentials resulting from cultural effects are in part self-explanatory. Modern man is a great user of electrical equipment and household accesories. Telephone lines and power lines are strung across much of America today. Therefore, field work should be conducted so as to eliminate or at least minimize the possibility of noise from these sources. Buried electrical cables are to be given sufficient clearance also, to avoid undesirable effects. Not all cultural noise results from electrical lines, however. Buried pipe lines, cased wells, partially buried fencing, calcium chloride and sodium chloride lying adjacent to roads to which it was applied to hold the dust, are but a few of the other problems to be encountered. While the last mentioned group does not necessarily create noise in the form of a voltage, an interference is set up by placing these "super-conductors" in the circuit. In general then, it can be seen that resistivity surveys should be conducted in areas where the cultural effects can be held to a minimum.

Natural interference. There are several different types of naturally created earth potentials, which to varying degrees may affect resistivity measurements. One of these occurs as several large current whorls which shift about the globe in a definite relationship to the sun's position as the earth rotates. These are known as telluric currents. It is generally thought that these currents are induced in the earth's surface by ionospheric currents, which are correlated with diurnal changes in the earth's magnetic field. The amount of current induced in the earth is controlled by the conductivities of the earth materials. Usually, these currents will have little effect on resistivity work, but during and immediately following periods of high solar activity these telluric currents could become large enough to necessitate cessation of resistivity field work. Despite this possible hindrance to resistivity surveying, telluric currents have provided the basis for another geophysical method of exploration.

Another natural earth potential results from the diffusion of solutions containing salts of different concentrations through a permeable membrane. For this reason they are known as diffusion potentials. Earth materials contain ground water differing greatly in dissolved mineral and salt concentrations. There is a tendency for solutions to equalize their salt concentrations; this results in a movement of ions from a solution of high salt concentration to one of a lower concentration. When the ions in a solution move an electrical current is established. The potentials produced are dependent on the absolute temperature of the solutions, the ionic valence, the mobility of the ions and the concentrations of the solutions. Usually these potentials are of low magnitude, but under certain conditions it would be possible for the potentials to create a serious interference problem for resistivity work.

Conducting ore bodies are capable of producing a significant voltage under certain conditions. For this reason the self-potential exploration method has been developed to locate this type of deposit. Several theories have been proposed to explain the production of self-potential currents. The theory which stands in best repute today, involves the interaction of the oxidation potential and the acidity of the solutions surrounding part of the ore body. Since the conducting ore bodies necessary for the production of SP currents are non-existent in the area of the present study, no problems are to be expected from this source.

The last truly natural earth potential to be considered is the streaming or electro-filtration potential. In this case the potential is created by the movement of the solutions themselves, not just the movement of the ions in the solutions, through a porous media. The resulting potentials are quite small and will give little interference in most cases.

Natural-artificial noise. The remaining three types of interference potentials occur as a direct result of the resistivity survey but also depend in part upon certain properties of earth materials. This type of interference causes the greatest amount of noise in resistivity measurements. The first to be considered is the electrode potential. This potential is created simply by placing the electrodes in the ground. Part of the metal electrodes will dissolve and go into solution, while some of the ions of the solution will move to the electrode where they will be precipitated. The resulting movement of ions and electrons gives rise to the current flow. If the electrodes are of the same type of metal, but are placed in solutions of different concentrations, a potential will result. Also, if electrodes of different types of metals are placed in solutions differing in concentration, a potential will result. In the latter case greater potentials will be developed due to the added action of the different metals. This type of potential is controlled by the absolute temperature, the ionic valence involved, the solution concentrations and the solution pressure of the metals.

Since it is unlikely that the concentrations of the soil moisture solutions will be the same over anything but a very small area, due to various factors such as differences in soil and vegetation types, these potentials can be expected to occur any time electrodes are placed in the ground. To minimize the effect of this type of potential, the electrodes should be made from the same original piece of metal. This then leaves the difference in solution concentrations as the main contributing factor in the production of these potentials and will greatly reduce the interference created.

One technique used with DC equipment to eliminate electrode potentials is to build the instrument with a manual reversing circuit. A reading is then taken with the artificial current flowing in one direction, then the current is reversed manually and another reading is taken. These two readings are then averaged to eliminate the variations of the soil moisture solution concentrations and moisture content of the soil. Current reversal will be discussed further in another section.

The next type of interference is created by polarization potentials. This is more of an artificial potential than it is natural. However, it is independent of the artificial current. When a current is introduced to the ground through electrodes (conduction), different concentrations of ions will build up about the electrodes; negative ions about the anode and positive ions about the cathode. This difference in ion concentrations sets up a counter potential which opposes the artificial current. Again the magnitude of this potential is controlled by the absolute temperature and the valence of the ions; it is also dependent on the solution pressure of the electrode metal and the osmotic pressure of the solutions. The buildup of this counter electromotive force is quite slow, however, it can become quite large.

There are several methods of overcoming interference caused by this type of potential. Quite often porous unglazed ceramic pots containing the electrodes and a solution of a salt of the same metal as the electrode have been used. Field operation with porous pot electrodes is quite difficult since the solutions and electrodes must be chemically pure and must be the same for each electrode; a supply of the salt solution must be carried to replace that which seeps from the porous pots and; the pots themselves are fragile and are not ideally suited for hard field usage.

To get away from the problems created by the use of porous pots and to still eliminate the polarization potentials several procedures remain. If the instrument can be adjusted very quickly while the current is being applied to the ground, the polarization of metal electrodes will be minimized. Polarization builds up slowly and therefore can be reduced by taking the readings as quickly as possible.

Another means of decreasing the effect of polarization is to put a large enough current into the ground with the instrument so that the counter potential created by polarization will be negligible compared to the applied voltage. If the method described in the preceeding paragraph and the method just described are combined; fast instrument reading and a high instrument voltage; the result will be an almost complete elimination of polarization potentials when metal electrodes are used.

The process of current reversal discussed in connection with electrode potentials may be applied to eliminate polarization potentials. One slow current reversal is not sufficient, however. Hand cranked commutators have been employed frequently in the past to accomplish this purpose. With this type of equipment the current is reversed from 15 to 30 times per second. The reversing nature of this current prevents the buildup of ions near the electrodes and also provides an automatic averaging of the effects caused by differences in soil moisture percentages and salt concentrations. The net result is the cancellation of both polarization and electrode potentials.

The final method of reducing these potentials can be considered to be a further development of the current reversal process. An alternating current is used in the place of the straight DC or commutated DC current. The use of AC in resistivity surveying can lead to another problem, however. Alternating current can produce an induced counter current in the earth. The magnitude of this induced current will follow Faraday's Law which states that the potential developed will be dependent on the magnetic susceptibility and the change of field strength with respect to time. The conductivity of the material is more important that either of these factors, however. The current must pass through the material before a counter current will be induced. Although the induced counter current is detrimental to resistivity surveying it is the basis for electro-magnetic geophysical exploration.

Conductivities of earth materials are comparitively low in this area and hence the induced current won't be able to build up. In the area of the present survey, few rocks are found with a large enough magnetic susceptibility to create a large induced potential. Since this potential is also dependent on the rate of change of the applied field strength (frequency), it is still possible to obtain induced voltages if high frequency current is used. In geophysics, high frequency is generally considered to be above 10,000 cycles per second, while low frequency lies in the range below 100 cps.

The counter potential is actually created by the electromagnetic field set up by the applied current. If the frequency is increased to increase the amount of current entering the ground it is found that the depth of current penetration is then reduced. The increased effect of the induced counter potential causes a crowding of the current flow lines near the earth's surface. This is a problem in electro-magnetic surveying as well as in resistivity work. 1/

The instrument used in this survey will be described shortly, but since it utilizes a 97 cps alternating current this particular feature will be discussed briefly in this section. It will be noted that the working frequency is quite close to the upper limit of the low frequency range and therefore some adverse affects could be expected. However, on checking resistivity measurements obtained with this instrument against readings obtained with a conventional DC instrument, the results were quite comparable, indicating that the induction effects are essentially negligible.

1/ The discussion in the paragraphs dealing with interference potentials has been taken from lectures given by Dr. W. J. Hinze in the advanced geophysics class at MSU during spring term, 1962.

CHAPTER III

ROCK PROPERTIES CONTROLLING RESISTIVITY

The amount and distribution of electrical current in the earth will depend on the effective resistivity (or its reciprocal, conductivity) of the earth materials. The resistivity of any material is defined as the resistance in ohms between opposite faces of a unit cube of the material. Mathematically this will be

$$R = (l/A)\rho \qquad (1)$$

$$\text{or } \rho = (A/l)R \qquad (2)$$

where ρ is the resistivity, R the resistance A the cross-sectional area and l is the length. If R is expressed in ohms, A in square centimeters and l in centimeters, the unit of resistivity will then be expressed in ohm-cm. This unit or the ohm-meter (ohm-meter = ohm-cm x 10^{-2}) will be used in this paper.

We are interested in the conduction of an electrical current by the earth's near surface materials. Conduction may occur by several means. In moist non-metallic rocks the flow of current is mainly due to electrolytic conduction which is the transfer of ions in the earth solutions (soil moisture and ground-water).2/ In metallic and dry non-metallic

---

2/ J. J. Jakosky, Exploration Geophysics (Newport Beach, Calif.: Trija Publishing Company, 1950), pp. 437-438 rocks conduction will be electronically achieved, in which case there is an actual movement of free electrons. 3/ In some cases, when an alternating current of high frequency is used, dielectric conduction or the movement of the nuclei of atoms will occur. 4/ Since this study uses low frequency AC this latter type of conduction will not be considered further. Metallic rocks are of minor importance in the glacial drift in the part of Michigan in which this study was located so they need not be considered further. We are then concerned with only electrolytic and electronic conduction in non-metallic rocks.

A 1937 laboratory study 5/ has shown that electrical resistivity is an inverse function of the percentage of conductive water found in the pores of non-metallic rocks. As the moisture percentage increased the resistivities approached the resistivities of the electrolyte (conductive solution), indicating electrolytic conduction, while for the very low moisture percentages the resistivity values approached that of the rock materials, indicating electronic conduction.

3/ W. J. Hinze, lecture notes from geophysics class, spring term, 1962.

4/ Ibid.

5/ J. J. Jakosky and R. H. Hopper, "The Effect of Moisture on the Direct Current Resistivities of Oil Sands and Rocks," Geophysics, vol. 2 (1937), p. 33

Since most rocks are porous and contain some moisture, particularly in the study area, the current flow will be largely by electrolytic conduction. Most rocks will be fair conductors despite the fact that the component minerals of the rocks are poor conductors. For dry rocks we can expect the measured resistivity to approach that of the rock materials, while for saturated rock the measured resistivity will approach the resistivity of the solutions contained in the rock. Intermediate percentages of moisture will result in resistivity values between those exhibited by the dry rock and saturated rock.

Four main factors control the resistivity of rocks. 1) Pore volume; this controls the maximum amount of water a rock may hold. Going from dense metamorphic and igneous rocks to dense sedimentary rocks, to unconsolidated rocks and finally to loose soils, mucks and peats, shows a large increase in porosity with an equally large decrease in the ratio of the resistivity of the rock to the resistivity of the solution. For the dense metamorphic and igneous rocks the porosity range is 0-2% and the resistivity ratio is greater than 100; peat has a porosity of 80-90% and a resistivity ratio of unity.

The next factor, 2) the arrangement of the pore spaces and the degree of packing of the individual grains, controls the size of the pores, the effective porosity and the permeability of the rock. This determines the path of the current flow since electrolytic conduction depends on the movement of ions through water in interconnected pores. Permeability will effect the duration of contact of water and rock.

The next contributing factor, 3) is the portion of the pores filled with water. If we have a pore space of 40%, which is relatively high, but only 2-3% of this pore space is occupied by water, the resistivity will be quite high and will approach that of the rock materials.

The last factor, 4) is the resistivity of the water. In the final analysis, the resistivity of the solution will depend on, a) the concentration of ions present in the solution, which is controlled by the concentration of the electrolyte and its degree of ionization. Conductivity will usually increase with increasing ion concentrations up to a maximum point after which it tends to decrease. Essentially conductivity will show a logarithmic increase as the percentage of salts increases. The concentration of ions present is dependent on the following. (1) The primary conductivity or resistivity of the water entering the pore spaces. The slight dissociation of demineralized water into its basic and acidic constituents provides only a few ions for current flow. As the ionic content of this water increases, the primary conductivity will also increase. The resistivity of water varies greatly, depending largely on where it is found. Precipitation generally has the highest resistivity with sea water having the lowest resistivity. Surface water and ground-water have intermediate resistivities. Current flow is due mainly to, (2) the secondary conductivity of the water, which is acquired through the dissociation of soluble salts in the rocks. 6/ Secondary conductivity is determined by, (a) the duration of contact between the rock and the water. As mentioned previously, this is controlled by the permeability of the rock. Longer contact between the rock and water will increase the amount of dissolved salts. In addition, (b) the soluble minerals present in the rock also determine what ions will be found in the water.

Finally, b) the resistivity will depend on the mobility and velocity of the ions. The ions being in solution will have their mobility affected by (1) temperature and (2) pressure. An increase in temperature will decrease the viscosity of the solution and make it easier for the ions to move, hence the resistivity will also decrease (conductivity will increase). With increasing temperature the rate of resistivity decrease will be somewhat reduced by the decrease in dissociation of dissolved salts into ions brought about by the higher temperatures. Increasing pressure

---

6/ Due to the natural movement of ground-water, rocks may receive water of secondary conductivity from surrounding rocks. Under the above system this would be termed water of primary conductivity as it entered a different rock and would make the primary conductivity paramount in determining current flow.

will increase resistivity since the pore volume and pore size will decrease giving a somewhat higher viscosity and less ion mobility. 7/

Different rock types then will have different resistivities depending on the above factors. The same rock type may exhibit different resistivities with variations of these same factors. In addition a resistivity survey conducted at the same site, but under a different set of above variables, will show different resistivities. Quite a few rocks also exhibit resistivity anisotropy, depending on the direction of measurement in relation to the rock unit. It is possible that the direction of glacier movement can be determined by evaluating the resistivity anisotropies of glaciated areas such as Michigan.

7/ The discussion of the factors which control rock resistivities compiled from Hinze, loc. cit.; Jakosky and Hopper, op. cit., pp. 51-52; and Carl A. Heiland, Geophysical Exploration (New York: Prentice-Hall Inc., 1950), p. 634.

CHAPTER IV

FIELD MEASUREMENT OF RESISTIVITY

In 1915 Frank Wenner 8/ developed the basic equation used today for earth resistivity determinations. In developing this formula he assumed a uniform resistivity and indicated that unless the resistivity was homogenous that a solution is usually not possible. However, he also indicates that his method might be used to locate ore deposits of high conductivity. Today we use this equation and assume that deviations in the computed resistivity are caused by a heterogenous earth.

He presented a general formula for resistivity in which the electrodes are each at different spacings. From this formula he went to his specific equation in which the electrodes are equally spaced from each other and in a straight line. Through the two outside electrodes the current is introduced to the earth and the potential drop is measured across the two inner electrodes. This electrode alignment is now referred to as the Wenner configuration. With this arrangement the resistivity value "obtained depends mainly upon the resistivity near and between the potential electrodes" and very little on the resistivity of the

---

8/ Frank Wenner, A Method of Measuring Earth Resistivity, U.S. Bureau of Standards Sci. Paper 258, (1915), pp. 469-478.

material at distances from them greater than the distance between the current electrodes. 9/

The equation is as follows:

$$\rho = \frac{4\pi AR}{1 + \frac{2A}{\sqrt{A^2 + 4B^2}} - \frac{A}{\sqrt{A^2 + B^2}}} \qquad (3)\ \underline{10/}$$

where

ρ = resistivity in ohm-cm.

A = distance between electrodes in cm.

R = resistance in ohms.

B = depth of electrodes in the earth in cm.

If B is small in comparison to A then

$$\rho = 2\pi AR \qquad (4)\ \underline{11/}$$

The resistance R, is computed from the measured value of the current I, introduced to the earth through current electrodes and the potential drop E, measured between the two potential electrodes. This is the equation for resistivity in the semi-infinite case in which there is an air-earth interface. The general formula and equation (4) are derived in several of the basic texts and papers concerning earth resistivity measurements (ie. Jakosky, pp. 467-474). Equation (4) applies only to situations in which the electrodes

---

9/ Ibid., p. 477.

10/ Ibid., p. 470.

11/ Ibid., p. 470.

lie in a straight line and are equidistant from each other. Other methods involve the use of three, or more often, five electrodes and different systems of arranging these electrodes. In these cases the equation must be altered.

Since equation (4) gives the resistivity for a homogenous earth any variation of this limitation will result in a variation in resistivity. The variables which may be altered are the size and shape of the electrode array, the geometry of the subsurface materials (size, shape, depth and location), the natural resistivities involved and the interference potentials discussed earlier.

In the survey method used most often (and for this study), the center of the electrode spread is held at the same place and the electrodes are moved outward from this point and each other, keeping the distance between each electrode equal, however. This procedure increases the depth of current penetration. During the early days of resistivity work and often in the present time, some writers have felt that the depth of current penetration into the subsurface was equal to the electrode spacing used. Actually this would be the case for ideal conditions only; the effective depth of current penetration is seldom more than 1/2 to 3/4 of this value. There are several reasons for this. Subsurface inhomogeneities such as different geometrical shapes and different resistivity ratios of the subsurface formations are the primary factors which alter the depth to which current will penetrate. 12/

The net effect is a reduction in the depth of current penetration. The configuration and separation of the electrodes are only two of the factors then which control this depth. In this study the maximum spacing between electrodes was usually either 100 or 200 feet. Using the correction discussed in the previous paragraph this gives a maximum depth of current penetration range of 50 to 75 feet and 100 to 150 feet respectively.

Since we can't alter any of the various factors limiting the depth of current penetration except the electrode configuration and spacing this is the only means we have of increasing current penetration. The effect on R of an increasing value of A is seen in figure 1. This figure shows that for the larger values of A that the rate of change of R becomes quite small. Although this figure applies to a homogenous earth of resistivity ρ, the same general type of situation exists for a multi-layered earth. A thin formation near the surface can have as much or more of an effect than a much thicker formation at some depth

---

12/ J. J. Jakosky, Exploration Geophysics (Newport Beach, Calif.: Trija Publishing Company, 1950), pp. 508-509.

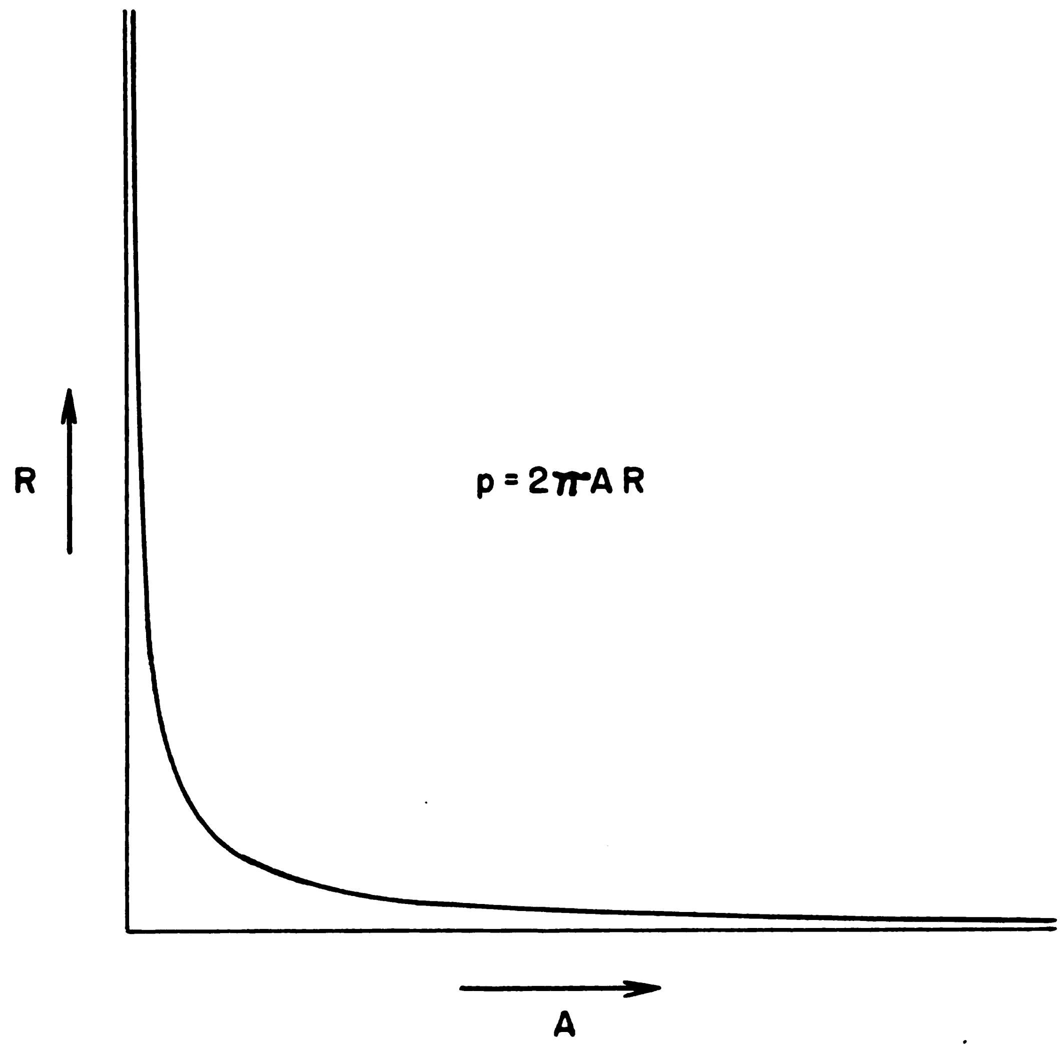


FIGURE 1

VARIATION OF R WITH INCREASING VALUES
OF A FOR A HOMOGENOUS EARTH
OF RESISTIVITY ρ.

below the surface. One result of this is that it is unnecessary to use the same electrode spacings for the entire survey at a station. Preferably the spacings are small for the lower values of A and increase as A becomes larger. The second result is a corollary of this; since the degree of discernment decreases as very large values of A are used this method will be limited in its effective depth. Resistivity surveys for civil engineering and hydrological work are usually limited then, to an effective working depth of only several hundred feet.

The type of survey which has been discussed thus far, in which the spacing between the electrodes is gradually increased, is known as vertical profiling. This type of approach is useful in locating horizontal discontinuities and is the type of survey used in the present study. Another type of survey which has proven successful in locating vertical discontinuities such as faults and gravel-filled preglacial drainageways, is the so called horizontal survey or horizontal profiling. In field operations the electrodes are spaced such that the depth to the formation will at least be reached, then the whole electrode array is moved as a unit from station to station with this same electrode separation. Formations with anomalous conductivities which are shallower than the depth of current penetration will be shown as anomalies on isoresistivity diagrams such as contour maps and profiles. Interpretation of the results

from this method of surveying is empirical and highly qualitative. For some reason it hasn't received the theoretical treatment which has been applied to vertical profiling. This will be discussed shortly.

As explained previously, the resistivity value given by equation (4) is the true resistivity only for a homogenous earth. For any other subsurface configuration this value is called the apparent resistivity (ρ_a). Apparent resistivity is defined as the resistivity of a material that would produce the same ratio of potential drop to impressed current ($E/I = R$) with the same configuration and separation of electrodes. 13/ This is a type of average resistivity but it is not a true average; it is weighted according to the ratio of the resistivities involved and the ratio of the electrode spacing to the depth of the interface. This apparent resistivity must then be interpreted to give the true resistivities of the formations involved before the geologic picture can be deduced.

Another important characteristic of equation (4) should be discussed at this point. I have computed the percentage errors which result from using equation (4) when equation (3) should have been used (when B <u>is not small</u> in comparison to A). Table I shows these percentage

---

13/ Hinze, *loc. cit.*

errors for various values of A and B. Resistivities from equation (4) will be less than those computed from equation (3). Since the electrodes I use are usually not inserted over 2 feet in the ground this is the maximum value of B appearing in the table. To hold the error under 2.0% the following limitations should be observed; at an electrode spacing of five feet the electrode depth should not exceed six inches; at a ten foot separation no more than twelve inches; at a fifteen foot spacing eighteen inches is the limit; and at spacings of twenty feet or more the electrodes may safely penetrate to twenty-four inches or more if necessary to secure a good contact with the soil moisture.

