APPLICATION OF WELL-LOGGING METHODS TO SHOT HOLES

by

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Nothing Is Too Wonderful To Be True

Faraday

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SECTION I

1. Preface

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PREFACE

Electrical exploration, or the "well-logging," of drill holes, for the oil industry, is a recent geophysical technique, dating only from 1928. There is no need to emphasize the absolute necessity of gathering reliable and complete information of all the formations encountered in the course of drilling. The oil industry has witnessed a continuous improvement in the manner of securing subsurface information. Drilling-speed charts, driller's logs based on examination of cuttings, mechanical coring, paleontological analysis, wire-coring, etc., each furnishes some valuable data. But there is a constant urge to develop new means of investigation for the purpose of reducing the cost of drilling and obtaining more complete and reliable data. Today, electrical measurements constitute a new step forward, towards achieving this end.

The purpose of the work done by this author is to apply well-logging methods to the shot holes that are drilled by seismograph crews. In seismic prospecting it is necessary that the depth, below the surface, of the bottom of the low velocity or "weathered" layer be known accurately. By the methods now in use, this depth is calculated from the velocity of the seismic waves traveling through the weathered layer. However, by logging shot holes, one should be able to determine the thickness of the low velocity layer with a high degree of accuracy.

Another problem in seismic prospecting is the location of the top of the water table. At the present time this is done by noting the level at which the water stands in water wells. If no water wells are present one must simply guess at about the level of the top of the water table. By logging shot holes, it would seem probable that one should be able to locate the top of the water table accurately.

Thus by applying well-logging methods to shot holes, the author intends to locate the top of the water table, and, of greater importance, to locate the bottom of the weathered layer.

Acknowledgements

The author is indebted to Mr. Herbert Hoover, Jr., President of the United Geophysical Company of Pasadena, California, for making this work possible. Especially to Dr. Raymond A. Peterson, under whose supervision this work was carried out, the author is indeed grateful. Most sincere thanks to Dr. Harold Washburn who offered many helpful suggestions in the design of the electrical apparatus; to Mr. H. Hart Pratley for the use of the commutator; to Mr. Reed Lawlor who offered suggestions and criticisms in the preparation of the manuscript; and to Mr. Charles L. Watson for his suggestions in the design of the field apparatus. To the above men, and to the entire personnel of the United Geophysical Company, the author wishes to express his appreciation of their spirit of cooperation and of the interest which they have shown in the preparation of this thesis.

HISTORY OF ELECTRICAL PROSPECTING

The foundations of electrical prospecting were laid in 1830 when the Englishman, R. W. Fox, discovered that electrical currents and potentials were associated with certain ore deposits in Cornwall. He made measurements of these potentials and also of the resistivity of certain of the minerals and surrounding rocks. As a result of Fox's work a number of others made similar measurements and proposed the use of these measurements for prospecting. However, the apparatus used by these early electrical prospectors was too crude for practical work.

In 1900 Brown carried out the first research by measurement of the electrical resistance, but without success, since he used only one circuit, and thus measured primarily the resistance of the earth contacts. In 1911 Lowy and Leimbach undertook some research work in connection with Hertzian waves.

All these attempts, however, were without result, and it was only in 1912 that Conrad Schlumberger, then Professor at the Ecole des Mines de Paris, began his first systematic studies, which, continued perseveringly, finally led to the perfecting of the electrical methods. This research work was interrupted by the war, then continued in 1919, and in 1920 the first industrial applications coincided with the publication of Schlumberger's book "Etude sur la Prospection electrique du sous-sol," which gave the fundamental basis of electrical surveying of the underground.

From the beginning, electrical prospecting was applied by Schlumberger to tectonic studies, whereas all the other research workers had limited, and were still limiting, their applications to the survey of metallic mines.

As far as the use of resistivity methods in oil work is concerned, the Schlumberger Company had proved the practicability of the method in structural studies since 1921. Work was then begun in the Pechelbronn oil region and continued until 1926. In Roumania, commercial work was carried out, among others, for the Steaua Roumania in 1923-1926. Salt domes were located in the Alsace region in 1926-1927.

Resistivity prospecting for oil structures was begun in the United States by 1925, when the Schlumberger Company was engaged to work for the Roxana Petroleum Corporation and the Shell Oil Company of California.