TABLE I

PER CENT ERRORS RESULTING FROM EXCESSIVE

ELECTRODE PENETRATION AT SMALL ELECTRODE SPACINGS

		Electrode spacing A, in feet			
		5	10	15	20
Electrode depth B, in feet	2.0	18.4%	6.2%	2.9%	1.7%
	1.5	13.4%	3.6%	1.7%	
	1.0	6.2%	1.7%		
	0.5	1.7%			

As was noted in the section on rock properties which control resistivity, moisture is of primary importance in electrolytic conduction. For this reason a soil auger was used at each survey station to determine the depth of the soil horizon with adequate soil moisture. Observing the limitations of Table I, this depth or a greater depth was used for electrode penetration at that station. This assured a good contact with the soil moisture solution thus increasing the effectiveness of a given amount of current. In the arid Southwestern U.S. a high current is necessary to overcome the effects of a dry, highly resistant surficial layer.

The reversal of the current applied to the ground as a means of eliminating electrode potentials has been considered previously. It should be understood that this procedure eliminates electrode potentials for each individual electrode spacing only. If the electrodes for any one spacing were placed in soil moisture of different electrolyte concentrations, the current reversal would eliminate possible electrode potentials. If at the next spacing the same situation existed and the same procedure was followed, the same result would occur. However, since at the two different electrode spacings the soil moisture solutions were different we would have the resistivity altered by this. This is a direct result of lateral variation of soils.

The best method of eliminating this variation is to conduct the survey in areas of constant soil type. As discussed earlier, this is an infrequent occurrence in Michigan. The next best method of removing this effect is to conduct the survey in the normal manner, then, keeping the same center position, another set of readings is taken at right angles to the first electrode spread. These two sets of readings are averaged. In most situations this procedure will be quite helpful in eliminating spurious readings due to the lateral variation in the soil. Several stations in this study were treated in this manner and will be discussed later.

Instrument description. The resistivity instrument used in this survey is the Model 274M Vibroground, which was developed and manufactured by Associated Research Incorporated. This instrument works on a null-balance principle. The voltage drop developed by the current flowing through the ground is measured by comparing it to a portion of the voltage drop developed by this same current flowing through a calibrated potentiometer.

The instrument consists of a power supply, a current supply circuit and a measuring circuit. The power supply changes the low DC battery voltage (3 volts) to an alternating current by a 97 CPS synchronous vibrator. This voltage is stepped up to 125 volts AC by the power transformer. In the current supply circuit, this transformer is connected in series with a calibrated potentiometer and the two electrodes completes the circuit.

The measuring circuit consists of the secondary of the potential transformer and its associated range selector switch, two metering resistors, the galvanometer, a blocking capacitor to prevent stray DC entering this circuit, and the two potential electrodes. The resistance of the earth

between these two electrodes completes the circuit.

The current flow between the current electrodes causes a voltage drop across the earth resistance between the potential electrodes; this voltage drop causes a current flow in the measuring circuit. The current flow through the potentiometer causes a voltage drop which is fed to the primary of the potential transformer which induces a voltage drop in the secondary also causing a current flow in the measuring circuit. This current tends to cancel the current flow due to the voltage drop across the earth resistance. Proper adjustment of the range selector switch and the potentiometer will cause the two currents to cancel; indicated by a galvanometer reading on the zero point. The conductance reading from the calibrated dial multiplied by the range switch setting will then give the earth conductance in mhos between the two potential electrodes. The instrument gives conductance values but they are easily converted to resistance and resistivity.

When the galvanometer is in balance at zero, there is no current flow in the measuring circuit, thus, the resistance of the potential leads will have no effect on the reading. Since the same current flowing through the ground causes the voltage drop on the potentiometer, the resistance of the leads connected to the current electrodes are also relatively unimportant. Because the meter current is rectified by the vibrator at 97 CPS, only current of this frequency will cause a meter indication, leaving the instrument relatively unaffected by any stray 60 cycle power line or ground currents. The blocking capacitor in the potential circuit prevents stray DC ground voltages from affecting the readings. As noted previously, the alternating nature of the current is effective in eliminating the effects of electrode and polarization potentials.

PART B

INTERPRETATION METHODS

CHAPTER V

THEORETICAL vs. EMPIRICAL METHODS OF INTERPRETATION

The interpretation of resistivity curves is an interesting subject, not only because of the nature of the problem itself, but because of the varied and numerous interpretive methods in use. Interpretation involves finding the depths of the interfaces between resistivity units, and deducing the lithology of these units from their resistivity values or from the relationships of the resistivities involved. From a network of carefully interpreted curves, the subsurface geology of an area may be inferred to a fair degree of accuracy. One of the purposes of this study is to determine just how accurate the different interpretive methods are.

Broadly speaking, there are two main schools of thought dealing with the interpretation of resistivity curves. As in many other fields, the early attempts at interpretation were with empirical methods. Soon, however, theoretical methods were applied to curve interpretation. As will be shown, three of the theoretical methods are identical, but there are innumerable empirical methods. Undoubtedly, many in this latter group are being used which have never been published.

The theoretical methods usually involve some type of master curve computed from theoretical data. If the field curves match the theoretical curves, it may be assumed that the actual geologic conditions parallel the assumptions for the theoretical curve.

Supporters of empirical methods of interpretation hold, that unless field geology conditions are quite similar to the assumptions upon which the matching theoretical curves are based, no match will be possible. Since in nature, almost anything is possible, a great multitude of master curves must be available to provide matches for all the possible geologic conditions. The theorists, in support of their interpretations, hold that a smaller number of curves are all that is necessary for most normal situations. The theorists do have the added support of having a scientifically sound method.

The empiricists use various characteristics of resistivity curves for interpretation, and also do some manipulating of the basic data to come up with a curve which is distorted in such a manner as to allow interpretation.

The objection raised most often to the empirical method of interpretation is that certain of the basic assumptions used are unsound. In the case of the empiricists who use some type of distortion, the distortion itself is usually mathematically correct, but the assumptions leading to the distortion are more apt to be in error. In addition, the empirical methods are not as objective as the theoretical methods and hence, are more subject to the effect of the personal factor.

In the next few chapters, theoretical and empirical interpretive methods will be explained and discussed. This is not an attempt to present all of the interpretive methods used, but only some of the more common ones. Since they are scientifically sound, the theoretical methods will be discussed first.

CHAPTER VI

TAGG'S GRAPHICAL THEORETICAL METHOD 14/

Wenner's formula will give actual resistivity values for the homogenous earth case, and apparent resistivity (ρ_a) values for nonhomogenous cases. For a two layer case with d as the depth to the interface, ρ_1 and ρ_2 as the respective actual resistivities for the overburden and underlying stratum, and a as the electrode separation, Lancaster-Jones has shown that the apparent resistivity value obtained from Wenner's formula is related to these parameters as follows

$$\rho_a/\rho_1 = 1+4F \qquad (5)$$

where F is a function representing the sum of the following infinite series

$$F = \sum_{n=1}^{n=\infty} \left[\frac{K^n}{\sqrt{1+(2n\,d/a)^2}} - \frac{K^n}{\sqrt{4+(2n\,d/a)^2}} \right] \qquad (6)$$

in which k is the reflection coefficient and has the value

$$k = (\rho_2 - \rho_1)/(\rho_2 + \rho_1). \qquad (7)$$

The notation n represents the number of images of the source of the potential which are considered in solving the equation.

The solution of equation (5) is then dependent on the value of F, which in turn is dependent on the values of k and d/a. Rewriting equation (7) as

---

14/ G. F. Tagg, "Interpretation of Resistivity Measurements," A.I.M.E. Trans., Vol. 110, (1934), pp. 135-47; and G. F. Tagg, "Interpretation of Earth-resistivity Curves," Trans. A.I.M.E., vol. 138, (1940), pp. 399-407.

$$k = (1-\rho_1/\rho_2)/(1+\rho_1/\rho_2) \tag{8}$$

it is seen that k depends only on the ratio ρ_1/ρ_2. For equation (5) we then have

$$\rho_a/\rho_1 = 1+f(d/a, \rho_1/\rho_2) \tag{9}$$

where f denotes function.

From field measurements we know ρ_a and a; ρ_1 we can determine from very careful measurements at small electrode spacings. This leaves d and ρ_1/ρ_2, or k, as unknowns which must be determined. By assuming values for k and d/a we can solve equation (6) and finally (5). A series of master curves can then be drawn, which express the relationship between ρ_a/ρ_1 and d/a, for different values of k.

Tagg 15/ summarizes the interpretation as follows:

(1) Determine the surface resistivity ρ_1 by a series of careful measurements at small electrode intervals.

(2) Determine the apparent resistivity for a number of values of electrode interval.

(3) Plot a curve of apparent resistivity against electrode separation.

(4) From this curve read off the values of apparent resistivity ρ_a for various values of the electrode separation a, and for each value of a determine the value of ρ_a/ρ_1 if ρ_a is less than ρ_1, or the value of σ_a/σ_1 (ρ_1/ρ_a) if ρ_a is greater than ρ_1.

(5) From the master curves read off, for each value of a, a series of corresponding values of d/a and k, and from these calculate a corresponding series of values of d and k(d = a times d/a value).

15/ Tagg, 1940, p. 400.

(6) Plot curves, for each value of electrode interval, of d against k. These curves should all intersect in a point giving the true values of d and k.

From the value of k and ρ_1 we can determine ρ_2 using equation (7).

Since this method of interpretation is based on the assumption that each of the two layers are of uniform resistivity and that the interface is horizontal and smooth, it should only be applied in situations very closely approximating these assumptions.

In the two examples given by Tagg 16/ the following values for station A of ρ_1 = 6703 ohm-in., d = 142 ft., and k = 0.702 were given, while for station B ρ_1 = 45,700 ohm-in., d = 156 ft. and k = -0.6. He offers a probable explanation for the large differences in the resistivity of the surface limestone (both stations are near each other) as, at station A the underlying formation is clay which would tend to hold moisture in the limestone thereby reducing its resistivity, while at station B the underlying formation is sand which would allow water to drain from the limestone and increase its resistivity. Computing the value of ρ_2 for each station we obtain at A a value of 38,006 ohm-in. for the clay and at B 11,425 ohm-in. for the sand. The resistivity of the clay is thus over three times the

---

16/ Tagg, 1934, pp. 140-144.

resistivity of the sand. This could be explained as due to the increased electrolyte in the sand carried down to it by the water percolating through the limestone, while in the case of the clay, very little of the water in the limestone moved downward; rather, it moved laterally through the limestone under hydrostatic pressure.

Tagg 17/ has extended this method of analysis to the three-layer problem also. He has altered his basic method so that it is unnecessary to compute the surface resistivity in solving the three-layer problem. This was accomplished in the following manner.

At any known electrode spacing a, the apparent resistivity is ρ_a. From equation (1),

$$\rho_a / \rho_1 = 1+4F(a) \qquad (10)$$

where F(a) is a function of d/a and k. At any other interval na, when n is any number greater than one, the apparent resistivity will be ρ_{na} and

$$\rho_{na} / \rho_1 = 1+4F(na) \qquad (11)$$

where F(na) is a function of d/na and k

If ρ_1 is greater than ρ_2, dividing equation (11) by equation (10) yields

$$\rho_{na} / \rho_a = \frac{1+4F(na)}{1+4F(a)} \qquad (12)$$

If ρ_1 is less than ρ_2, dividing equation (10) by equation

17/ Tagg, 1940, pp. 401-403.

(11) gives

$$\sigma_{na}/\sigma_a = \rho_a/\rho_{na} = \frac{1+4F(a)}{1+4F(na)} \tag{13}$$

For any value of n, values of ρ_{na}/ρ_a, or its reciprocal, may be computed for any values of d/a and k; master curves of these values can then be drawn.

The interpretation involves selecting an apparent resistivity value at some a spacing beyond the maximum or minimum point of the field curve. Another point is then selected at a greater electrode spacing: at na where the value of n has been selected previously. For each electrode spacing the ratio ρ_{na}/ρ_a may be computed. Going to the master curves for the particular value of n and the above ratio, a series of corresponding values of d/a and k can be read off. After determining the values of d, they may be plotted against their respective k values for each electrode spacing and curves drawn. The intersection of these curves will give a point which determines the true value of d and k.

Tables for plotting the master curves are included in Tagg's paper.

CHAPTER VII

ROMAN'S THEORETICAL METHOD

Roman has presented formulas involving infinite series and given corresponding derived values to be used for resistivity curves for several electrode configurations. These theoretical curves can then be superimposed on field observation curves and the resistivities and the thickness of the upper layer may be determined directly. These curves were developed for the two layer case only.

This method of analysis is based on the departure of measured resistivity from that calculated for a uniform earth. Roman points out that the resistivity will depend on the type and size of electrode configuration and on the location and direction of the electrode spread. However, for any one type of configuration, the limiting value of the resistivity will be determined as the size of the configuration is decreased. This limiting value he calls the "normal resistivity" for that point. The normal resistivity of a uniform medium will be independent of the size of the configuration, its location and its direction. 18/ A uniform medium is homogenous and isotropic: the resistivity is the same for all points and all directions. 19/

18/ Irwin Roman, *Apparent Resistivity of a Single Uniform Overburden*, USGS Prof. Paper 365 (Washington: Government Printing Office, 1960), pp. 4, 5.

19/ *Ibid.*, p. 2,3.

He defines apparent resistivity (ρ_a) as the resistivity computed from a potential drop for a selected current in a certain configuration. The normal resistivity (ρ_o) of the medium was defined above. Variations of ρ_a from ρ_o indicate a nonuniform medium. 20/

For any one electrode configuration the apparent resistivity will have a diagnostic value. For this reason he defines a disturbing factor M where

$$M = \rho_a/\rho_o \qquad (14)$$

A disturbing factor equal to unity indicates a uniform material. If the disturbing factor is greater than one, a buried insulator of higher resistivity is indicated. A disturbing factor less than unity indicates a conductor of lower resistivity at some depth. 21/

The potential drop for the two layer case will be different (other things being equal) than the potential drop for the uniform earth situation. For the two-layer case Roman defines the potential drop in terms of a modified potential W(Q,a), which can be calculated and which he has values for in his publication. Q is the reflection factor defined as

$$Q = \frac{\rho_s - \rho_o}{\rho_s + \rho_o} \qquad (15)$$

20/ *Ibid.*, p. 5.

21/ *Ibid.*, p. 5,6.

where ρ_1 is the resistivity of the bottom layer and ρ_o is the resistivity of the overburden or surface layer. Q takes on values from +1.0 to -1.0. Tagg's k and Roman's Q are the same thing. The other factor in the modified potential is

$$a = 1/2h \tag{16}$$

where l is the electrode separation in the Wenner configuration and h is the depth of the overburden. 22/

In terms of the modified potential, the disturbing factor for the Wenner configuration will be

$$M = 1 + \frac{2l}{h}\left[W(Q,l/2h) - W(Q,l/h)\right] . \tag{17}$$

The modified potential therefore makes it possible to determine the disturbing factor, M, as a function of l/h, while the observations will determine the apparent resistivity as a function of the electrode separation. Since

$$M = \rho_a/\rho_o$$

then

$$\log M = \log \rho_a - \log \rho_o \tag{18}$$

and in the same manner

$$\log (l/h) = \log l - \log h. \tag{19}$$

Then, if log M is plotted against log (l/h) to form reference curves, and log ρ_a is plotted against log l to form observed

---

22/ Ibid., p. 7.

field curves, either may be interpreted as a chart of the other, if a proper value of Q has been selected and if the earth approximates the two layer assumption. 23/

Values of the disturbing factor for various values of 1/h and Q are given for the two layer cases of a buried insulator and a buried conductor. When plotted on logarithmic paper these values will result in two sets of curves, one for positive values of Q and the other for negative values of Q.

On these sheets of curves the resistivity index will be at M = 1 and the depth index will be at 1 = h. The intersection of these two index lines is the index point. These reference curves are usually drawn on transparent paper so that matching with the observed curves will be easier. The interpretation involves matching the observed curve with the best fitting curve from the reference sheet, keeping relative axes parallel. If a satisfactory match is obtained it may be assumed you have a two layer situation. The value of Q is noted for this curve of best fit and the location of the index point on the reference sheet is marked on the observation sheet. The overburden resistivity and the depth of this layer are indicated directly by the location of this index point. The resistivity

---

23/ *Ibid.*, p. 9.

of the bottom layer may be computed from

$$\rho_b = \left(\frac{1+Q}{1-Q}\right)\rho_o \tag{20}$$

which is another form of equation (15). 24/

24/ *Ibid.*, p. 9, 10.

CHAPTER VIII

THEORETICAL METHOD OF MOONEY AND WETZEL, AND ITS COMPARISON TO TAGG AND ROMAN

In 1956, Mooney and Wetzel published a book containing the tables necessary for computing the potentials about a point electrode for a multilayered earth. Along with the book was a set of about 2400 theoretical master resistivity curves, which had been drawn from data computed from the potential tables.

The authors evaluated the following equation to obtain the necessary data to draw the curves,

$$F(a) = 2a\int_0^\infty A(t)\, J_0\,(at)dt. \qquad (21)$$

F(a) is related to the potential V(a), through

$$V(a) = \left[\rho_1 I/2\pi a\right]\left[1+F(a)\right]. \qquad (22)\ \underline{25/}$$

The terms of equation (21) will not be identified since it was presented here only to show the form of the equation which was evaluated. F(a), which occurs in both equations, is the potential integral as a function of the electrode spacing a. All other characters in equation (22) have been designated earlier in this thesis.

25/ H. M. Mooney and W. W. Wetzel, The Potentials About a Point Electrode and Apparent Resistivity Curves for a Two, Three and Four-layer Earth, (Minneapolis: Univ. of Minnesota Press, 1956, p. 18.

Rearranging equation (22), we have

$$\frac{2\pi aV(a)/I}{\rho_1} = 1+F(a), \tag{23}$$

but as noted earlier, the apparent resistivity is

$$\rho_a = 2\pi aV(a)/I. \tag{24}$$

Substituting this into equation (23) gives

$$\rho_a/\rho_1 = 1+F(a). \tag{25}$$

From the discussion of Tagg's Method, equation (5) is

$$\rho_a/\rho_1 = 1+4F. \tag{26}$$

This is the same as equation (25); the only difference is that

$$4F = F(A) \tag{27}$$

which is just a difference in the definition of this term.

Roman's disturbing factor is expressed as

$$M = \rho_a/\rho_o = (1+S\{W\}) \Big/ (h\ S\ \{I/r\}) \tag{28}$$ 26/

where the last term of the right-hand expression is equivalent to the F(a) of Mooney and Wetzel. This makes the basis for these three theoretical methods the same.

Roman's curves exactly match those of Mooney and Wetzel for the two-layer case. Tagg's method differs slightly, in that he uses the ratio of the depth to the electrode spacing rather than the ratio of the electrode spacing to the depth of the interface (cf. the terms in brackets of equations (6) and (17), as in the other two

---

26/ Roman, op. cit., p. 9.

methods. These two ratios are reciprocals and hence, will not alter the value of ρ_2/ρ_1 at all.

From the procedure involved in using Tagg's method, it can be seen that it would be much simpler to use one of the other two methods and get equivalent results. Tagg's method appears to be more accurate, since the value of the reflection factor can be obtained to two decimal places, but this actually is not the case. The number of master curves for the other two methods could be increased to give the same degree of accuracy for the reflection factors but this usually isn't necessary. Since the value of ρ_1 must first be estimated, when using Tagg's two-layer method, this is a possible source of error.

Mooney and Wetzel have used equations (22) and (21) to develop master curves for the three and four-layer cases as well. These master curves are used with a matching technique similar to that used for Roman's Curves. Since all three of these theoretical methods should give the same results, an interpreter would probably be better off using Mooney and Wetzel's curves, since a greater variety of situations are covered.

In the use of these curves, the following prerequisites must be satisfied. 27/

1. The assumption of uniform horizontal layers in the field

27/ Mooney and Wetzel, op. cit., pp. 7-9.

should be met. Lateral variations can be detected as irregularities in the field curve. These can be eliminated by taking readings with the electrode spread rotated 90 degrees. A moderate dip of less than 10 degrees in the formations can be tolerated.

2. Field data must be reliable. As mentioned earlier, the field curve should be smooth with no sharp breaks. Mooney and Wetzel recommend frequencies of less than 20-30 cycles for AC equipment. A later section of this thesis will show that 97 cps can also be used.

3. The interpreter must have developed an intuitive feel for the general behavior of apparent resistivity curves in various situations.

CHAPTER IX

INFLECTION METHOD

One of the earliest methods used in resistivity interpretation is based on the potential bowl theory, in which the depth of measurement is assumed equal to the distance between adjacent electrodes for the Wenner configuration.

The resistivity obtained for each spacing is plotted against the electrode spacing taken as the depth. Gish and Rooney 28/ proposed that inflections in the resulting curves be interpreted as points indicating changes in earth materials. The depth to the interface could be read from the curve at these inflection points. A graph of resistivity vs. electrode spacing on regular graph paper is usually called a Gish-Rooney curve.

In some cases this interpretation was entirely satisfactory, but where the plotted curves were smoothly rounded, no inflection points can be selected, and this method is useless. Heiland, in the discussion of Moore's 1944 paper, indicated that for several hundred shallow resistivity measurements no curves resulted which had abrupt breaks. He also indicated that if abrupt changes in a resistivity curve had been found they could be explained as being due

---

28/ O. H. Gish, "Improved Equipment for Measuring Earth-Current Potentials and Earth-Resistivity," Bulletin of the National Research Council, vol. 11, no. 56 (1926), p. 86.

to variations in contact resistance. 29/ As early as 1937 Heiland stated that, "theory and practice show that no sharp breaks are obtained at formation-boundaries.....". 30/ In his text book on geophysical methods, he contends that theoretical curves of resistivity versus depth, prove that even for large differences in conductivity no abrupt change in the apparent resistivity will be noted. He advises that since irregular curves and breaks obtained in the field are uaually due to local soil conditions, as they effect the contact established by an electrode with the ground, these breaks should be eliminated before any interpretation is tried. 31/ Heiland also points out that apparent resistivity will continue to change with electrode separation long after the true resistivities no longer change with depth. 32/

In reference to the basic assumption of this method that the effective depth of measurement is equal to the "a" spacing, Jakosky points out that the equipotential

---

29/ Heiland, discussion of Moore's paper, (1945), P. 220.

30/ C. A. Heiland, "Prospecting for Water With Geophysical Methods," Transactions, American Geophysical Union, (Part II, 1937), p. 580.

31/ Carl A. Heiland, Geophysical Exploration, (New York: Prentice-Hall Inc., 1950), p. 717.

32/ Ibid., p. 728.

surface will be distorted by subsurface inhomogeneities. As a result of this distortion the depth of measurement will usually vary from about 1/4 to 1/6 the distance between the current electrodes or in other words from 3/4 A to 1/2 A. The depth of measurement is thus not a constant fraction of the electrode spacing, but will vary with such factors as the relative conductivities of the various layers and with the lateral variations in conductivity. 33/

Meidav pointed out a few methods of using the inflection point for multilayered cases where the second or middle layer has the lowest resistivity.

> Generally, the point of minimum resistivity is related to change in lithology in the following manner: (a) If the gradient of the resistivity curve increases sharply beyond the minimum, then the minimum point signifies change in rock types. (b) If the gradient to the left of (above) the minimum is very steep, whereas the gradient to the right of (below) the minimum point is not, then the bottom of the layer is too the left of the minimum. (c) If both left and right slopes are gentle, the bottom of the layer with which the minimum is associated is to the right of the minimum point. 34/

These are only rules of thumb and are by no means quantitative. Experience would be the only means of determining how far off the minimum you should shift in selecting a point. Although not indicated, it can probably be assumed

---

33/ J. J. Jakosky, Exploration Geophysics (Newport Beach, Calif.: Trija Publishing Company, 1950), p. 509.

34/ Tsvi Meidav, "An Electrical Resistivity Survey For Ground Water," Geophysics, XXV, no. 5 (Oct., 1960), p. 1080.

that the same type of general rules could be applied to multilayered cases in which the resistivity curves exhibit a pronounced maximum. The reservations about the use of inflection points mentioned earlier should be noted, however, before applying these rules of thumb.