In 1928 the electrical coring technique was applied by the Schlumberger Company, and developed with incredible rapidity, first of all in U.S.S.R. and then, from 1932, in the United States.

SECTION II

Underlying Principles of Geo-Electrical Methods

UNDERLYING PRINCIPLES OF GEO-ELECTRICAL METHODS

Any geophysical survey to be of commercial and practical value must be interpreted in conjunction with the necessary geological studies. Geophysics and geology are complementary to each other, their fields do not overlap inasmuch as one supplies information which can only be interpreted in light of the other. The proper interpretation of geophysical data requires a knowledge of structural and geological conditions.

All geophysical exploration methods are based on the fact that it is possible to detect and locate from the surface a certain subsurface formation, if this formation differs from its surroundings in regard to some physical property, and if it is not too small in size or too deep seated.

The physical property one is concerned with by the use of geo-electrical methods is the electrical conductivity of rock formations, that is, their ability to carry electrical currents. For practical reasons, this conductivity is usually expressed by its inverted value, the specific resistivity (the units of which are ohm-centimeters,) which expresses the resistance a certain material one centimeter long and one centimeter square offers to the passing of an electric current.

(An interesting new theory of electric conduction in the ground is set forth by F. W. Lee in the Buoreau of Mines Information Circular 6899, August, 1936, entitled "Geophysical Prospecting for Underground Waters in Desert Areas." Lee states: "Many writers assume that the electric current always passes through the ground with what may be called ohmic conductivity, in very much the same manner as current flows through a metallic conductor. Under this supposition the ground has various degrees of ohmic conductivity, differing in value and in direction under a given set of geologic conditions. Actual observations show that other factors often are controlling. It appears that a system of electrolytic cells is gradually built up in the ground that opposes the passage of an electric current through it. In such a system there would be a chain of cells from one zone of influence in the near vicinity of the ground current stakes that would be electrically weaker than the adjacent chains. The weak chain will break down first and thus confine the path of the current to definite channels instead of distributing it uniformly through the whole medium according to ohmic conductivity. In other words, the flow of current would be similar to that through a broken artificial electrical insulation, except that in the soil the voltage gradient is of the order of microvolts per centimeter, while in an artificial insulation it is of the order of hundreds of kilovolts per centimeter. In support of this theory, oscillographic records of the current in dielectrics and in the ground are strikingly similar in character. Also it is often possible to observe the gradual building up of the resisting cells in the change of current that accompanies resistivity measurements. A ground characteristics of this kind may account for the fact that at some electrode spacings a great difference of apparent electrical resistivity is observed. This question is not definitely settled, nor have its many phases been examined experimentally.")

The electrical conductivity shows a very wide variation between different rock formations. The sedimentary beds that form the sandstones, shales and limestones have, in general, conductivities hundreds of times larger than the conductivities of volcanics or igneous rocks like granite, syenite, and basalt. In the same way, there is also a very pronounced variation of conductivity between the successive beds forming a particular sedimentary column.

The comparatively high electrical conductivity of sedimentary beds is due to the fact that such rocks nearly always hold in their pores a considerable amount of moisture, which is electrically conducting; the minerals (such as quartz, feldspar, mica) that make up these rocks are all non-conducting. The factors that determine the conductivity of a certain formation are therefore:

1. The percentage volume of water contained; and
2. The conductivity of this water.

The essential fact that governs the electrolytic conductivity of a solution is that the electrical current

> is conducted by the transfer of ions through the solution. These ions may be in part those of the solvent itself, but are mainly ions due to dissociation of the soluble salts forming the solute. This specific conductance of any solution will depend chiefly upon: (1) the concentration of the ions present, (2) their mobility, i.e., the velocity of their migration, and (3) their electrical charge. The concentration of the ions will depend upon the concentration of the electrolyte and upon its degree of ionization. With an increase in concentration, the specific conductance will increase due to the larger number of ions present, but generally reaches a maximum and then decreases because of smaller ionization and greater friction due to the ionic motion, at the higher concentrations.

The percentage volume of water contained in a rock formation depends largely on the porosity of the rock, that is, the volume of the interstices or voids between the grains, in per cent of the total volume of the rock mass. The porosity of sandstones runs into figures up to some 25 per cent, as compared with something like half a per cent for igneous rocks; for sands the porosity generally ranges between some 25 per cent to 40 per cent, and for clays between 30 per cent and 50 per cent. It is evident, therefore, that such formations are able to hold large quantities of water in their pores. This is exemplified by the water sands met with by oil field drilling; however, it must be remembered that fine grained beds, like clayey shales, may hold even larger percentage volumes of water, although their water content is firmly retained in the microscopic pores.

The electrical conductivity of water is due to the presence of dissolved salts. Distilled water of highest purity is practically non-conducting, the fresh waters of rivers and lakes have resistivities of some 30,000 down to 300 ohm-cms, while the brackish ground-waters of hot climates have resistivities of only a few hundred ohm-cms. The saline subsurface waters met with in oil fields have resistivities anywhere from a couple of hundred ohm-cms down to only some 10 ohm-cms. A notable feature about the resistivity of salt water is that it decreases with increasing temperature, at the rate of some one to three per cent per one degree Fahrenheit; since the rock temperature increases with depth (at the rate of one degree Fahrenheit per every 40-75 feet) it is therefore to be expected, if everything else remains the same, that the electrical conductivity of sedimentary formations will increase with depth.

Both the above factors that govern the electrical conductivity of rocks, are so variable between different members of a sedimentary formation, that one would expect the conductivity to show great differences between successive beds in the sedimentary column. This fact has been abundantly proved by resistivity measurements on fresh drill cores and by determinations of the resistivities, by well-logging methods, of the formations traversed by drill holes.

On the other hand, both the water content of a certain bed, and especially the salinity of the water contained, show a high degree of consistency in all directions along the bedding planes; in many cases structure mapping from drill hole data has been carried out on water of a certain salt content, when the particular bed carrying the water has been hard to identify.

It can thus be said that the typical sedimentary formation dealt with by geo-electrical methods has an "electrical structure," which is conformable with the geological structure. It is therefore conceivable that one should be able to use electrical measurements to map the geological structure of such formations.

The simplest geo-electrical measurements that could be used for the above purpose would be to measure the electrical resistivity of the materials traversed by a drill hole, from the bottom to the surface, using the resistivity profile thus obtained for correlations of the sedimentary column between different drill holes, instead of the usual stratigraphic or paleontologic correlation.

Such a procedure has been in use for some time, for the correlation between drill holes, (see page 28), and it has in many cases been of great value, especially where the beds found by drilling to moderate depths have been hard to identify in the usual way.

It is of interest to note why electrical methods cannot locate oil directly. The reason for this failure is the following: It is an uncontested fact, known from physical theory and experiments, that a subsurface formation, which is practically non-conducting to electrical currents, will show an electrical effect at the surface no larger (practically speaking) than if its conductivity were only ten times smaller than the surroundings. An oil horizon will therefore not give any larger electrical effect at the surface than a dense shale or any other bed with an electrical conductivity some ten times lower than the surroundings, and such beds occur in great numbers in any sedimentary formation and at any depth, as shown by resistivity measurements in drill holes. An electrical method working at the surface, and trying to locate "non-conducting" beds, like oil horizons, in the subsurface, will therefore get plenty of positive reactions almost everywhere (naturally also if applied in a producing oil field); the practical value of such a process is thus obviously nil.