CHAPTER X

MOORE'S CUMULATIVE METHOD

This method has been used for several years by the Bureau of Public Roads and by many other persons, with some success. At the same time it has been subject to strong criticism from the theorists. Essentially, this method involves plotting a summation resistivity at each equal electrode interval. This summed resistivity value is the resistivity of the particular electrode spacing plus all preceding resistivities. At the initial spacing the computed resistivity is plotted; at the second interval the first two resistivities are summed and plotted, and so on through the entire set of data. Tangents are then drawn through points lying on straight lines on the resulting cumulative curve; the point of intersection of these tangents represents the depth of the interface between materials of different resistivities. This method will be referred to as Moore's method or the cumulative method.

The cumulative curve is drawn on the same sheet of paper as the Gish-Rooney curve and thus requires a greatly reduced scale for the cumulative resistivity. This reduced scale, plus the summation process, tends to eliminate minor resistivity variations caused by surface heterogeny and measurement errors. Moore has indicated that this method is probably best suited to shallow two-layer cases. 35/

This method is based on the assumption that, for a two-layer case, the resistivity curve will asymptotically approach the resistivities of the upper and lower layers, at small and large electrode spacings respectively. For the cumulative curve of this case, the slopes of the tangents would approximately equal the resistivities involved.

In the original paper and in many subsequent papers, Moore has presented curves which give results which are as accurate or more accurate than any other method. However, in the discussion which followed his first paper, the method was roundly attacked because of its lack of a theoretical basis; at the same time, it was praised by some as a novel and fresh approach to the problem of resistivity depth interpretation. Moore's answer to the men who questioned the lack of a theoretical base, could be paraphrased as; So what?, it works!

The next paper in the same volume as Moore's original paper was written by Muskat. 36/ He analyzed Moore's method theoretically and found that the only unique asymptotes or

---

35/ R. W. Moore, "An Empirical Method of Interpretation of Earth Resistivity Measurements," A.I.M.E. Tech. Pub. No. 1743, with discussion, Trans. A.I.M.E., vol. 164, (1945), pp. 197-223. Also see bibliography for his other papers.

36/ Morris Muskat, "The Interpretation of Earth-resistivity Measurements, "Trans. A.I.M.E., vol. 164, (1945), pp. 224-231.

tangents, which could be drawn to a cumulative curve, are at very large or very small electrode spacings. Muskat also found that the depth predicted by Moore's method will be at least one and a half times the actual depth. This value of one and a half times the true depth is obtained only where the resistivity of the lower medium is much less than that of the surface layer. As the resistivity of the lower layer increases and becomes greater than that of the surface material, the depth indicated by Moore's method will become greater and greater, and eventually be many times the actual depth.

In the same year, Ruedy 37/ showed that Moore's method was correct in theory and in practice. Supporters of the theoretical method do not go along with Ruedy's conclusions, and Moore himself, still considers the cumulative method to be without theoretical basis.

With, or without a theoretical basis, there are a few other problems to be encountered with this method. Muskat pointed out one of them: unique tangents are found only at very large and very small electrode spacings. In practice this usually isn't such a severe limitation, since tangents can usually be drawn. Often there are several positions that a tangent could occupy; a decision must be

---

37/ R. Ruedy, "The Use of Cumulative Resistance in Earth-Resistivity Surveys," Canadian Journal of Research. vol. 23, sec. A, no. 4 (July 1945), pp. 57-72.

made as to where it should be placed. The upper tangent usually passes through the origin and the first one or two plotted points of the cumulative curve; the lower tangent is located by the next group of points which fall in a straight line. This second tangent often presents problems because the cumulative curve is smoothly rounding, and doesn't possess a series of points on a straight line. In this case, about all that can be done, is to draw the tangent through the last two points of the curve and hope this is close enough to a large electrode spacing to give an accurate result. For the multi-layered case, this problem is compounded. The effect of the lower layers often prevents the apparent resistivity from approaching the value of the second layer.

The final problem concerns the summation interval. If different intervals are used for the summation, in the case of a uniform earth, each cumulative curve will have a different slope, but be correct in itself. The same thing will happen for a layered earth problem. Obviously, each station must be summed throughout, with the same interval. If different summation intervals were used, this would produce a change in slope which was not due to change in lithology.

CHAPTER XI

BARNES LAYER METHOD

The Michigan State Highway Department is now using the earth resistivity method to obtain added and more accurate subsurface information on earth textures and quantities than was being obtained by conventional methods of subsurface investigation such as hand augering. Their work with resistivity began in 1949 with the purchase of a resistivity instrument, but using conventional interpretation methods, they were unable to obtain satisfactory results. In 1952 a Department engineer published a paper in which he explained a new method of interpretation which he had developed and tested in the field. This method gave better results than any other method and was considerably faster than any of the theoretical methods.

The so called Barnes Layer Method, is "based on the premise that Wenner's formula is a truly fundamental expression for determining the average apparent resistivity of any thickness of an earth mass." 38/

Assuming that layers of earth are analogous in behavior to parallel resistors in a circuit an equation was developed

---

38/ H. E. Barnes, "Soil Investigation Employing a New Method of Layer-Value Determination for Earth Resistivity Interpretation," Highway Research Bulletin 65, (1952), p. 28.

whereby the value of the resistance for any particular layer can be determined. The equation is:

$$R_N = \frac{E_N}{I_N - \frac{E_N}{\bar{R}_{N-1}}} \qquad (29)$$

where

R_N = average resistance of any individual layer where all layers are assumed of equal thickness.

E_N = potential difference across the inner or potential electrodes.

I_N = current introduced to the earth through the outer or current electrodes.

$\bar{R}_{N-1}$ = average resistance of the earth from the ground surface to the top of the layer.

N = number of layers.

In developing this equation, Barnes assumed a homogenous earth, as did Wenner. Barnes notes that the resistance used in Wenner's formula will only approximate the actual resistance encountered, since the equipotential bowl theory does not take into consideration the warping effect on flow lines in heterogenous material. However, he feels that the resistance indicated by his formula will give a comparitive value with which soils may be differentiated 39/, since his method of determining layer-values of resistance is not seriously

---

39/ Ibid., p. 31.

affected by the warping of the equipotential bowl in heterogenous material. 40/

Actually Barnes equation for layer resistance values is simply another way of expressing the value of a resistor in a parallel circuit and can be expressed as such:

$$1/R_N = 1/\overline{R}_N - 1/\overline{R}_{N-1} \tag{30}$$

where

$1/R_N$ = conductance of any layer.

$1/\overline{R}_N$ = average conductance of the earth between the ground surface and the bottom of the layer.

$1/\overline{R}_{N-1}$ = average conductance of the earth between the ground surface and the top of the layer.

With the type of instrument used in this study, the values $1/\overline{R}_N$ and $1/\overline{R}_{N-1}$ are read directly, and $1/R_N$ is easily computed. However, with the type of instrument for which values of the amperage and potential are read separately, equation (29) must be used.

Wenner's formula now becomes:

$$\rho_N = 2\pi AkR_N \tag{31}$$

where

ρ_N = resistivity in ohm-centimeters of any individual layer.

A = thickness in feet of the layer interval.

40/ Ibid., p. 36.

k = conversion factor for converting feet to centimeters.

R_N = resistance of the layer in ohms.

The layer value of resistivity is, in effect, an average resistivity of all materials lying within the limits of any layer.

Layer resistivity values are determined for the entire profile under study and are plotted on a graph against the respective midpoints of the layers. These points are then connected by "transition lines". Where these transition lines cross resistivity range lines a boundary for different earth materials is established. Typical range values used in the Southern half of the Lower Peninsula are shown in Table II. These boundary points may be connected from station to station along a center line profile to show horizontal and vertical change in earth materials.

TABLE II

RESISTIVITY RANGE LIMITS FOR SOUTHERN MICHIGAN

ρ_N (ohm-cm)	Earth material
0 - 10,000	clay and saturated silt
10,000 - 25,000	sandy clay and wet silty sand
25,000 - 50,000	clayey sand and saturated sand
50,000 - 150,000	sand
150,000 - 500,000	gravel

Values over 500,000 necessitate boring to clarify the interpretation since conditions ranging from dry loose sand and gravel to weathered rock and bedrock will give high resistivity values. 41/

In practice the Highway Department has found that resistivity values vary from location to location, with values for the same soil type generally increasing as you go to the north. This necessitates the development of new resistivity range values at practically every new location. This is done by taking correlation borings with a mobile drilling unit. An average of about one boring is made for every ten resistivity stations. This establishes a correlation between the resistivity values obtained and the actual subsurface geology. In addition, the borings provide samples for mechanical analysis so the qualities of the various materials for road construction may be determined.

Contrary to Barnes' opinion, since this method uses the same assumptions as the potential-bowl theory, it is subject to the same reservations. Some persons have felt that this method assumes that the deeper strata have no effect on the computed layer resistivities since the earth is divided into layers. Actually, the effect of these deeper strata are included, since they will effect each individual instrument reading. When the layer resistivities are determined the effect of these lower layers is largely removed by the subtraction step. This is what Barnes intended to do: this will give layer values approximating the true

---

41/ Barnes, *loc. cit.*

resistivity of any particular layer.

In the next section of this thesis, you will note that the Barnes layer curve follows the standard curve quite closely, except that it does have a few sharp breaks in it. These breaks will be the result of lithological changes (sharp breaks are desired in this case) and also as a result of minor variations in the measured resistivity. Not only must the limitations regarding the effective depth of current penetration be observed, but since minor variations in the readings can cause a sharp kick in the curve, their effect will have to be considered in interpretation.

One theoretical two-layer curve was analyzed by this method and gave a correct interpretation. Time restrictions did not allow following this up further with a check of the remaining two-layer curves and some of the multi-layered curves. If a study of these curves by Barnes' method was to reveal that the layer method is correct it could provide an accurate and simple method of determining depths and resistivities. The theoretical curves are limited to a certain set of conditions, whereas the Barnes method could be applied in any situation. For the correct interpretation mentioned above, the layer values were plotted at the electrode spacing for the bottom of the layer and not at the layer midpoints as suggested by Barnes. Five foot layers were used in this analysis. Plotting the layer resistivities at the midpoints (2.5', 7.5', etc.) resulted in an error of 2.5 feet in the interpretation. Plotting the layer resistivities at the bottom of the layer (5.0', 10.0', etc.) gave the accurate depth interpretation.

The major problems with the use of this method then, are in the effect of minor surface variations on the readings, and in the selection of the proper resistivity range values to be used in any certain area. Adequate geologic control is necessary in all new areas to establish these resistivity range limits.

CHAPTER XII

CALIBRATION CURVES AND CURVE CORRELATION

For a reliable and accurate interpretation of earth-resistivity data calibration tests should be made over known geologic formations in any given area. 42/ Particularly in the cases where the object of the search is bedrock, its presence or absence. Quite often the resistivity curves for unconsolidated materials and for solid rock are so different in shape, trend and magnitude of values that just a visual inspection of the curves is all that is required to establish whether bedrock is present or not. 43/

In any new area it is desirable to obtain calibration curves for that area, since the same geologic materials can exhibit different electrical properties in different geographic areas. These calibration tests will give a resistivity curve in relation to a known sequence of geologic formations. It is preferable to make these calibration tests over formations thought to be typical of the area. 44/ The general shape of these calibration curves

---

42/ R. Woodward Moore, "Geophysics; Effects, Economy and Efficiency in Subsurface Exploration," No publisher, no date, p. 6.

43/ R. Woodward Moore, "Geophysical Methods Adapted To Highway Engineering Problems," Geophysics, vol. 17, no 3 (1952), p. 519.

44/ Arthur B. Cleaves, "Electrical Resistivity," Roads & Streets, vol 93 (1950), p. 54.

will be dependent on the conductivity, thickness and sequence of formations included in the measurements. 45/

Through the use of these calibration curves qualitative and quantitative analysis may be made of other test curves by correlation. Curves obtained over unknown geologic conditions are compared with the calibration curves and usually the formations present can be selected with a fair degree of accuracy. The depth to the various formations can usually be estimated fairly well also. 46/

Field work by other workers, shows that in favorable situations, a characteristic pattern in one section of a curve can be followed through a series of curves from adjacent areas, even though variations in thickness occur in parts of the geologic section. Favorable situations are those where the lithology is fairly uniform and the resistivity varies sufficiently with depth. 47/

Meidav 48/ working in Missouri has found that this type of interpretation provides more favorable results

---

45/ J. J. Jakosky, Exploration Geophysics (Newport Beach, Calif.: Trija Publishing Company, 1950), p. 509.

46/ R. Woodward Moore, "Geophysical Methods of Subsurface Exploration in Highway Construction," Public Roads, vol. 26 no. 3 (August 1950), p. 56.

47/ Jakosky, op. cit., pp. 509, 510.

48/ Tsvi Meidav, "An Electrical Resistivity Survey For Ground Water," Geophysics, XXV, no. 5 (Oct., 1960), pp. 1077-1093.

than theoretical methods of analysis. This was a result of the variation in the resistivity values for any particular rock type. Results using curve correlation methods of analysis were best wherever a continuous, traceable change of resistivity occurred.

> It is possible to distinguish bedrock empirically by means of continuous extension of stations from a locality where lithology is known to the point of interest. Such a procedure, if workable, will be independent of the absolute resistivities of bedrock and drift, and will depend only on the lithological continuity of the area. 49/

In any method of interpretation, either empirical or theoretical, calibration curves can be used to establish a range for resistivity values and in some cases to attribute a certain resistivity value to a particular rock type.

49/ *Ibid.*, p. 1089.

PART C

DATA COLLECTION AND ANALYSIS

CHAPTER XIII

INSTRUMENT PERFORMANCE

Everything done in this study was dependent on the performance of the instrument. If the resistivity measurements obtained with the AC Michmho compared favorably with results from DC apparatus, then no problems were to be expected from inductive effects or the lose of current penetration.

In the spring of 1962 the GLG 877, Advanced Geophysics class at MSU performed a series of resistivity surveys with standard DC gear. This provided an excellent opportunity to check the Michmho out. The results were quite favorable as will be seen on Figures 2 and 3.

On Figure 2, stations 6 and 7 were run at right angles to each other to later be averaged to eliminate the effects of lateral variation in soils. The Michmho curve closely follows the curve from DC equipment. The slight variations just above and just below 120' are probably due to the fact that the Michmho was used about 1/4 mile to the East of stations 6 and 7. Also on Figure 2, station 12 is not as good a match as was 6 and 7. The dryer soil conditions for the Michmho probably created much of the divergence of these curves.

On Figure 3, station 15 is an excellent fit. It was possible to get about the exact same location with the Michmho

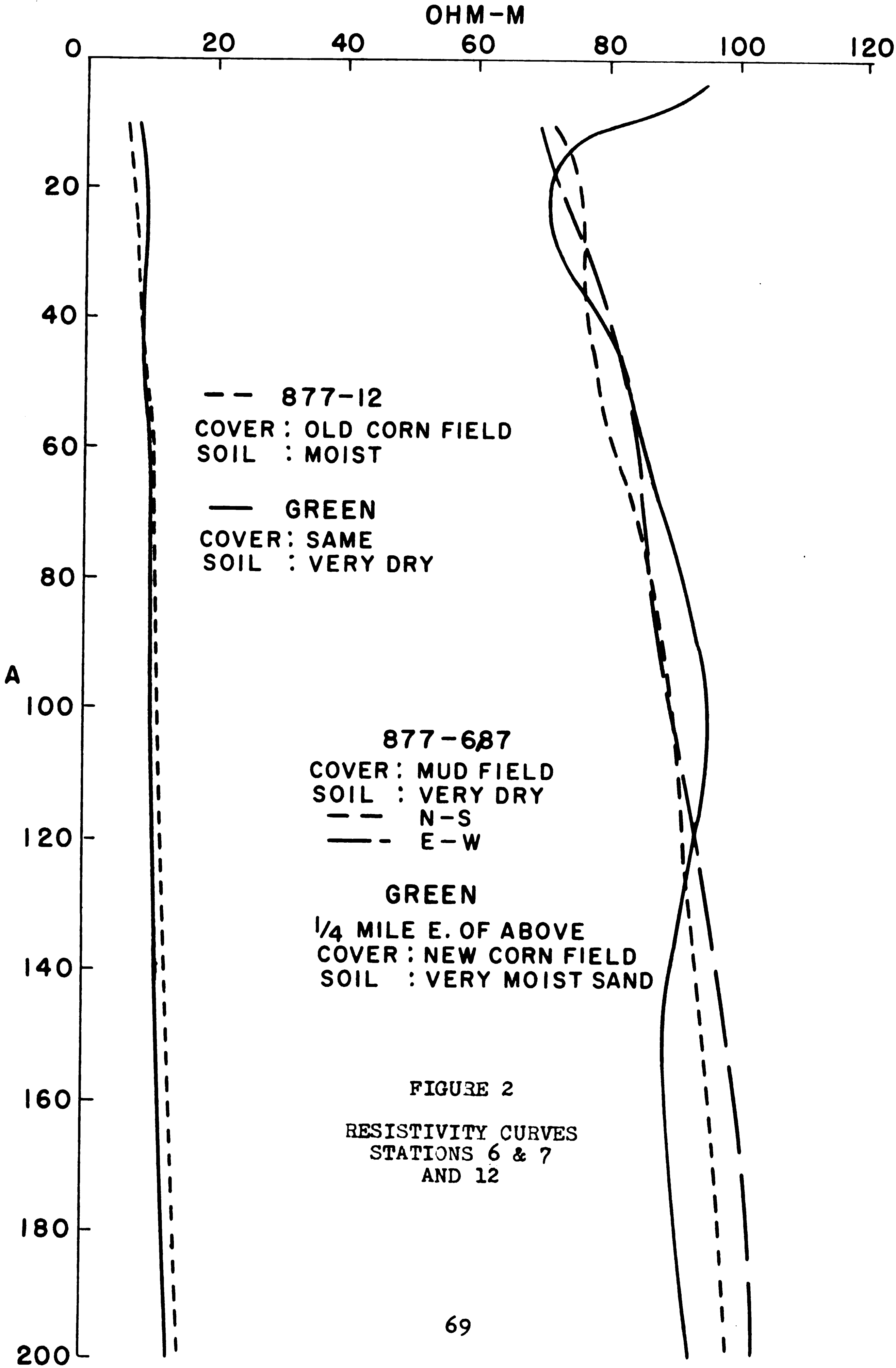


FIGURE 2

RESISTIVITY CURVES
STATIONS 6 & 7
AND 12

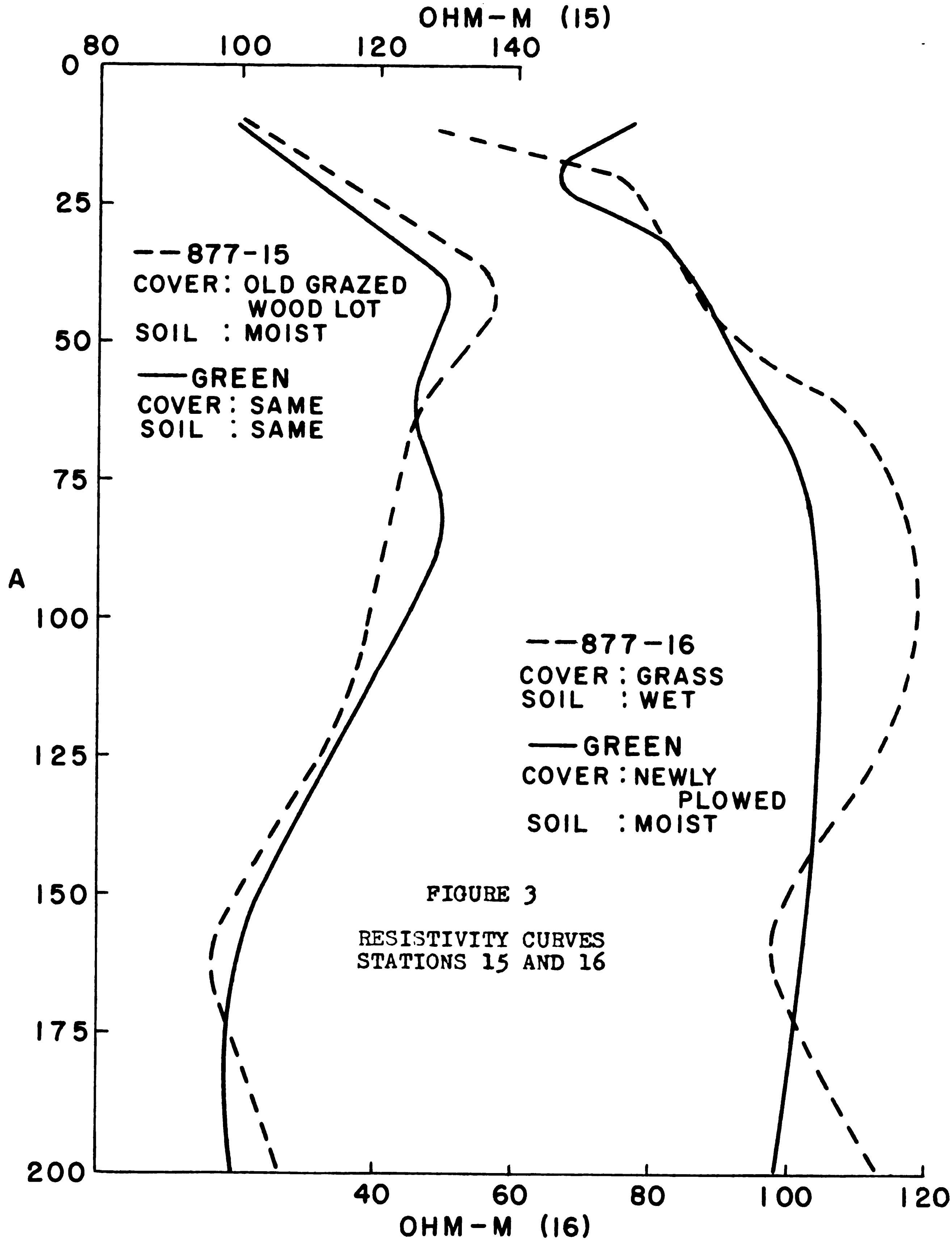


FIGURE 3

RESISTIVITY CURVES
STATIONS 15 AND 16

as when the DC gear was used. Moisture conditions were the same for all practical purposes. The curves for station 16 show a bit of divergence below 50 feet. This could be due to the fact that the field had been plowed prior to the check survey, and this created some lateral soil variation.

CHAPTER XIV

SURVEY PROCEDURES

Existing wells were selected to provide control for most resistivity stations. Additional stations were selected at the site of previous surveys conducted with standard DC resistivity equipment by the MSU geophysics class. The use of wells for control allows a quantitative comparison of the various interpretation methods. The data obtained at the sites used by the geophysics class was used for a qualitative comparison of the two different instruments.

Ideally, the resistivity survey is conducted and then holes are drilled for control. However, for the present study, this was not feasible and would not have fit in too well with one of the goals of this study. Since it was desired to test the applicability of the resistivity method under various geologic situations, preliminary control was necessary to establish the geologic conditions to be encountered.

The available well schedules for Ingham County were examined at the Lansing office of the Ground Water Branch of the U.S. Geological Survey. Well logs which had bedrock at a depth of approximately 100 feet or less and seemed to be usable in all other respects were selected. The formations from each well log were then grouped into what was believed to be the units which would be indicated by the resistivity data. These revised well logs were then put into a rough classification according to the lithologies and relative depths of the various formations. This rough classification included relatively thick or thin surface layers (course textured or fine textured materials) over bedrock and interbedded coarse and fine textured surface layers over bedrock. This is probably the most common situation to be encountered in Michigan.

The depths to the various formations are not the only depths that will be indicated by the various interpretation methods. As discussed earlier, water is the primary factor controlling the resistivity of rocks. The depth of the water table can be expected to show up in some cases then, where the change from unsaturated materials to saturated formations is sharp and distinct. Since water is so important in controlling the resistivities of rocks, it follows that different materials may contain the same amount of water of the same conductivity and thereby be indistinguishable by their resistivities. Not all of the lithologic interfaces set up will be discernible by their resistivities.

At each of the selected locations, a site was picked for the resistivity survey so as to minimize the effects of artificial interference but still remain close enough to the well to retain effective control. Level topography was also a criterion used in station location at each site. At each station the distance to the well was determined, and using a hand level, the elevation differential between the well and the station was obtained. This elevation differential was used to correct the well log depths to the depths presumed under the station. The elevation of the bedrock was assumed to be the same at the resistivity station as that at the well. The elevation differential was prorated between the depths of the different glacial drift formations. Additional bedrock formations were assumed to have the same thickness at the resistivity station as at the well. This is a possible source of error in the procedure and a case in support of drilling subsequent to the resistivity survey at exactly the same site. However, the situation at each individual station will be the same for all interpretation methods. In any case, this procedure was felt to be the most applicable for the present study.

The main part of the field data obtained were the electrode spacings and their respective instrument readings. A table was prepared which gives the resistivity value for any instrument reading and a five foot electrode spacing. Knowing this value and the electrode spacing (as a multiple of five feet), the resistivity is easily calculated. The resistivity values were plotted against their corresponding electrode spacings and subjected to the various interpretive methods.

In summary, the field procedures discussed earlier are as follows. Stations were located at a minimum distance of 300 feet from the control well, power and telephone lines, buried pipe and cables, roads and any other cultural feature which could have created interference. The levelest area available was used. The Wenner four electrode configuration was used with the vertical profiling method. Depth to adequate soil moisture was determined at each station and usually served as the minimum depth of electrode penetration. The alternating current cancelled the effects of polarization and electrode potentials, but the frequency of this current was not high enough to have a notable inductive effect. Apparent resistivity values were then computed for each instrument reading and recorded with their respective electrode spacings. Figure 4 shows a typical field setup with a small A spacing.

The effect a lateral variation in soils and a few days of hot weather will have on resistivity measurements can be seen in Figure 5, station 14. Because the alfalfa field was extremely dry the Michmho station was located about 25' West of the control station. The soil was coarser and dryer than for the DC station. The two curves have practically the same shape, but the Michmho curve's axis has shifted about 25 ohm-m to the right. The Williamston School station shows two curves which were obtained at right angles to each other. Both electrode spreads were run the same day

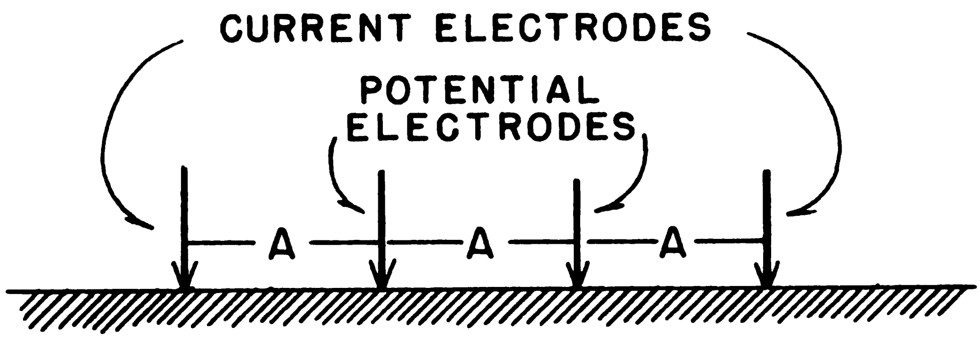


FIGURE 4

TYPICAL FIELD SETUP WITH A SMALL "A" SPACING

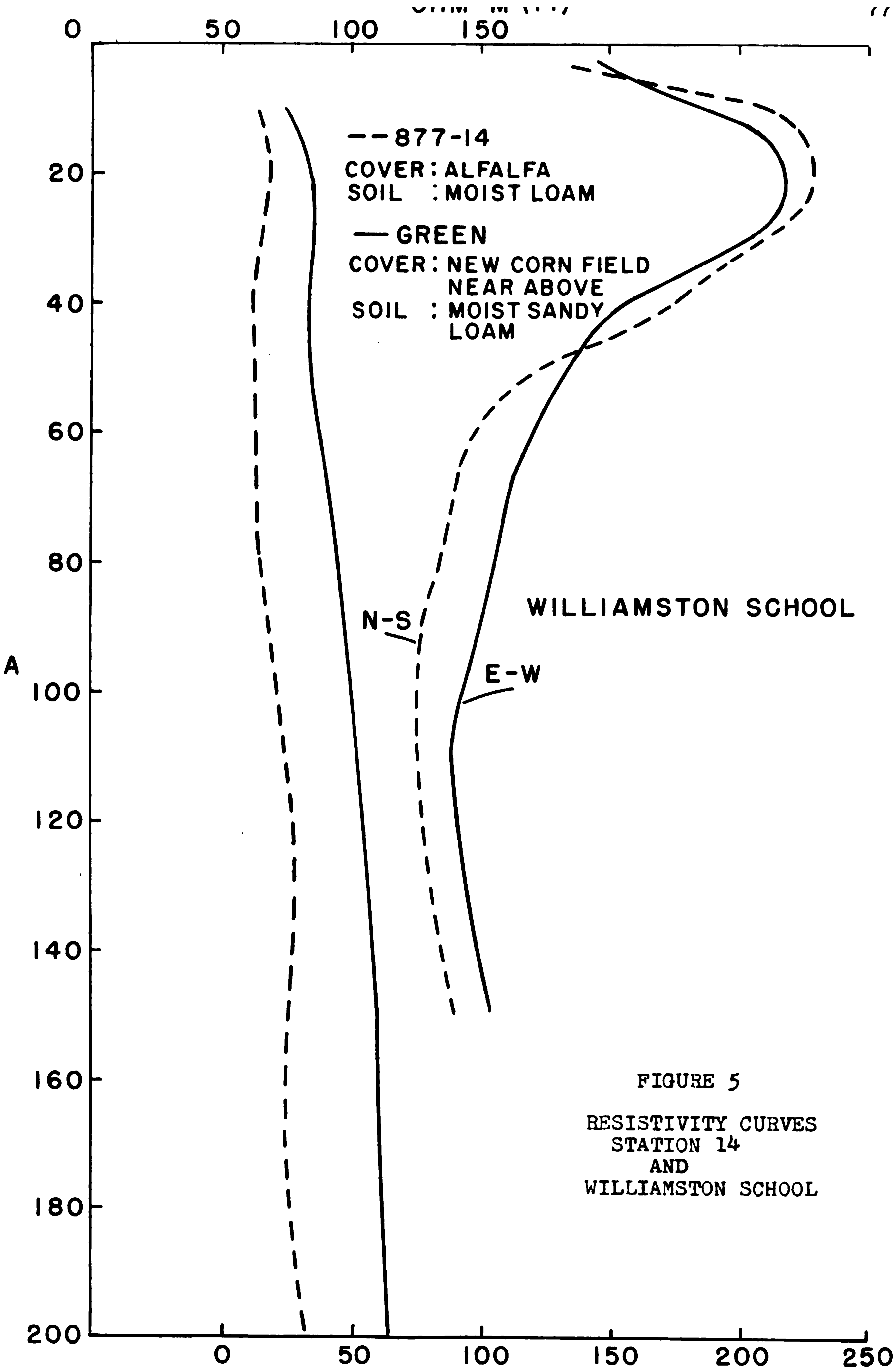


FIGURE 5

RESISTIVITY CURVES
STATION 14
AND
WILLIAMSTON SCHOOL

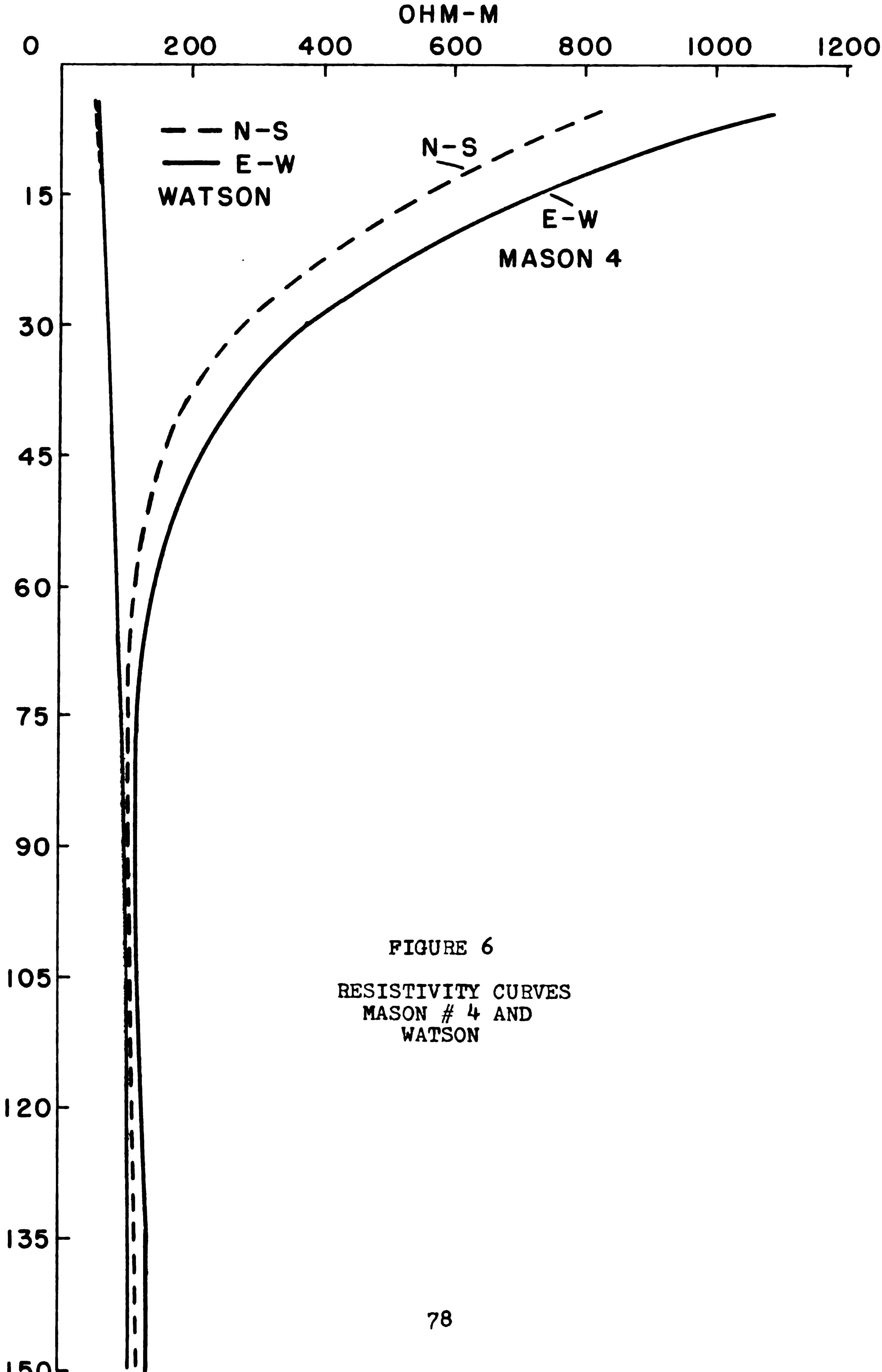


FIGURE 6

RESISTIVITY CURVES
MASON # 4 AND
WATSON

with the Michmho. The curve used in the analysis is the average of these two curves.

Figure 6 shows two other stations which were run in a similar manner to the Williamston School station. Again, these curves were averaged to eliminate the effects of a lateral variation in soil and moisture conditions. Two other stations were adjusted in a similar manner.

CHAPTER XV

APPLICATION OF INTERPRETIVE TECHNIQUES

The field data was analyzed by the methods described previously. Mooney and Wetzel's curves were used for the theoretical method. Field data were plotted on log-log paper (K & E 359-112L, 2 X 3 cycles), and matches were obtained with the master curves. In no case was it possible to use the apparent resistivities at electrode spacings of less than ten feet. To use these values would have required five or six-layer theoretical curves. It is possible though, to simply ignore these values as if they had never been obtained. Computed resistivities from the matched curves may be slightly in error due to this elimination of the soil layer. The first indicated layer will have a resistivity value which is an average of what it actually should be and the resistivity of the soil layer. Lower horizons should be affected very little by this. Depths and resistivities were calculated from their respective ratios and index point values.

Good matches were not obtained in all cases since only a limited number of resistivity and depth ratios are available to select from. The best possible match was obtained in all cases, however. Electrode spacings could have been carried out further for a few stations to obtain additional data. This didn't create too much of a problem except in a few cases where the resistivity of the lowest formation turned out to be quite small. A little more data would have allowed a better fit to be made and a more natural resistivity would have been obtained.

Time required for matching, varied with the closeness of the match. Field curves which matched very well, took five minutes or less, while those which didn't match as well, and for which any of several theoretical curves could have been used, often took over thirty minutes. In the latter case, additional sets of curves could have proven useful. However, if these additional curves were still not of the correct resistivity and depth ratios, they would only have added to the problem. In addition to these problems, it was discovered that a few curves were missing from the set. If they had been necessary for interpretation the interpreter would have had to wait until a replacement was available.

Moore's method was fairly simple to use in most cases. A ten foot summation interval was used. The upper tangent was drawn through the origin and the first one or two plotted points. Subsequent tangents were drawn through any three or more points lying on a straight line. Most often, more than three points were used to establish these tangents. Depths were read off at the intersections, and the relationships of the resistivities were determined by the slopes of the tangents. In a few cases, there were only two or three tangents (one or two intersections) which could be drawn, due to the curvature of the cumulative curve.

Layer values were determined by the Barnes Layer method as described earlier. Resistivity range limits were usually chosen so as to cross the transition lines where they had the lowest slope. This makes the boundary fall between layers differing considerably in resistivities. These layer values were also selected so as not to create just a lot of layers of small thicknesses. Values usually selected for range limits were between 100 and 500 ohm-m. Different values were used for each station depending on the appearance of the layer resistivity curves. As mentioned previously, the resistivities were plotted at a spacing equal to the bottom of the layer, instead of at the layer midpoints as suggested by Barnes.

The selection of the resistivity range limits may be a source of error for this method, but no other means of determining appropriate values could be envisioned. The Michigan State Highway Department uses correlation borings with their resistivity surveys and often finds it necessary to change their range limits slightly, even when working in the same area, depending on what the borings tell them. Resistivity relationships were obtained from the magnitudes of the layer resistivities.

Picking inflection points from the curves in the Gish-Rooney method was a bit difficult with a few stations, due to the uniform curvature shown. Several curves exhibited a pronounced maximum or minimum (or both) which were used for a depth. Some depths were selected at the middle of large gentle curves. Resistivity relationships were determined from the appearance of the different segments of the curve.

Several typical field curves were selected from the various stations and used as calibration curves. The log-log plots were used since they seemed to show the curve shapes better than the linear plots. The depths of the various interfaces were marked on the calibration curves. The other field curves were then compared to them. Ideally, curves of about the same shapes and distributions would have their interfaces fall on the depth indices of the calibration curves. Results with this method were entirely erroneous. Not a single good correlation was obtained.

Undoubtedly, persons who have specialized in any of these types of interpretation, for a period of years, would obtain slightly different and presumably better results than the present author has obtained. It is felt, however, that each method was applied correctly enough to enable a comparison of the methods to be made.

CHAPTER XVI

RESULTS OF INTERPRETATION AND ANALYSIS OF RESULTS

In figures 7-18 are shown the corrected strip logs for each control well (key to symbols on figure 19) and the predicted depths and resistivities obtained by the various interpretive methods. These are the complete well logs, color being the only characteristic omitted. In several of the logs the water table was not indicated; in these cases, a depth was selected for water table by averaging the resistivity depths in the area on the log where it was geologically feasible for water table to be. As indicated earlier in this thesis, all resistivities are in ohm-m. The Barnes Layer method and Mooney and Wetzel's theoretical method give a range of values or a specific value for each horizon; Moore's method and the Gish-Rooney Inflection method only give a general indication of the relative differences in resistivities. As noted in the previous chapter, curve correlation was entirely unusable, hence nothing is shown for this method. Due to the distance between stations (see appendix), the requirement of lithologic continuity was not met. In any area such as this, with complex Pleistocence geology, and without a close station spacing, this method can't be expected to give satisfactory results.

Observation of figures 7-18 shows that any one lithologic type did not exhibit a uniform resistivity. For the

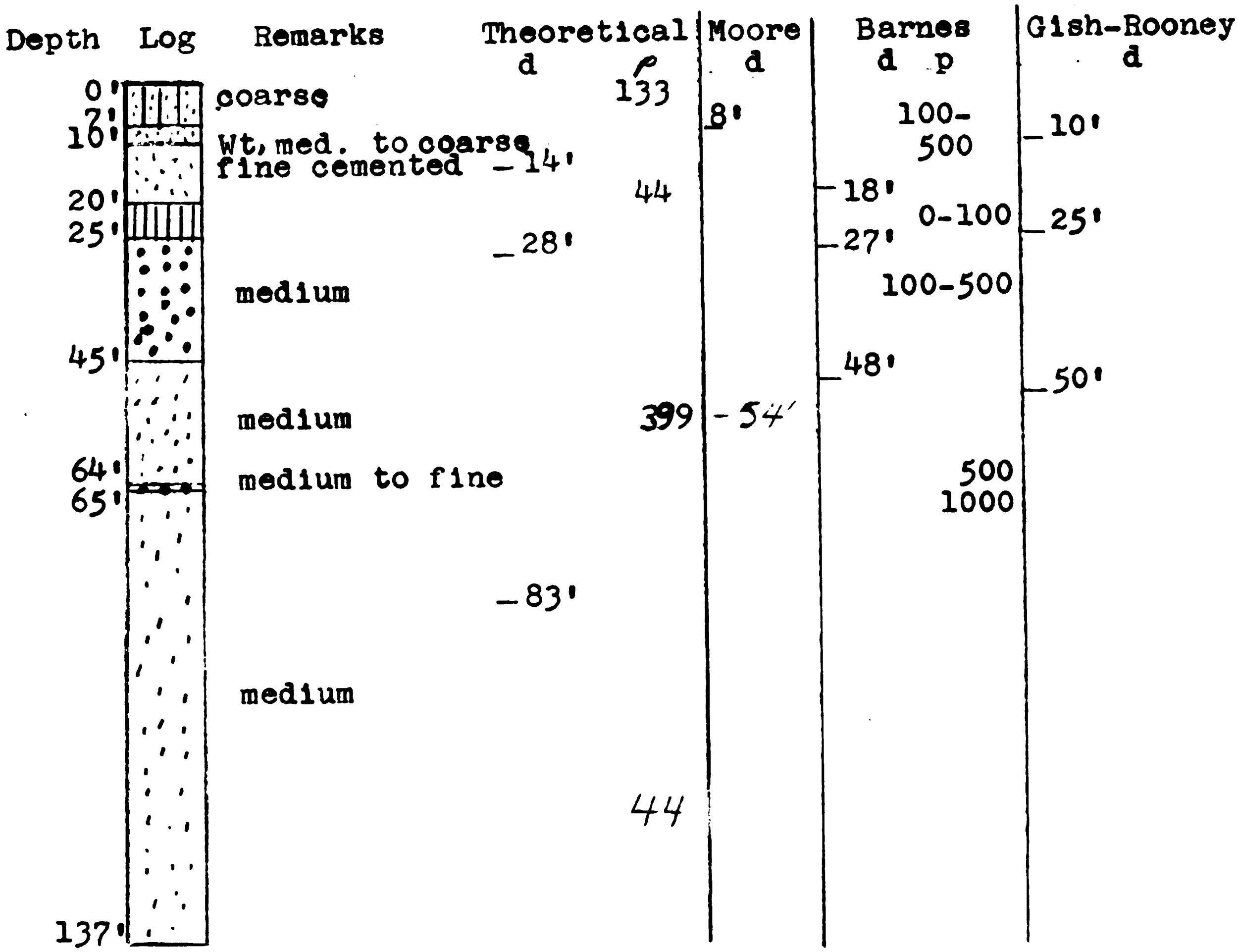


FIGURE 7

STRIP LOG AND RESISTIVITY INTERPRETATIONS
OKEMOS GRADE SCHOOL

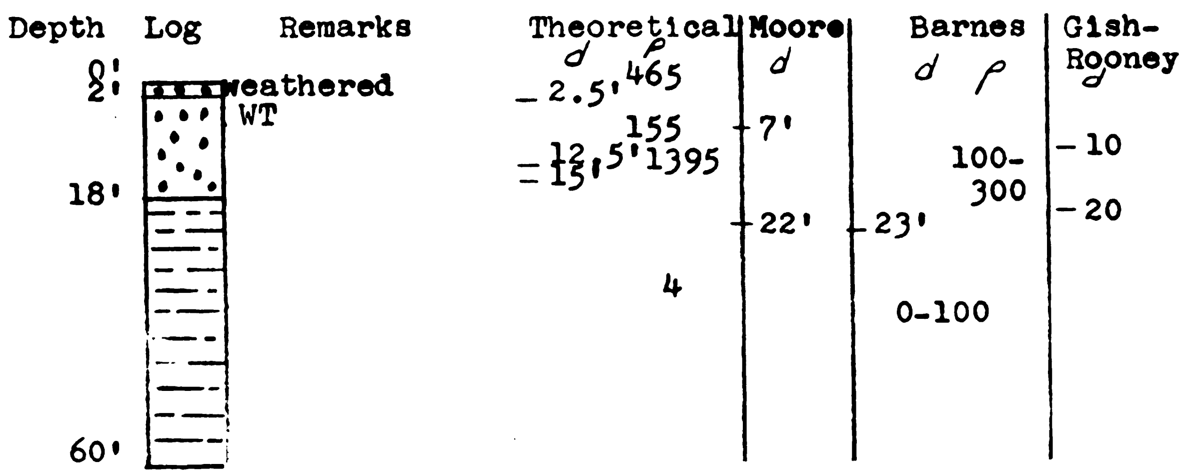


FIGURE 8

STRIP LOG AND RESISTIVITY INTERPRETATIONS
MASON (JEFFERSON ST.)