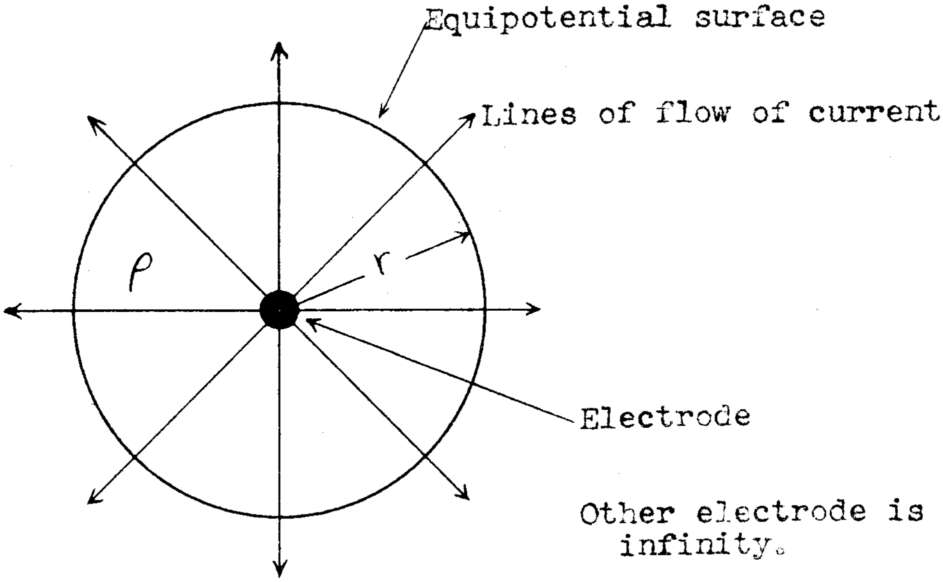
SECTION III

1. Derivation of Resistivity Formulae
2. Resistivity Defined
3. Average and Apparent Resistivity

DERIVATION OF RESISTIVITY FORMULAE

Electrodes in an Infinite Homogeneous Medium

Case I. One spherical electrode.



Other electrode is at infinity.

i = current density, in medium, a distance "r" out from the electrode.
i = amperes per square centimeter of surface.

I = current going into the electrode.

V = voltage at any point in the medium.
V = zero at infinity.

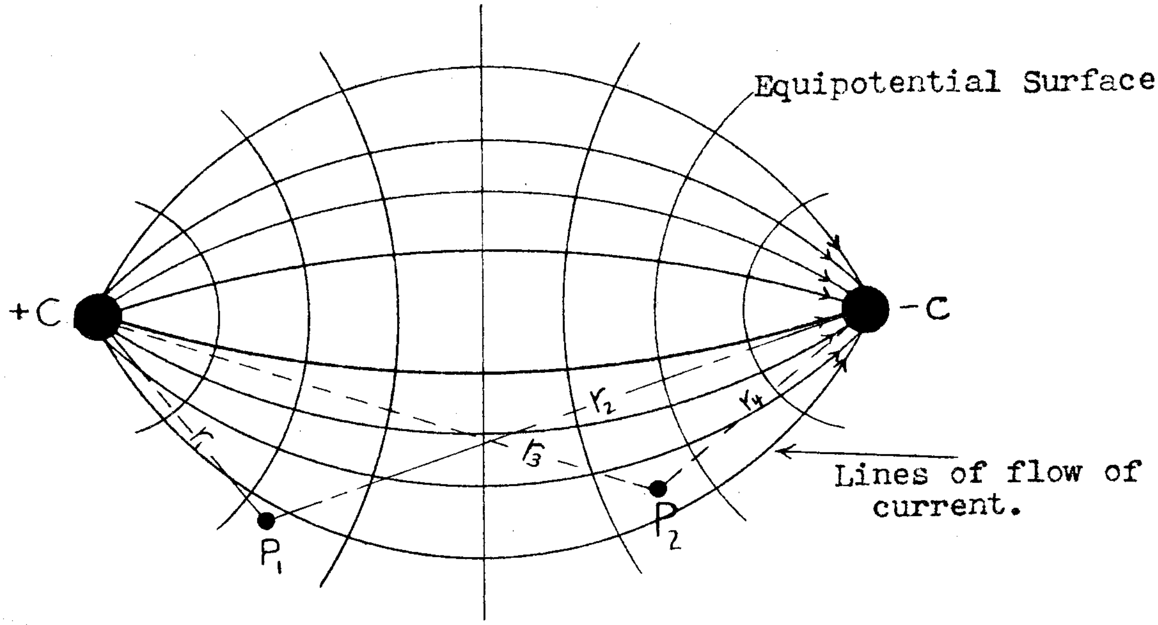
ρ = resistivity of the medium = $1/\sigma$ = ohm-cms.
σ = conductivity of the medium = mhos.