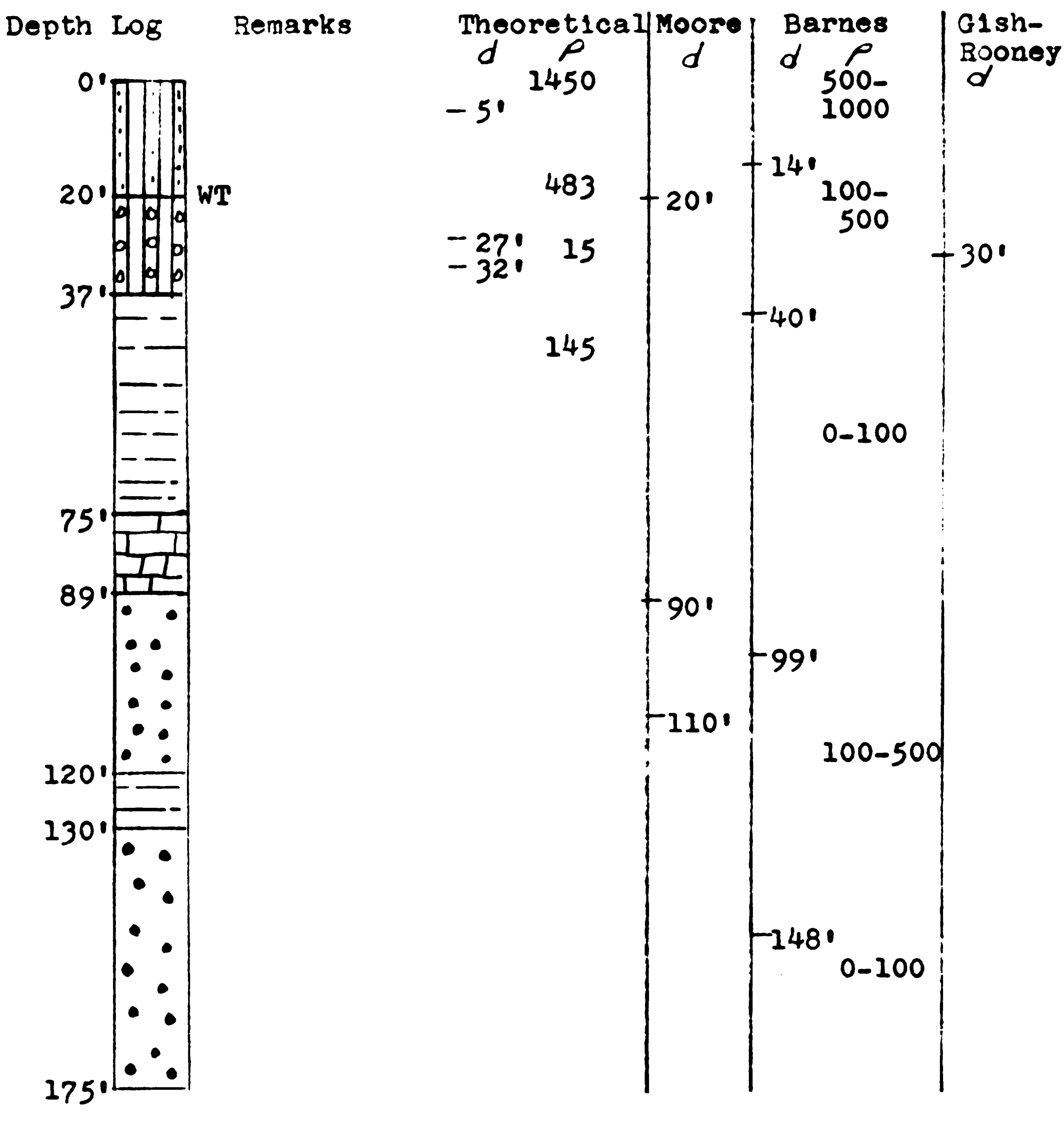


FIGURE 9

STRIP LOG AND RESISTIVITY INTERPRETATIONS
MASON #4

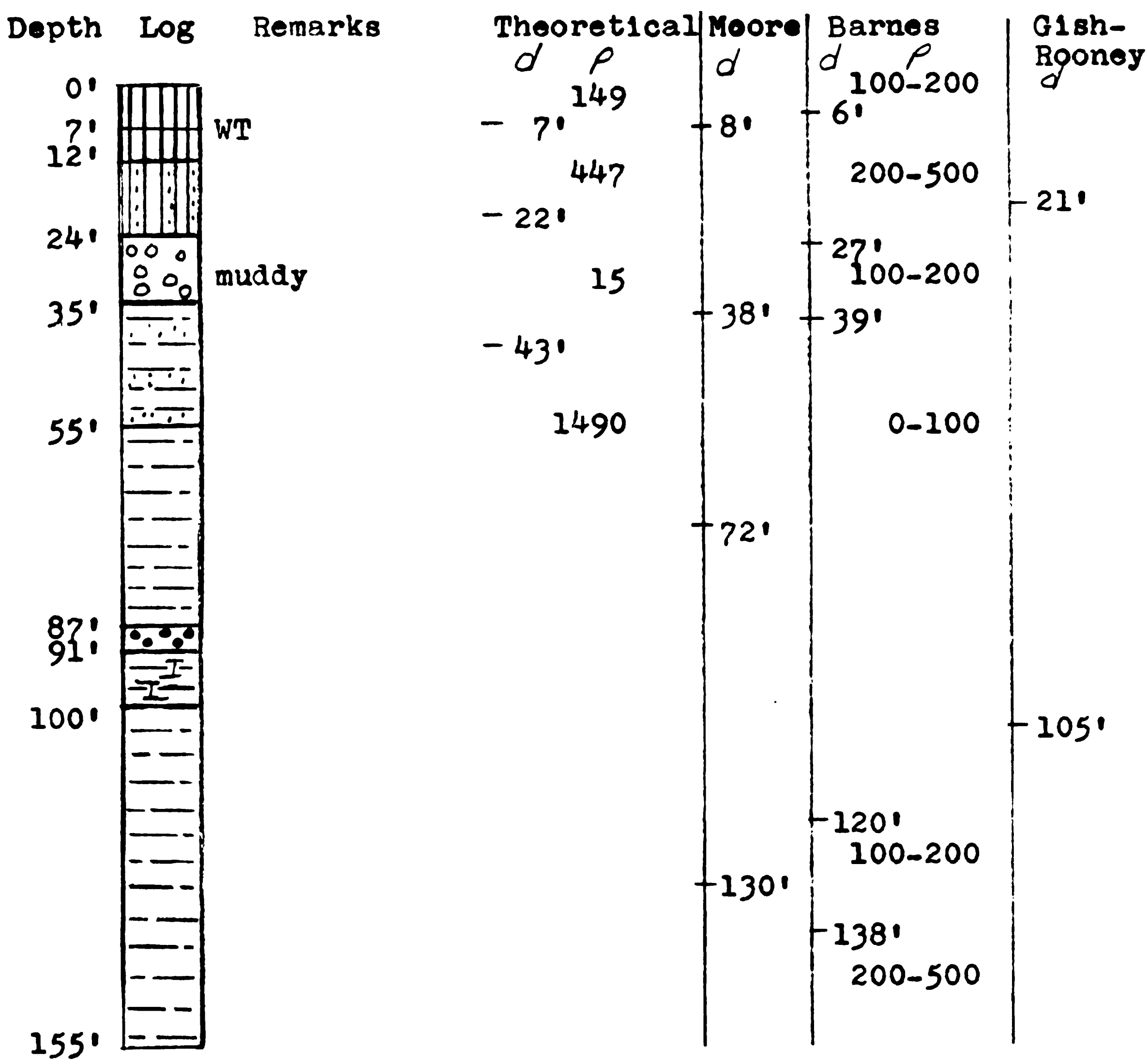
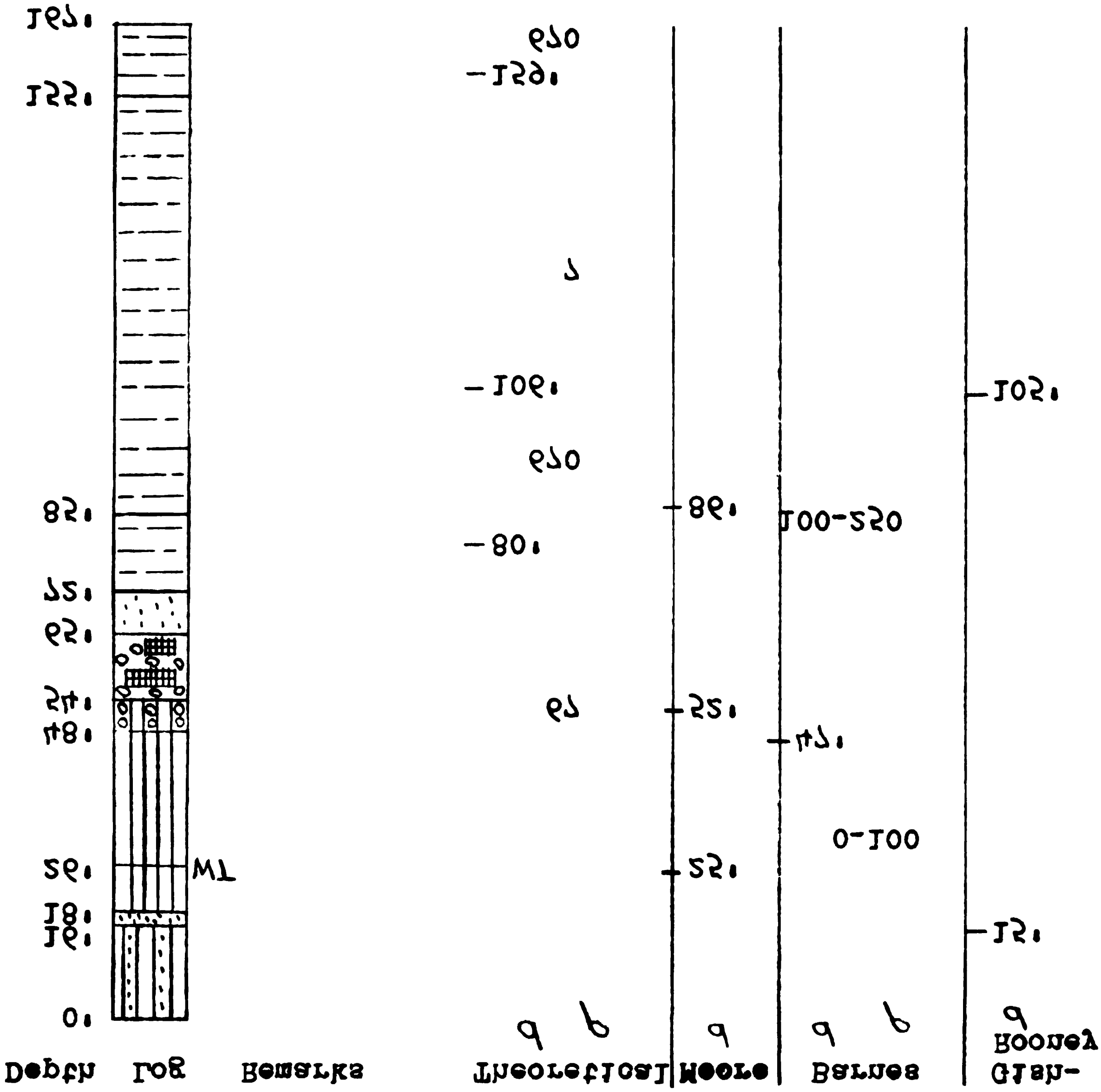


FIGURE 10

STRIP LOG AND RESISTIVITY INTERPRETATIONS
WILLIAMSTON SCHOOL

FIGURE 11

STRIP LOG AND RESISTIVITY INTERPRETATIONS
WATSON



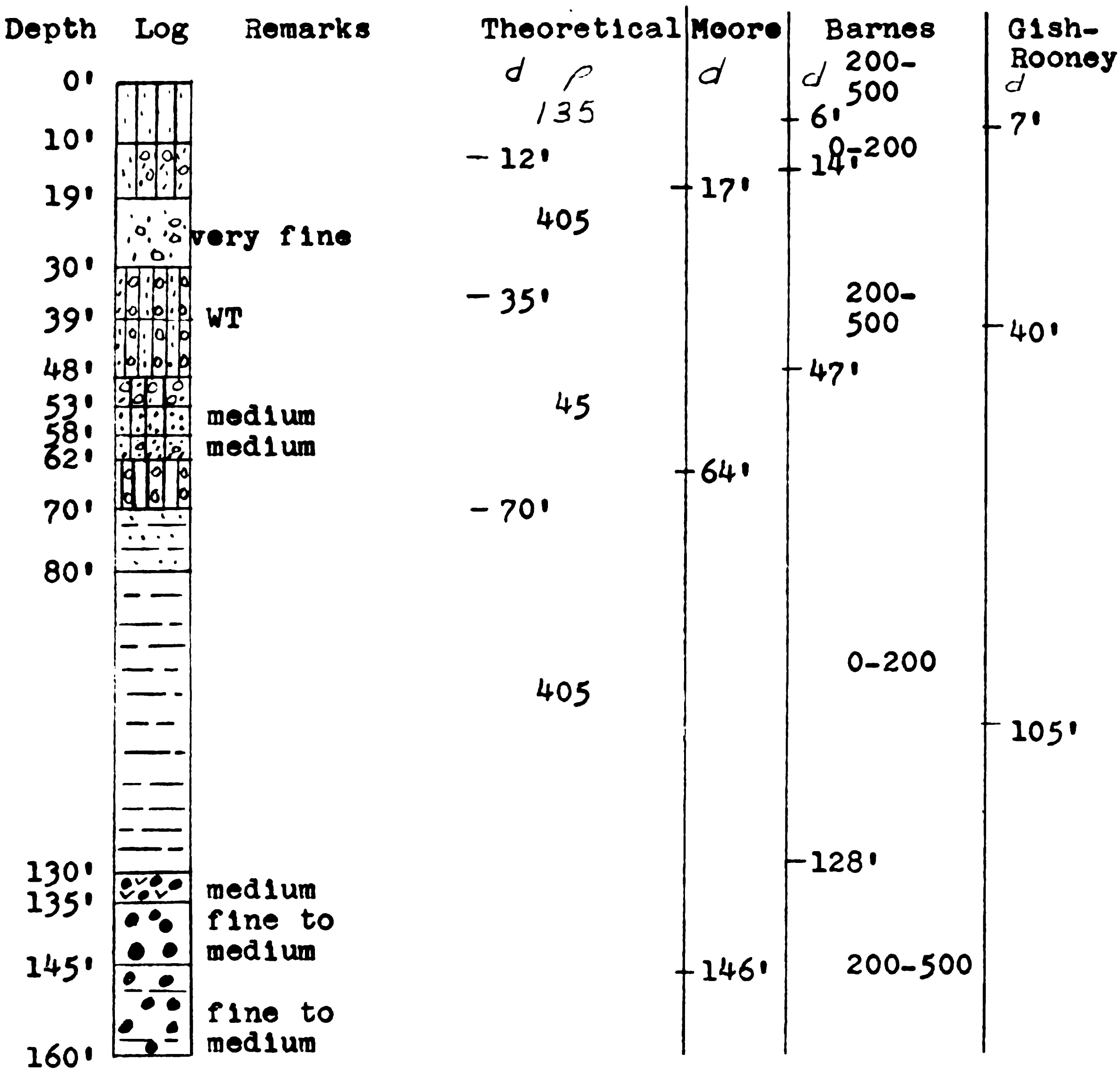


FIGURE 12

STRIP LOG AND RESISTIVITY INTERPRETATIONS
SOIL SCIENCE

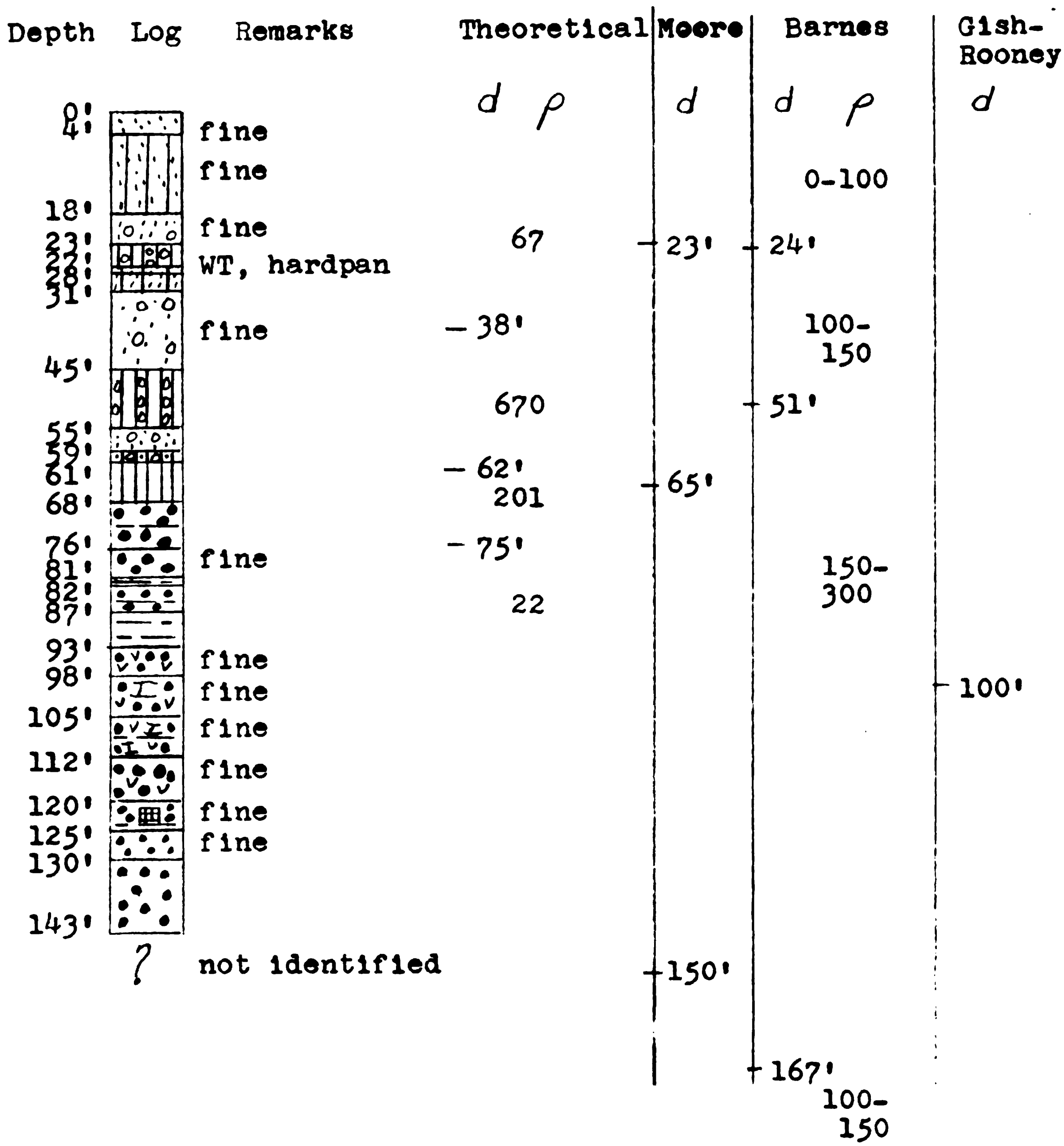


FIGURE 13

STRIP LOG AND RESISTIVITY INTERPRETATIONS
MORROW

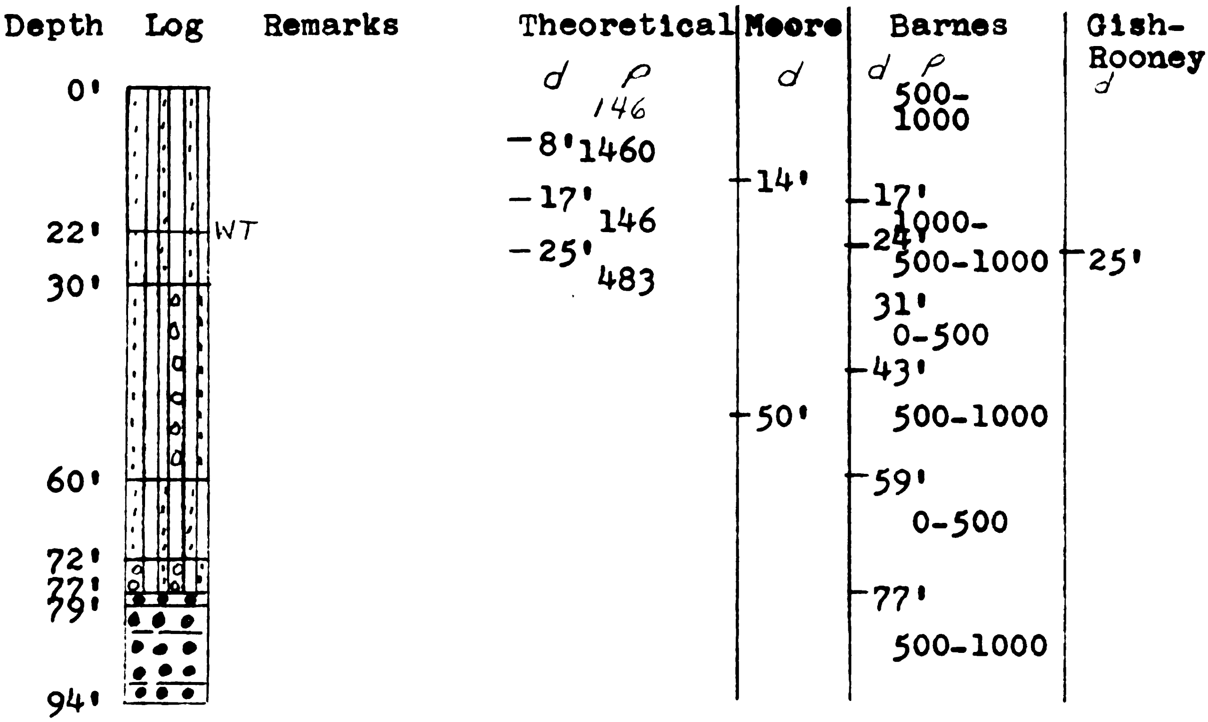


FIGURE 14

STRIP LOG AND RESISTIVITY INTERPRETATIONS
BEEF CATTLE BARNS (STA.#1)

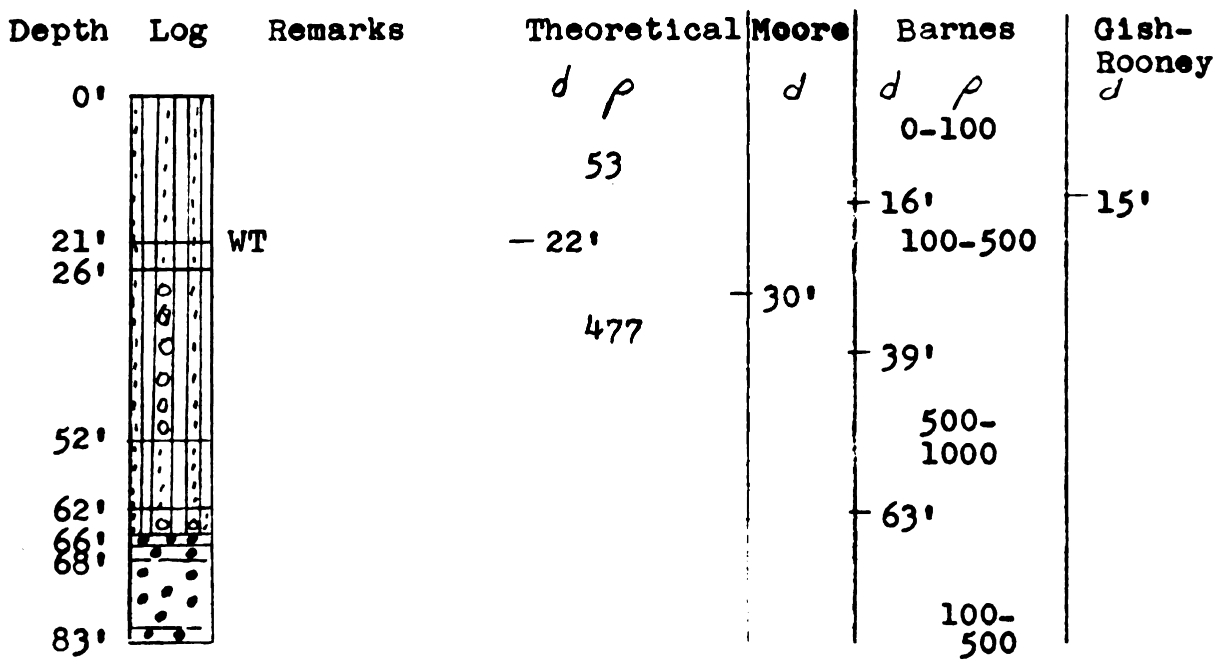


FIGURE 15

STRIP LOG AND RESISTIVITY INTERPRETATIONS
BEEF CATTLE BARNS (STA.#2)

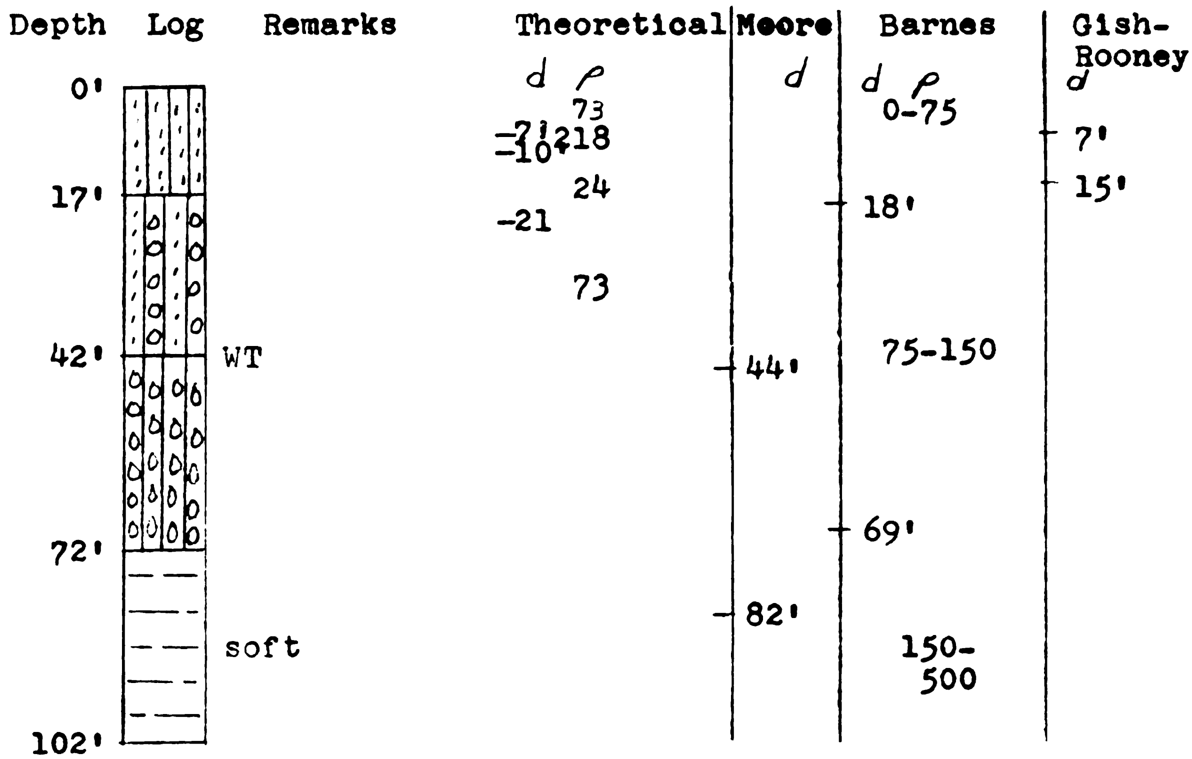


FIGURE 16

STRIP LOG AND RESISTIVITY INTERPRETATIONS
GROUND MAINTENANCE

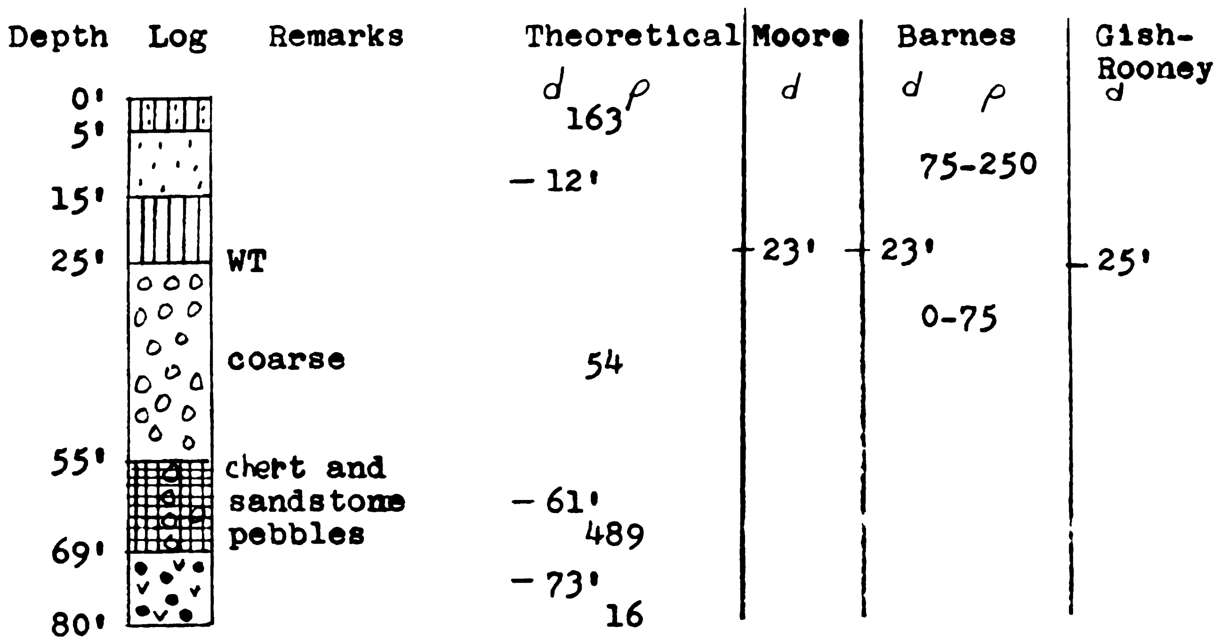


FIGURE 17

STRIP LOG AND RESISTIVITY INTERPRETATIONS
SCHMIDT

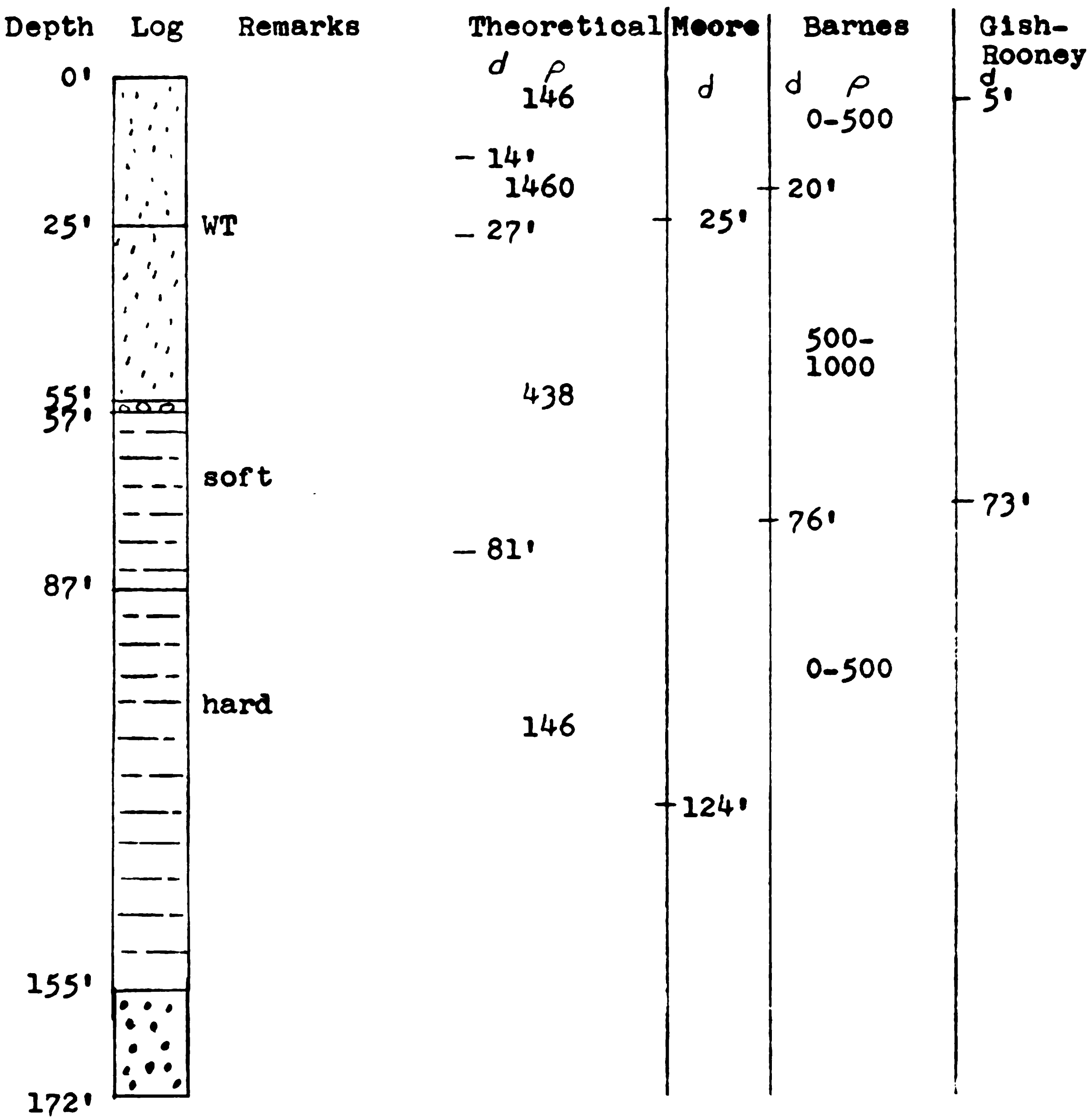


FIGURE 18

STRIP LOG AND RESISTIVITY INTERPRETATIONS
ONONDAGA

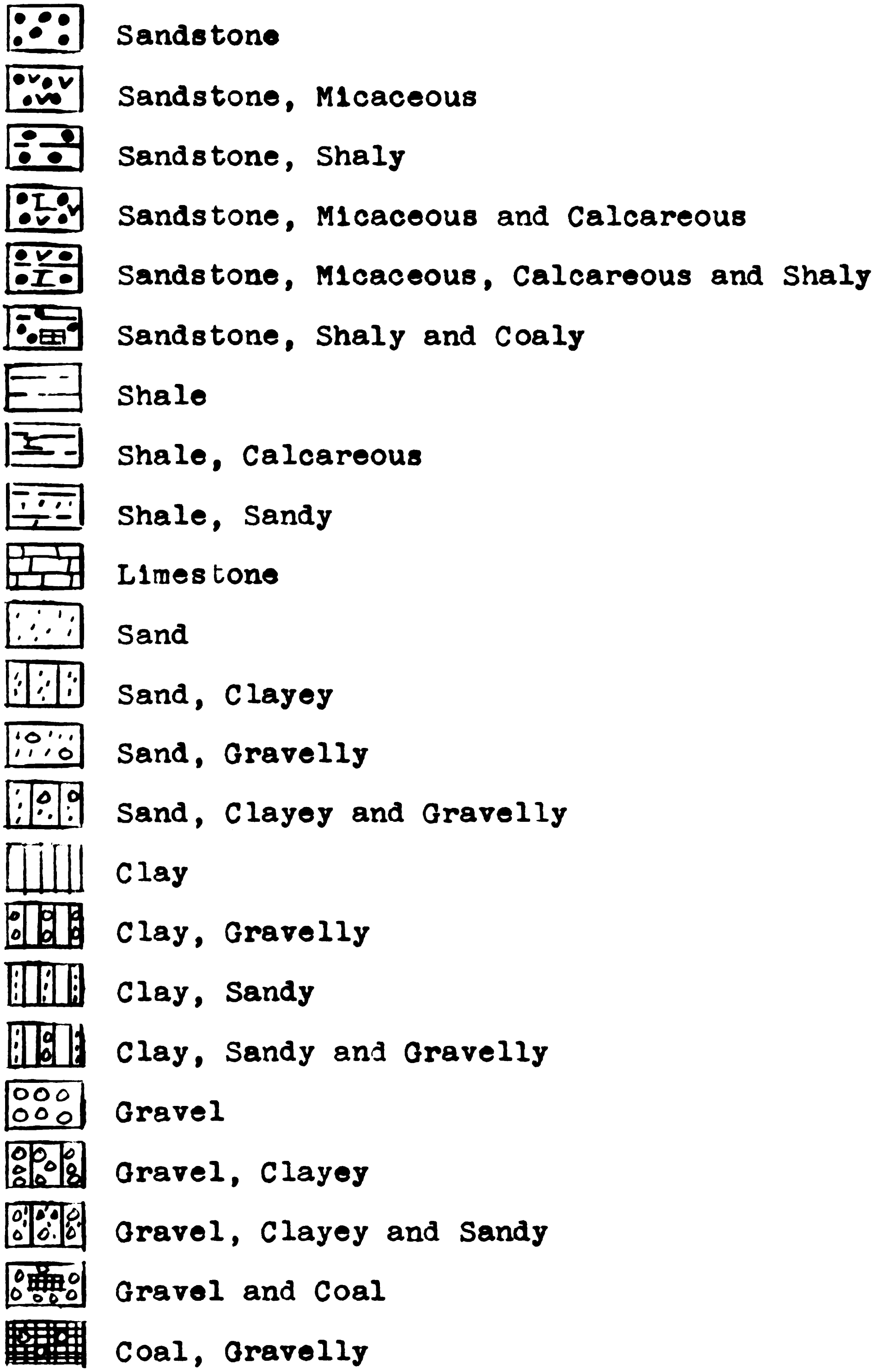


FIGURE 19

STRIP LOG SYMBOLS

theoretical method, sandstone varied from 16 ohm-m to 1395 ohm-m; for Barnes method, sandstone varied from a low range of 100-300 ohm-m to a high range of 500-1000 ohm-m. Other lithologies had similar variations and there was a considerable overlapping of resistivity values for several different rock types. This seems to indicate, at least in this area, that a particular lithology will not necessarily give the same resistivity value in different locations.

Not all units shown on the strip logs are indicated by the interpretive methods, probably because many of the units differ only slightly in the physical characteristics which control their resistivities. As mentioned earlier, the formations on the well logs had been grouped into units of similar lithologies; these grouped lithologic units were considered to be those which would be indicated by a resistivity survey. This grouping was based largely on the major differences in lithologies and lithification of the deposits and on the relative depths and thicknesses of the various formations.

The depths of these grouped formations and the interpreted depths are shown in Table III. Also shown are depth coefficient values: K equals the resistivity depth divided by the geological depth. A K value of unity indicates that the resistivity depth is exactly the same as the geological depth, while K values greater or less than unity, indicates

TABLE III

RESULTS OF DEPTH ANALYSIS

Well depths		Theoretical		Moore		Barnes		Gish-Rooney	
d (a)	material	d	K	d	K	d	K	d	K
	1) Okemos Grade School								
0'	sand								
10'	water table in sand	14'	1.40	8'	0.80	18'	1.80	10'	1.00
25'	sandstone	28'	1.12	(b)		27'	1.08	25'	1.00
45'	sand	83'	1.84	54'	1.20	48'	1.07	50'	1.11
	2) Mason (Jefferson St.)								
0'	weathered sandstone								
2'	water table in sandstone	2.5'	1.25	(b)		(b)		(b)	
18'	shale	15'	0.83	22'	1.22	23'	1.28	20'	1.11
		one extra @ 12.5'		one extra @ 7'				one extra @ 10'	
	3) Mason (#4)								
0'	sandy clay								
20'	water table in gravelly clay	27'	1.35	20'	1.00	14'	0.70	(b)	
37'	shale	32'	0.87	(b)		40'	1.25	30'	0.8.
75'	limestone	not differentiated from shale by any method							
89'	sandstone	(b)		90'	1.01	99'	1.11	(b)	
120	shale	(b)		110'	0.92	(b)		(b)	
		one extra @ 5'				one extra @ 148'			

footnotes are at end of Table

TABLE III (continued)

Well depths		Theoretical		Moore		Barnes		Gish-Rooney	
d (a)	material	d	K	d	K	d	K	d	K
4) Williamston School									
0'	clay								
7'	water table in clay (c)	7'	1.00	8'	1.14	6'	0.86	(b)	
24'	muddy gravel	22'	0.92	(b)		27'	1.12	21'	0.88
35'	shale	43'	1.23	38'	1.09	39'	1.11	(b)	
				two extra @ 72',130'		two extra @ 120', 138'		one extra @ 105'	
5) Watson									
0'	sandy clay								
26'	water table in clay	(b)		25'	0.96	(b)		15'	0.58
54'	gravel, coal & sand	(b)		52'	0.96	47'	0.87	(b)	
72'	shale	80'	1.11	86'	1.19	(b)		(b)	
		two extra @ 106', 159'						one extra @ 105'	
6) Soil Science									
0'	sand, clayey								
10'	sand, clayey & gravelly	12'	0.92	17'	1.31	14'	1.08	7'	0.54
39'	water table in clay	35'	0.90	(b)		47'	1.20	40'	1.03
62'	clay, gravelly	(b)		64'	1.03	(b)		(b)	
70'	shale, sandy	70'	1.00	(b)		(b)		(b)	
130'	sandstone	(b)		146'	1.12	128'	0.98	105'	0.81
						one extra @ 6'			

TABLE III (continued)

Well depths		Theoretical		Moore		Barnes		Gish-Rooney	
d (a)	material	d	K	d	K	d	K	d	K
	7) Morrow								
0'	sand								
28'	water table in sand, clay & gravel (c)	38'	1.36	23'	0.82	24'	0.86	(b)	
55'	sand, gravelly	62'	1.13	(b)		51'	0.93	(b)	
68'	sandstone	75'	1.10	65'	0.96	(b)		(b)	
143'	? (d)	(b)		150'	1.05	167'	1.17	100'	0.70
	8) Beef Cattle Barns (sta. #1)								
0'	sandy clay								
22'	water table in sandy clay (c)	25'	1.14	14'	0.64	24'	1.09	25'	1.14
77'	sandstone	(b) two extra @ 8', 17'		50'	0.65	77' four extra @ 17', 31', 43', 59'	1.00	(b)	
	9) Beef Cattle Barns (sta. #2)								
0'	sandy clay								
21'	water table in sandy clay (c)	22'	1.05	30'	1.43	16'	0.76	15'	0.71
66'	sandstone	(b)		(b)		63' one extra @ 39'	0.96	(b)	

TABLE III (continued)

Well depths		Theoretical		Moore		Barnes		Gish-Booney	
d (a)	material	d	K	d	K	d	K	d	K
10) Ground Maintenance									
0'	sand & clay								
17'	sand, gravel & clay	21'	1.24	(b)		18'	1.06	15'	0.88
42'	water table in gravel & clay	(b)		44'	1.05	(b)		(b)	
72'	shale	(b) two extra @ 7', 10'		82'	1.14	69'	0.96	(b) one extra @ 7'	
11) Schmidt									
0'	sandy clay								
15'	clay	12'	0.80	(b)		(b)		(b)	
25'	water table in gravel (c)	(b)		23'	0.92	23'	0.92	25'	1.00
55'	coal, gravelly	61'	1.11	(b)		(b)		(b)	
69'	sandstone	73'	1.06	(b)		(b)		(b)	
12) Onondaga									
0'	sand								
25'	water table in sand	27'	1.08	25'	1.00	20'	0.80	(b)	
57'	shale	81'	1.42	(b)		76'	1.33	73'	1.28
155'	sandstone	(b) one extra @ 14'		124'	0.80	(b)		(b) one extra @ 5'	

(a) depth to material.

(b) no depth obtained.

(c) interpolated depths of water table.

(d) well ended at 143' and did not identify this information.

resistivity depths greater or less than the geological depth.

For the stations at which the depth of water table was interpolated, a footnote is added in the table. Where no depth was indicated for an interface is an additional footnote. Additional depths were indicated by all methods where no lithologic break occurred; these are also noted. Possible some alteration in moisture conditions caused a change by a change from a fine to a medium texture caused these depths to be indicated. These extra depths will be considered as extraneous material which detracts from the general usefulness of the interpretive method.

As mentioned previously the formations for each well log were grouped into units of similar lithology. Only one formation, which was retained as a unit by itself, did not show up for any interpretive method. This was the fourteen foot thick limestone bed (in location 3) of Table III. The limestone could not be differentiated from the overlying shale, probably because of its small thickness and depth of burial.

The corrected well logs fell into three general categories: bedrock at a shallow depth with variable surface layers (locations 1-4 in Table III); bedrock at greater depths, with at least one other formation between the water table and bedrock (locations 5-7 in Table III); bedrock at depth with the water table as the only interface above bedrock (locations 8-12 in Table III. These categories were not considered large enough to allow any type of analysis to be made. Quite a few more locations in each category would be necessary before any conclusions could be drawn from data separated into these categories.

No publication dealing with the interpretation of resistivity data, which this writer has seen, has contained any statistical interpretation of data. Consulting with a member of the Statistics Department of Michigan State University confirmed the suspicion that no statistical test is applicable for this type of data.

The depth coefficient was selected as a possible means of altering the basic data so that it would be comparable. For each interpretive method the means and standard deviations were computed for the K values obtained. The number of interfaces which were not indicated, and the number of interfaces indicated for which there was no lithological basis, are considered as errors in the interpretation. This information is shown in Table IV. The Gish-Rooney inflection method and the theoretical method had total errors of 27 and 22 respectively. This is about one undetermined or missed depth for each correct depth. Completeness of prediction, which will be defined as the ratio of the number of actual predicted depths to the number of actual geological depths expressed as a percentage, is

TABLE IV

COMPARISON OF INTERPRETIVE METHODS

Method	$\bar{K}$ (a)	s (b)	Extra depths	Missed depths	Total error	C.P. (c)
Theoretical	1.13	0.23	9	13	22	66%
Moore	1.02	0.19	3	13	16	66%
Barnes	1.05	0.22	8	12	9	68%
Gish-Rooney	0.91	0.21	5	22	27	42%

(a) mean value of depth coefficient.

(b) standard deviation of K values.

(c) completeness of prediction: equals number of predicted depths divided by number of actual depths.

42% and 66% for the Gish-Rooney and theoretical methods. $\bar{K}$ for the inflection method was 0.09 too low and 0.13 too high for the theoretical method. Moore's method had the fewest number of errors and had the best $\bar{K}$ value (16 errors and $\bar{K}$ = 1.02). Barnes' method is almost as good (20 errors and $\bar{K}$ = 1.05). The standard deviation for Moore's method (0.19) is the lowest of all the interpretive methods. The theoretical, Moore's and Barnes' methods missed about the same number of depths while the Gish-Rooney method missed ten more. The completeness of prediction is 66% for Moore and 68% for Barnes. The actual interfaces which were indicated, were predicted quite accurately. Barnes' and Moore's methods appear to be the most accurate interpretive methods used.

Moore's method had the fewest extra depths which the theoretical method and Barnes' method had about three times as many extra depths as this. The theoretical method usually gave an extra depth where at least one other depth was missed. Some variation in the resistivity curve caused the extra depth to be indicated. The extra depths from Barnes method are a result of setting up resistivity range limits for each curve. Because the range of resistivity values was not precisely known, any deviation of the proposed limits from what they should be will cause the creation of several additional interfaces.

Since the depths to ground-water and the depth to bedrock are often the primary features, which are to be obtained with resistivity surveys, each method of interpretation was analyzed to determine the accuracy of these depth predictions. The resulting data is shown in Table V. The inflection method, again, is completely inferior to the other methods largely because of its completeness of prediction values (50% for water table and 42% for bedrock). Overall, Moore's method appears to be the best. Completeness of prediction is 83% for water table and 67% for bedrock. $\overline{K}$ is 0.98 for water table and 1.02 for bedrock. Barnes layer method and the theoretical method are quite comparable to each other.

Since Barnes' method has a $\overline{K} = 1.00$ for water table this would seem to be the best. However, this is not the case since the standard deviation is equal to a third of the $\overline{K}$ value, which is quite high. Moore's method, while not having the lowest standard deviation is sufficiently accurate.

All methods, except the Gish-Rooney inflection method, missed a total of six water table and bedrock depths. The Gish-Rooney method missed a total of thirteen.

From these two analyses, Moore's method appears to give the best depth interpretations. This method, as well as the others, is not absolutely correct. Some lithologic interfaces were missed by the interpretations and extra

TABLE V

ANALYSIS OF DEPTHS TO WATER TABLE AND BEDROCK FOR EACH METHOD OF INTERPRETATION

Method	Boundary (a)	$\bar{K}$ (b)	s (c)	Missed depths	C.P. (d)
Theoretical	WT	1.17	0.18	3	75%
	BR	1.09	0.18	3	75%
Moore	WT	0.98	0.21	2	83%
	BR	1.02	0.20	4	67&
Barnes	WT	1.00	0.34	3	75%
	BR	1.11	0.15	3	75%
Gish-Rooney	WT	0.91	0.22	6	50%
	BR	1.00	0.20	7	42%

(a) WT - water table, BR - bedrock.

(b) mean value of depth coefficients.

(c) standard deviation of K values.

(d) completeness of prediction.

depths were also predicted which did not appear on the well logs. The depths that were predicted for actual interfaces varied both above and below the actual geologic depths. This variance was not dependent on the surface materials or the deeper strata. Observation of Table III shows, that for the same type of materials, depths both above and below the geologic depth were predicted.

In most cases, depths are the most important feature to be obtained from resistivity interpretation. The resistivities of the various layers are also diagnostic characteristics of the geologic formations. Resistivities for Moore's method are indicated by the different slopes of the tangents drawn to the cumulative curve. It is not possible to give these slopes a value which is indicative of the resistivities of the formations, where several formations are involved. All the layers contribute something to the various apparent resistivity readings, and these contributions cannot be separated into their component resistivities by Moore's method. Probably the only way of comparing the resistivities, is simply to note if the resistivity of any layer (slope of tangent) is greater or less than the resistivity of the layer immediately below this. This type of treatment can be used in comparing different stations but it is only qualitative.

Following are a series of curves for the stations not presented earlier. Figures 20 and 21 illustrate the interpretive methods used. Figures 22-26 show the standard resistivity curves.

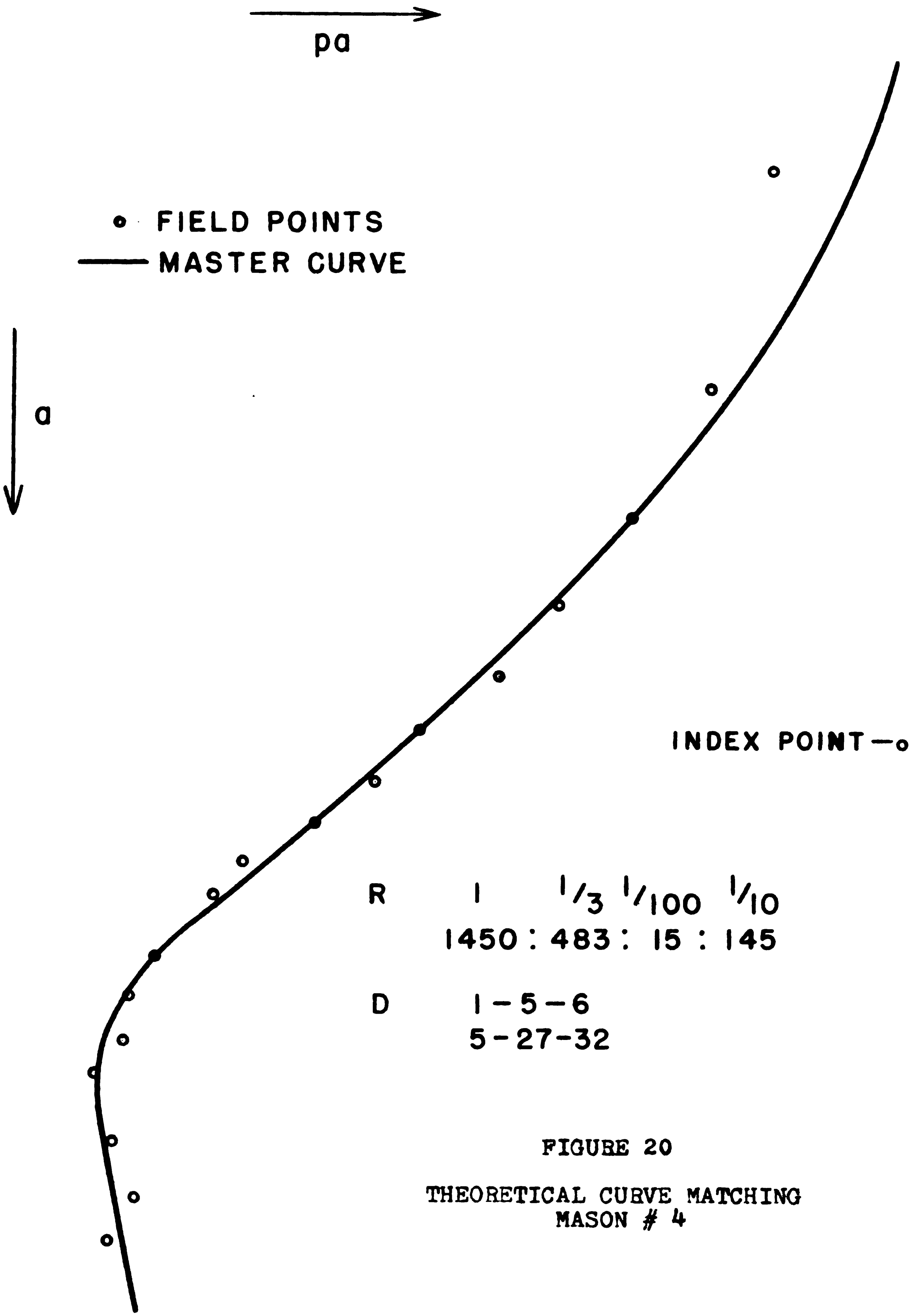


FIGURE 20

THEORETICAL CURVE MATCHING
MASON # 4

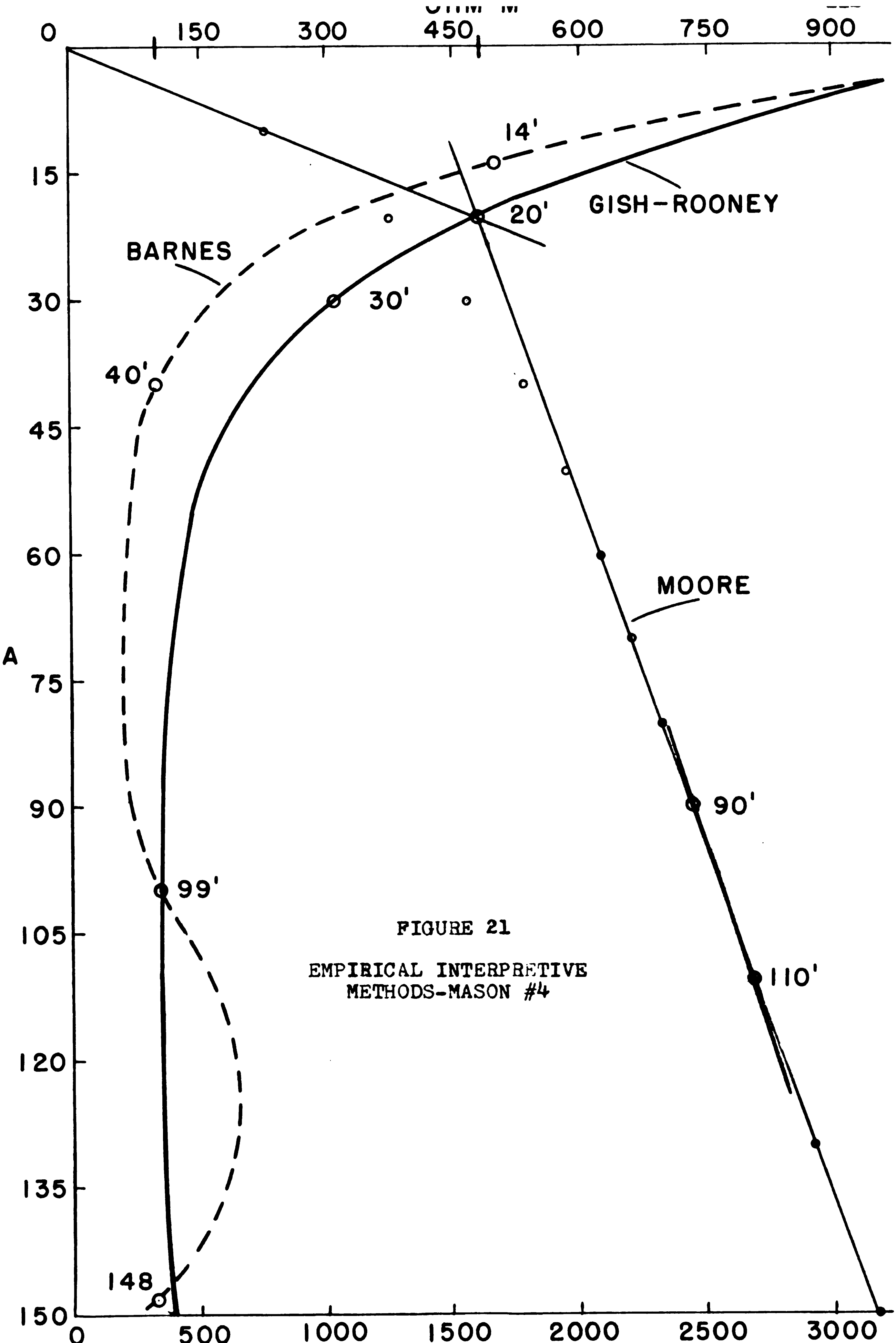


FIGURE 21

EMPIRICAL INTERPRETIVE
METHODS-MASON #4

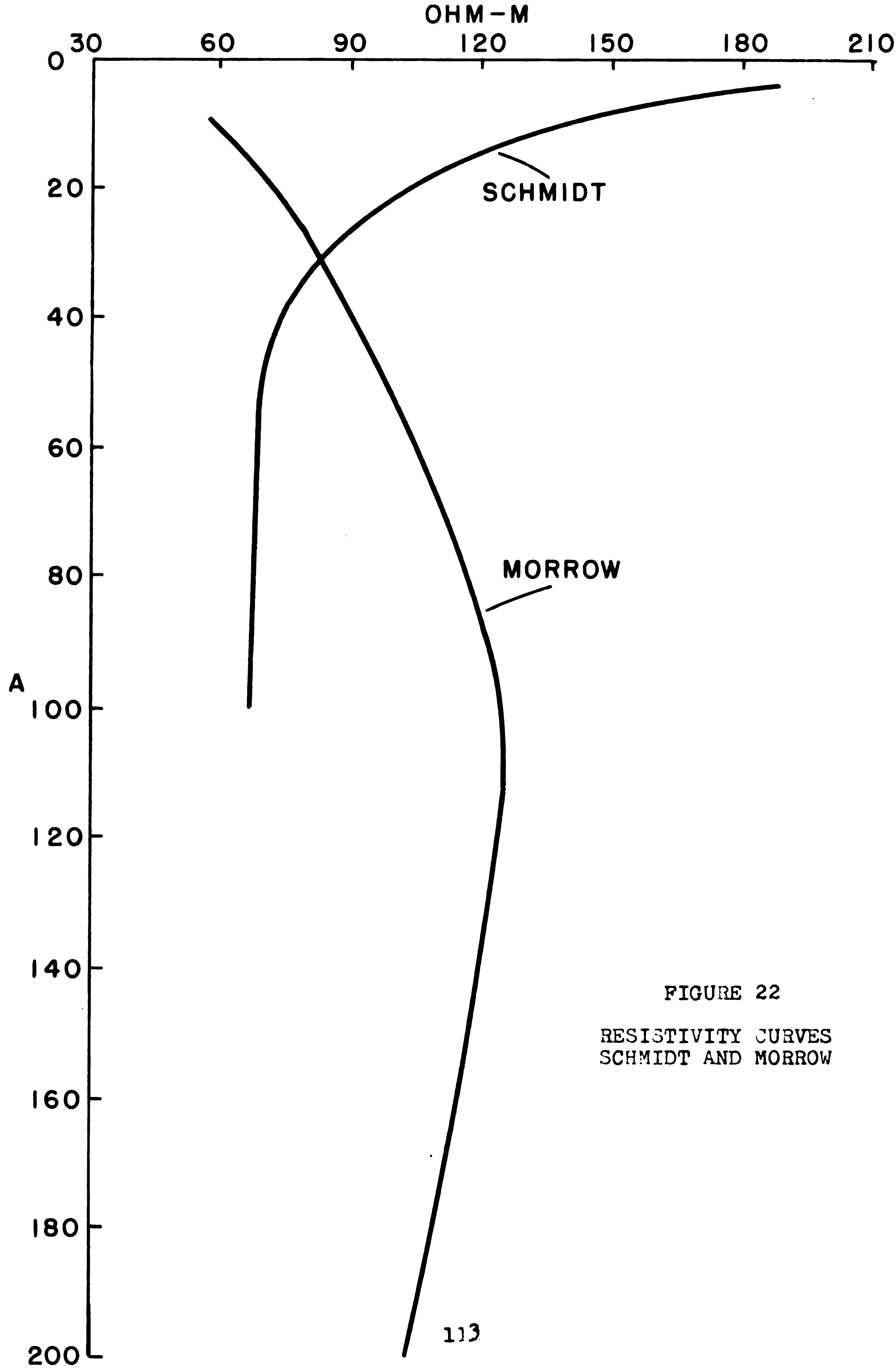


FIGURE 22

RESISTIVITY CURVES
SCHMIDT AND MORROW

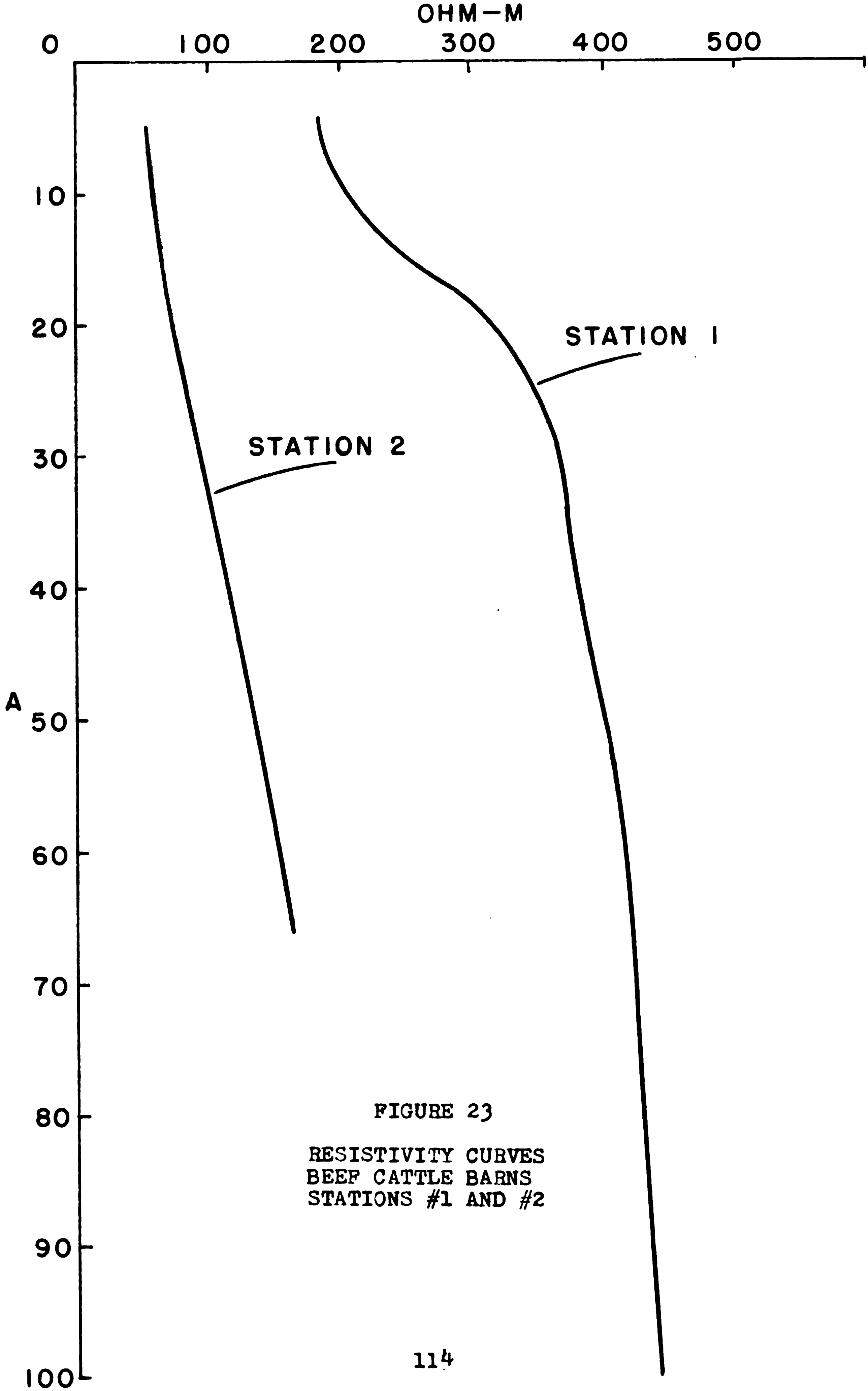


FIGURE 23

RESISTIVITY CURVES
BEEF CATTLE BARNS
STATIONS #1 AND #2

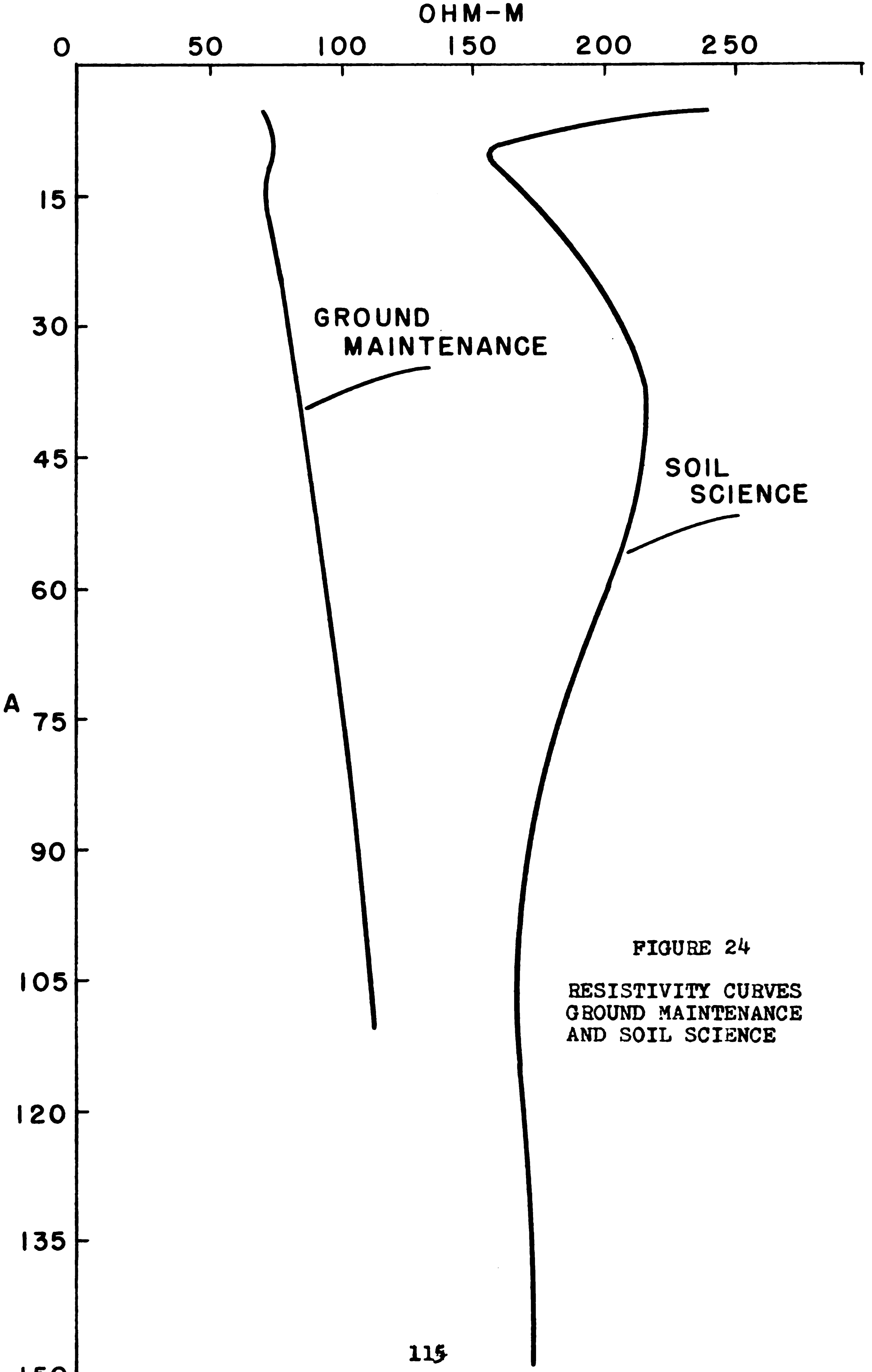


FIGURE 24

RESISTIVITY CURVES
GROUND MAINTENANCE
AND SOIL SCIENCE

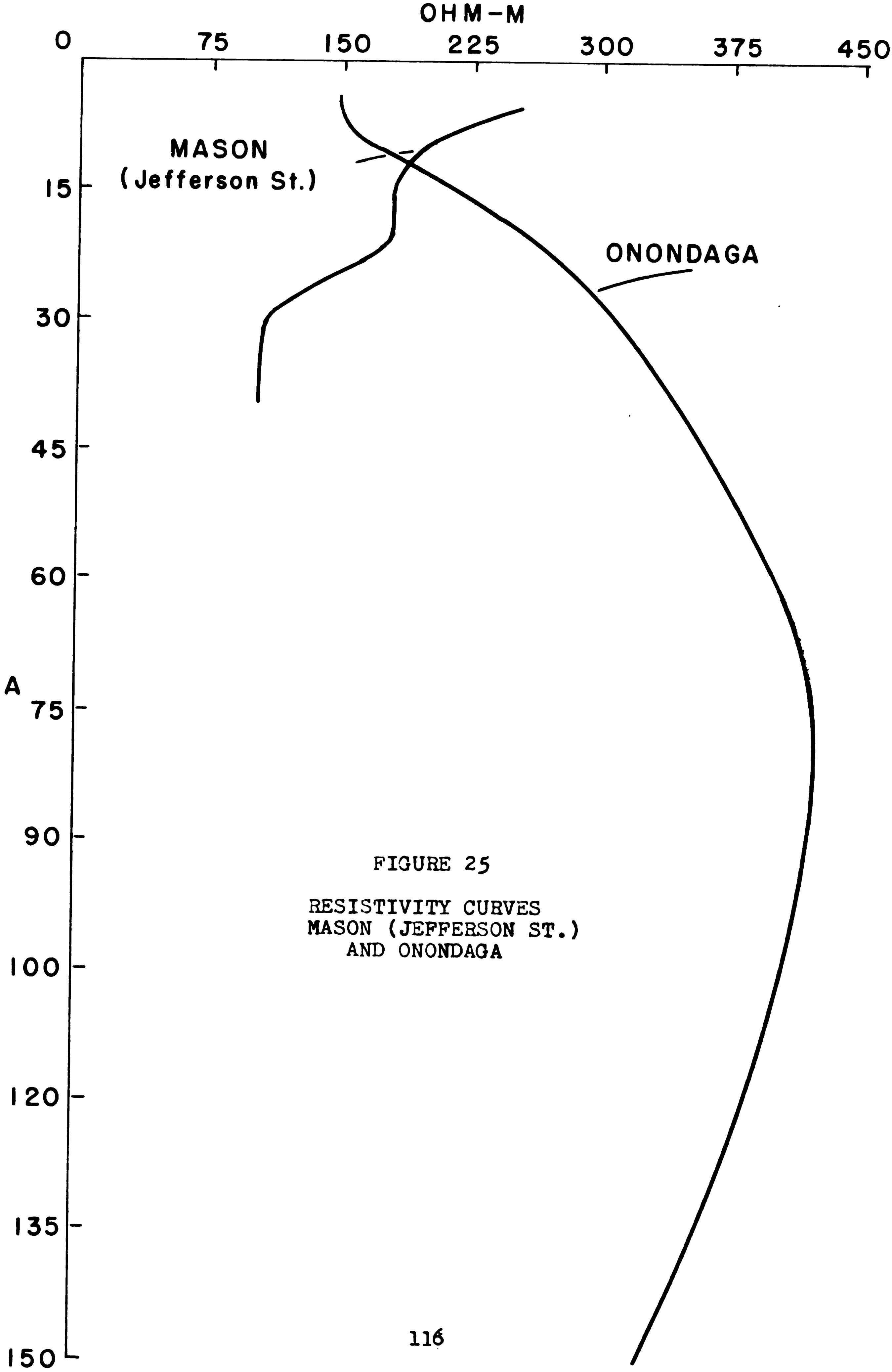


FIGURE 25

RESISTIVITY CURVES
MASON (JEFFERSON ST.)
AND ONONDAGA

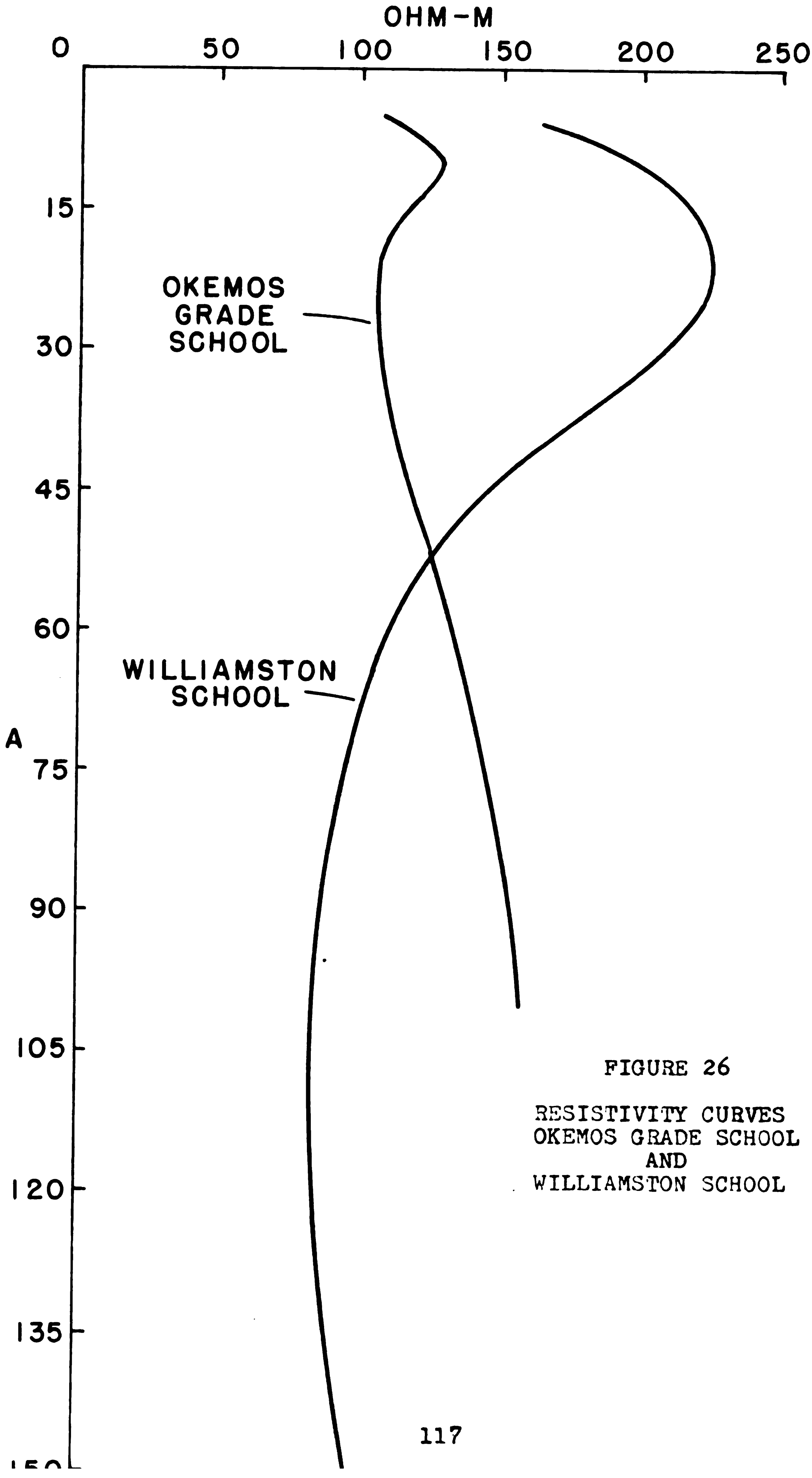


FIGURE 26

RESISTIVITY CURVES
OKEMOS GRADE SCHOOL
AND
WILLIAMSTON SCHOOL

CHAPTER XVII

CONCLUSIONS AND RECOMMENDATIONS

From the analysis of the previous chapter, Moore's cumulative method seemed to give the best all around results. Though this method can claim no theoretical basis, it was considerably better than the theoretical method of interpretation. The next best technique, Barnes' Layer method, was also better than the theoretical method. None of the four methods analyzed, however, was entirely correct. Depth values predicted were both above and below the actual geological depths. Since Moore's method gives two correct interpretations for each incorrect interpretation it was selected as the "best" method to use. Water table depths are obtained better than 80% of the time with a fair degree of accuracy.

No unique or indicative resistivity values were obtained for any type of material by either the Barnes' Layer method or Mooney and Wetzel's theoretical method. Neither Moore's method nor the Gish-Rooney method give numerical values for the resistivities.

Although resistivity interpretation does not "find" water directly it can give a fairly good estimate of the depth to water and the possible thickness of the formation containing the water. The water, however, may be in very poor aquifers such as sandy clay, which would not yield an economical supply of water. Correlation borings will be necessary to check the accuracy of the interpretive method and give a better idea of what the geologic materials are like.

Precautions mentioned earlier concerning the elimination of interference potentials should be followed in order to avoid erroneous readings. Field work should be carried to the point where more than enough data is obtained. Moore's method of interpretation will probably work equally as well in other areas which have similar geology: bedrock covered with variable thicknesses of different glacial deposits.

Other workers might want to experiment with other summation intervals to use with Moore's method, than was used in this study. The present writer feels that the ten foot interval is sufficiently accurate, yet involves a small enough number of operations so that it is fairly rapid to use. One of the factors in favor of Moore's method is its simplicity of use. This makes it considerably faster than either Barnes or the theoretical methods.

In the Bibliography are listed several references concerning the determination of the fresh-water-salt-water interface in coastal and island areas. In Michigan salt-water intrusion is a problem in some parts of the Thumb area. The author had intended to include several stations from this area in this thesis, but this was not possible.

The salt-water boundary should be picked up very nicely in this area. Even if the salt-water has diffussed into the fresh-water, the conductivity change from fresh-water to the contaminated water should be sufficient to give the depth. Resistivity surveys have been conducted in water covered areas in the past by Moore, and he has obtained good results. Perhaps, some time in the future the present author will have the opportunity to conduct surveys in the two above mentioned situations as well as in the more normal type situations.

BIBLIOGRAPHY

A. BOOKS, CIRCULARS AND BULLETINS

Barnes, H. E. Soil Investigation Employing A New Method of Layer-Value Determination for Earth Resistivity Interpretation. Highway Research Bulletin 65, 1952. pp. 26-36.

Bays, C. A. and Folk, S. H. Developments in the Application of Geophysics to Ground-Water Problems. Urbana: Ill. Geological Survey Circ. 108, 1944.

Buhle, M. B, "Six Case Histories of Resistivity Prospecting in Illinois," Geophysical Surveys in Mining, Hydrology and Engineering Projects. The Hague: Eur. Assoc. Ex. Geophy., 1958. pp. 205-213.

Dobrin, M. B. Introduction to Geophysical Prospecting. New York: McGraw-Hill, 1952.

Gish, O. H. Improved Equipment for Measuring Earth-Current Potentials and Earth-Resistivity. Bulletin of the National Research Council, vol. 11, no. 56, 1926. pp. 86-91.

Eby, J. B. Seismic and Resistivity Geophysical Exploration Methods. U. S. Waterways Experiment Station, Tech. Memo. No. 198-1, 1943.

Edwards, George J. A Preliminary Report On The Electrical Resistivity Survey at Medicine Lake, Montana. U. S. Geological Survey Circular 97, 1951.

Fisher, Gerhard R. Geophysical Prospecting for the Layman. Palo Alto, Calif.: Fisher Research Laboratory, 1949.

Heiland, Carl A. Geophysical Exploration. New York: Prentice-Hall Inc., 1950.

Jakosky, J. J. Exploration Geophysics. Newport Beach, Calif: Trija Publishing Company, 1950.

Kelly, S. F. "Geological Studies of Uranium-Vanadium Deposits by Geophysical Exploration Methods." Geophysical Surveys In Mining, Hydrological And Engineering Projects. The Hague: Eur. Assoc. Ex. Geophy., 1958. pp. 111-126.

Lee, F. W. Geophysical Prospecting for Underground Waters in Desert Areas. Washington: Information Circ. 6899, U. S. Bureau Mines, 1936.

Lee, F. W. Joyce, J. W., and Boyer, P. Some Earth Resistivity Measurements. U. S. Bur. of Mines, Inf. Circ. 6171, 1929.

Malott, Donald F. Earth Resistivity Interpretation As Used By The Michigan State Highway Department. Ann Arbor: Michigan State Highway Department, 1960.

Malott, Donald F. Geophysics Applied To Highway Engineering Earth Resistivity. Michigan State Highway Department, nd.

McNish, Alvin Greene Utilitarian Aspects of Geophysics. Washington: Carnegie Institution of Washington, 1938.

Mooney, H. M. and Wetzel, W. W. The Potentials About A Point Electrode and Apparent Resistivity Curves for a Two, Three and Four-layer Earth. Minneapolis: Univ. Minnesota Press, 1956.

Moore, R. Woodward. Geophysical Methods of Subsurface Exploration Applied to the Location and Evaluation of Sand and Gravel Deposits. National Sand and Gravel Association, Circular No. 37, March 1950.

Moore, R. Woodward. Geophysical Methods of Subsurface Exploration Applied to Materials Surveys. Highway Research Board Bulletin 62, National Research Council Pub. 247, 1952. pp. 85-105.

Nettleton, Lewis L. Geophysical Prospecting for Oil. 1st. edition. New York and London: McGraw-Hill, 1940.

Perret, Wm. R. Electrical Resistivity Exploration. Vicksburg, Miss: Waterways Exp. Station, Bulletin 33, 1949.

Peters, L. J. and Bardeen, J. The Solution of Some Theoretical Problems Which Arise in Electrical Methods of Geophysical Exploration. Univ. of Wisconsin, Engineering Experiment Station Bulletin No. 71, 1930.

Roman, Irwin. How to Compute Tables for Determining Electrical Resistivity of Underlying Beds and Their Application to Geophysical Problems. U. S. Bureau of Mines Tech. Paper 502, 1931.

Roman, Irwin. Superposition in the Interpretation of Two-layer Earth Resistivity Curves. U. S. Geol. Survey, Bulletin 927-A, 1941.

Roman, Irwin. Resistivity Reconnaissance. Am. Soc. Test. Mat., Special Publication 122, 1951. pp. 189-197.

Roman, Irwin. Apparent Resistivity of a Single Uniform Overburden. USGS Prof. Paper 365. Washington: Govt. Printing Office, 1960.

Runcorn, S. K. Methods and Techniques in Geophysics. New York: Interscience Publishers, 1960.

Slichter, L. B. and Telkes, M. Electrical Properties of Rocks and Minerals. Geol. Soc. Am. Special paper no. 36, edited by F. Birch, J. F. Schaires, and H. Cecil Spicer, 1942. pp. 299-319.

Spicer, H. C. Investigation of Bedrock Depths by Electrical Resistivity Methods in the Ripon-Fond du Lac area, Wisconsin. U. S. Geological Survey Circular 69, 1950.

Spicer, H. C. Electrical Resistivity Studies of Subsurface Conditions near Antigo, Wisconsin. U. S. Geological Survey Circular 181, 1952.

Spicer, H. C. Resistivity Measurements of Salt-water Infiltration. U. S. Geol. Survey, Water Supply Paper 1255, 1955.

Wenner, Frank. A Method of Measuring Earth Resistivity. U. S. Bureau of Standards Sci. Paper 258, 1915. pp. 469-478.

Woollard, George, P. and George F. Hanson. Geophysical Methods Applied to Geologic Problems in Wisconsin. Wis. Geol. Survey Bull. No. 78, Scientific Series No. 15, 1954.

B. PERIODICALS

Barnes, H. E. "Electrical Subsurface Exploration Simplified," Roads and Streets, vol. 97, no. 5 (1954), 81-84.

Bays, C. A. "Prospecting for Ground-Water - Geophysical Methods," Jour. Amer. Water Works Assoc., vol. 42 (1950), 947-956.

Blondeau, E. E. "Shallow Resistivity Survey at South Elton, Louisiana", Geophysics, vol. IV (1939), 271-278.

Buhle, M. B. "Earth Resistivity in Ground Water Studies in Illinois," Min. Eng., vol. 5 (1953), 395-399.

Card, R. H. "Earth Resistivity and Geological Structure," Electrical Engineering, (Nov. 1935), 1156.

Cleaves, Arthur B. "Electrical Resistivity," Roads & Streets, vol. 93 (1950), 54-58.

Crosby, I. B. and Kelly, S. F. "Electrical Subsoil Exploration and the Civil Engineer," Eng. News Rec., (1929), 270-273.

Crosby, Irving B. and E. G. Leonardon. "Electrical Prospecting Applied to Foundation Problems," A.I.M.E. Geophysical Prospecting, vol. 31 (1929), 199-210.

Dizioglu, M. Y. "Underground-water Investigations by Means of Geophysical Methods (particularly electrical) in Central Anatolia," Proc. Ankara Symposium on Arid Zone Hydrology, UNESCO, Paris, (1953), 199-215.

Enslin, J. F. "Lateral Effects on Electrical Resistivity Depth Probe Curves," Trans. Geological Society of South Africa, vol. 51 (1949), 249-270.

Evjen, H. M. "Depth Factors and Resolving Power of Electrical Measurements," Geophysics, vol. 3 (1938), 78-95.

Fent, O. S. "Use of Geologic Methods in Ground-water Prospecting," Jour. Amer. Water Works Assoc., vol. 41 (1949), 590-598.

Foster, J. W. and Buhle M. B. "An Integrated Geophysical and Geological Investigation of Aquifers in Glacial Drift Near Champaign-Urbana, Illinois, "Econ. Geol., vol. 46 (1951), 368-397.

Gish, O. H. and Rooney, W. J. "Measurement of the Resistivity of Large Volumes of Undisturbed Earth," Terrestrial Magnetism, vol. 30 (1925), 161-188.

Hallenbeck, F. "Geo-electrical Problems of the Hydrology of West German Area," Geophysical Prospecting, vol. 1 (1953), 241-249.

Hawley, P. F. "Fault Location by Electrical Prospecting," Geophysics, vol. 8, no. 4 (October 1943), 391-403.

Heiland, C. A. "Geophysical Methods of Prospecting," Colo. School of Mines Quarterly, vol. 24 (1929), 106-111.

Heiland, C. A. "Prospecting for Water With Geophysical Methods," Transactions, American Geophysical Union, Part II (1937), 574-587.

Hummel, J. N. "A Theoretical Study of Apparent Resistivity in Surface Potential Methods," Trans. J. A. Malkovsky, Trans. A.I.M.E., vol. 97 (1932), 392-422.

Hummel, J. N. "Theoretical Study of Apparent Resistivity," A.I.M.E. Geophysical Prospecting, Tech. Pub. 496 (1937).

Jakosky, J. J., C. H. Wilson and J. W. Daly. "Geophysical Examination of Meteor Crater, Arizona," A.I.M.E. Geophysical Prospecting, (1933), 63-97.

Jakosky, J. J. and R. H. Hopper. "The Effect of Moisture on the Direct Current Resistivities of Oil Sands and Rocks," Geophysics, vol. 2 (1937), 33-55.

Jones, B. E. "Results to be Expected from Earth-Resistivity Measurements," Trans. American Geophysical Union, Part II (1937, 399-403.

Keck, William G. "Geophysical Measurements in Livingston County, Michigan," Papers of the Michigan Academy of Science, Arts and Letters, vol. 23 (1937), 463-476.

Keller, W. D. "Earth Resistivities at Depths Less Than One Hundred Feet," Bulletin of the American Association of Petroleum Geologists, vol. 18, no. 1 (January, 1934), 39-62.

Kelly, S. F. "Experiments in Electrical Prospecting," Engineering and Mining Journal, vol. 114, nos. 15 and 16 (October 7, 1922), 623-628 and (October 14, 1922), 673-676.

Kelly, S. F. "A Uniform Expression for Resistivity," A.I.M.E. Geophysical Prospecting, (1932), 141-143.

Koefoed, O. "Resistivity Curves for a Conducting Layer of Finite Thickness Embedded in An Otherwise Homogenous and Less Conducting Earth," Geophysical Prospecting, vol. 3 (1955), 258-267.

Koenigsberger, J. G. "Field Observations of Electrical Resistivity and Their Practical Application," A.I.M.E. Geophys. Prosp., vol. 81 (1929), 221-237.

Kurtenacker, Karl S. "Some Practical Applications of Resistivity Measurements to Highway Problems," Trans. A.I.M.E. vol. 110 (1934), 49-59.

Kurtenacker. Karl S. "Use of Resistivity Methods for Locating and Exploring Deposits of Stone and Gravel," Rock Products, (July 1934), 32.

Lancaster-Jones, E. "The Earth Resistivity Method of Geophysical Prospecting," Mining Magazine, vol. 42, 355-360 and vol. 43, 19-28 (1930).

Landes, K. K. and Wilson, J. T. "Ground-water Exploration by Earth-Resistivity Methods, Papers Mich. Acad. Arts, Sci. Let., vol. 29 (1943), 345-354.

Langer, R. E. "On The Determination of Earth Conductivity From Observed Surface Potentials," Bull. Am. Math. Soc. vol. 42 (1936), 747.

Leggette, R. M. "Prospecting for Ground Water -- Geologic Methods," Jour. Amer. Water Works Assoc., vol. 42 (1950, 945-946.

Logn, O. "Mapping Nearly Vertical Discontinuities by Earth Resistivities," Geophysics, vol. 19 (1955), 739-760.

Longacre, W. A. "A Study of the Problem of Depth Determination by Means of Earth Resistivity Measurements," A.I.M.E. Tech. Pub. 1392 (1941).

Lugeon, M. and C. Schlumberger. "The Electrical Study of Dam Foundations," Mining Magazine, vol. 48 (1933), 340-345.

Maillet, R. "The Fundamental Equations of Electrical Prospecting," Geophysics, vol. 12 (1947), 529-556.

Meidav, Tsvi. "An Electrical Resistivity Survey For Ground Water," Geophysics, XXV, no. 5 (Oct., 1960), 1077-1093.

Mooney, H. M. "Depth Determinations by Electrical Resistivity," Mining Engineering, vol. 6 (1954), 915-918.

Mooney, H. M. "Effect of a Variable Surface Layer on Apparent Resistivity Data," Mining Engineering, (1954), 1210-1212.

Moore, R. W. "An Empirical Method of Interpretation of Earth Resistivity Measurements," A.I.M.E. Tech. Pub. No. 1743, with discussion, Trans. A.I.M.E., vol. 164 (1945), 197-223.

Moore, R. Woodward. "Prospecting for Gravel Deposits by Resistivity Methods," Public Roads, vol. 24, no. 4 (July, 1945), 57-72.

Moore, R. Woodward. "Geophysical Methods of Subsurface Exploration in Highway Construction," Public Roads, vol. 26, no. 3 (August, 1950), 49-64.

Moore, R. Woodward. "Geophysical Methods Adapted To Highway Engineering Problems," Geophysics, vol. 17, no. 3 (1952), 505-530.

Moore, R. Woodward. "Applications of Electrical Resistivity Measurements to Subsurface Investigations," Public Roads, vol. 29, no. 7 (April, 1947), 163-169.

Moore R. Woodward, "Geophysics; Effects, Economy, and Efficiency in Subsurface Exploration," No Publisher, No date.

Muskat, Morris. "Potential Distribution About An Electrode on the Surface of the Earth," Physics, vol. 4 (1933), 129-147.

Muskat, Morris. "The Interpretation of Earth-resistivity Measurements," Trans. A.I.M.E., vol. 164 (1945), 224-231 including discussion.

Muskat, M. and H. H. Evinger. "Current Penetration in Direct Current Prospecting," Geophysics, vol. 6 (1941), 397-427.

Paver, G. L. "On the Application of the Electrical Resistivity Method of Geophysical Surveying to the Location of Underground Water, With Examples from the Middle East," Proc. Geol. Soc. London, (April 18, 1945), 46-51.

Paver, G. L. "The Geophysical Interpretation of Underground Water Supplies; A Geological Analysis of Observed Resistivity Data," Jour. Inst. Water Engrs., vol. 4 (1950), 237-266.

Perkeris, C. L. "Direct Method of Interpretation in Resistivity Prospecting," Geophysics, vol. 5 (1940), 31-42.

Pirson, S. J. "Interpretation of three-layer Resistivity Curves," A.I.M.E. Trans., vol. 110 (1934), 148-158.

Robertshaw, J. and P. D. Brown. "Geophysical Methods of Exploration and Their Application to Civil Engineering Problems," Proc. Inst. Civil Engrs., Part I, vol. 4 (1955), 644-690.

Roman, Irwin. "The Calculation of Electrical Resistivity For A Region Underlying Two Uniform Layers," Terr. Mag., vol. 38 (1933), 117-140 and 185-202.

Roman, Irwin. "Some Interpretations of Earth Resistivity Data," A.I.M.E. Trans., vol. 110 (1934), 183-200.

Rooney, W. J. "Earth Resistivity Measurements in the Copper Country of Michigan," Terrestrial Magnetism, vol. 32 (1927), 97-126.

Rooney, W. J. and O. H. Gish. "Results of Earth-Resistivity Surveys near Watheroo, Western Australia and Ebro, Spain," Terrestrial Magnetism, vol. 32 (1927), 49-63.

Rose, N. A. "Ground Water and Relation of Geology To Its Occurrence in the Houston District, Texas," Bull. Amer. Assoc. Pet. Geol., vol. 27 (1943), 1081-1101.

Rosenzweiq, I. E. "A New Method of Depth Determination in Earth Resistivity Measurements," A.I.M.E., Tech. Pub. No. 931 (1938).

Ruedy, R. "The Use of Cumulative Resistance in Earth-Resistivity Surveys," Canadian Journal of Research, vol. 23, sec. A, no. 4 (July, 1945), 57-72.

Sayre, A. N. and E. L. Stephenson. "The Use of Resistivity-Methods in the Location of Salt-Water Bodies in the El Paso, Texas, Area," Trans. Amer. Geophysical Union, vol. 18 (1937), 393-398.

Schlumberger, C. and M. and E. G. Leonardon. "Some Observations Concerning Electrical Measurements in Anisotropic Media, and Their Interpretation," A.I.M.E. Geophys. Prosp., vol. 110 (1934), 159-182.

Schlumberger C. and M. and E. G. Leonardon. "Electrical Exploration of Water-covered Areas," Trans. A.I.M.E., vol. 110 (1934).

Shepard. E. R. "Subsurface Exploration by Earth Resistivity and Seismic Methods," Public Roads, vol. 16, no. 4 (June, 1935).

Shepard, E. Raymond. "Subsurface Explorations By Geophysical Methods," A.S.T.M. proceedings, vol. 49 (1949), 993-1015.

Slichter, L. B. "The Interpretation of the Resistivity Prospecting Method for Horizontal Structures," Physics, vol. 4 (1933), 307-322.

Stickel, J. F., Jr., L. E. Blakeley and B. B. Gordon. Geophysics and Water," Jour. Amer. Water Works Assoc., vol. 44 (1952), 23-35.

Swartz J. H. "Resistivity Studies of Some Salt-Water Boundaries in the Hawaiian Islands," Trans. Amer. Geophysical Union, vol. 18-(1937), 387-393.

Tagg, G. F. "The Earth Resistivity Method of Geophysical Prospecting," The Mining Magazine (London) vol. 43 (1930), 150-158.

Tagg, G. F. "Interpretation of Resistivity Measurements," Trans., A.I.M.E., vol. 110 (1934), 135-147.

Tagg, G. F. "Earth Resistivity Surveying," Mining Magazine, vol. 53, no. 3 (1935), 148-154.

Tagg, G. F. "Interpretation of Earth-resistivity Curves," Trans. A.I.M.E., vol. 138 (1940), 399-407.

Tattam, C. M. "Application of Electrical Resistivity Prospecting to Ground Water Problems," Colo. School of Mines Quart., vol. 32, no. 1 (1937), 117-138.

Todd, D. K. "Investigating Ground Water by Applied Geophysics," Proc. Amer. Soc. Civil Engrs., vol. 81 (1955).

Way, H. J. R. "An Analysis of the Results of Prospecting for Water in Uganda by the Resistivity Method," Trans. Inst. Min. and Met., vol. 51 (1942), 285-310.

Wetzel, W. W. and H. V. McMurry. "A Set of Curves to Assist in the Interpretation of the Three-layer Resistivity Problem," Geophysics, vol. 2 (1937), 329-341.

Wilcox, S. W. "Sand and Gravel Prospecting By The Earth Resistivity Method," Geophysics, vol. IX, no. 1 (Jan., 1944).

Workman, L. E. and M.M. Leighton. "Search for Ground-waters By The Electrical Resistivity-Method," Trans. Amer. Geophysical Union, vol. 18 (1937), 403-409.

APPENDIX

CONTROL WELL AND RESISTIVITY STATION LOCATIONS

Control Well And Location	Remarks	Resistivity Station Location
Okemos Grade School T4N R1W NW of NE of 28	near back of school	500 ft. E. of well
Mason (Jefferson St.) T2N R1W NW of SW of 9	at W. edge of gravel pit	100 ft. S of well
Mason (#4) T2N R1W SW of NE of 5	near city water tank	800 ft. N and 200 ft. W of well
Williamston School T3N R1E NE of NE of 2	behind school near RR tracks	400 ft. S and 400 ft. W of well
Watson T4N R1E SW of SW of 29	at house	350 ft. S and 400 ft. E of well
Soil Science T4N R1W NE of SE of 19	irrigation well for Soil Science and Horticulture	250 ft. S and 600 ft. E of well
Morrow T3N R2E SW of NE of 12	behind farm house	200 ft. S and 600 ft. E of well
Beef Cattle Barns (station #1) T4N R1W NW of NE of 31	in front of barns	400 ft. N and 400 ft. E of well
Beef Cattle Barns (station #2) T4N R1W NW of NE of 31	in front of barns	200 ft. N and 200 ft. E of well
Ground Maintenance T4N R1W SW of NW of 19	S of maintenance building and N of RR tracks	250 ft. E of well

Schmidt T3N R2E SW of NW of 12	at farm house	100 ft. S and 400 ft. W of well
Onondaga TIN R2W NE of SW of 29	at MSU TV site	60 ft. S and 450 ft. W of well