Now $i = \frac{I}{4\pi r^2}$ and by Ohm's Law: $i = \frac{1}{\rho} \times$ gradient V.

or Gradient $V = \frac{\rho I}{4\pi r^2} = \frac{\partial V}{\partial r}$

$$\text{or } V = -\frac{\rho I}{4\pi r} + C \qquad \text{where } C = \text{constant} = 0$$

Case II. Two spherical electrodes.



+I = current going in +C electrode.
-I = current coming out of -C electrode after traveling through the ground from the +C electrode.

V_1 = potential at point P_1.
V_2 = potential at point P_2.

$V_1 - V_2$ = potential difference from P_1 to P_2.

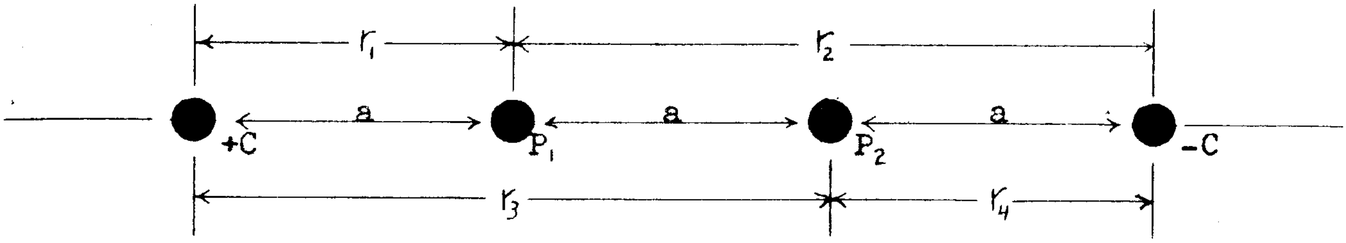
ρ = resistivity.

$$V_1 = \frac{\rho I}{4\pi r_1} - \frac{\rho I}{4\pi r_2} \qquad V_2 = \frac{\rho I}{4\pi r_3} - \frac{\rho I}{4\pi r_4}$$

therefore

$$V_1 - V_2 = \frac{\rho I}{4\pi}\left(\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}\right)$$

Case III. Special case of Case II.



The two current electrodes +C and -C, and the two potential electrodes P_1 and P_2, are in a straight line with a constant distance "a" between them.

Then $a = r_1 = r_4 = \frac{r_2}{2} = \frac{r_3}{2}$

Therefore the equation for the potential difference from Case II becomes:

$$V_1 - V_2 = \frac{\rho I}{4\pi}\left(\frac{1}{a} - \frac{1}{2a} - \frac{1}{2a} + \frac{1}{a}\right)$$

$$\vdots$$

$$\text{or} \quad V_1 - V_2 = \frac{\rho I}{4\pi a}$$

and the resistivity is therefore

$$\rho = \frac{(V_1 - V_2)(4\pi a)}{I}$$

which is the resistivity in an infinite homogeneous medium.

RESISTIVITY DEFINED

Resistivity is defined as the resistance of a cube of given material one centimeter on an edge measured between opposite faces. It must be realized that this may be entirely different from the resistance of a cubic centimeter of the given material. A long thin wire could contain a cubic centimeter of volume and would have a high resistance, whereas the same volume formed into a flat plate would have a very different, and quite low, resistance between faces. Consequently, it is not proper to express resistivity in ohms per cubic centimeter.

Actually, the resistivity of a conductor is found by multiplying the ohms resistance by the cross-section and dividing this product by the length. This follows from the law that the resistance of a substance is proportional to its length, and inversely proportional to its cross-sectional area, which may be written

$$R = L/A \times \text{Constant.}$$

The constant is the resistivity of the material, R is the resistance in ohms, L the length, and A the cross-section. Hence

$$\text{Resistivity} = \rho = A/L \times R.$$

This may be written

$$\rho = \text{ohm} \times \text{cm}^2/\text{cm}$$

or

$$\rho = \text{ohm-centimeter.}$$

One may express ρ in ohm-centimeters, ohm-meters, ohm-inches, or ohm-feet.

AVERAGE AND APPARENT RESISTIVITY

The value of resistivity found by surface resistivity exploration methods must be considered as an average in which the resistivity of the earth nearest the line of terminals is most heavily weighted. The weighting decreases with the distance from this line until at a depth equal to the distance between adjacent terminals, the weights have become so small that all the earth beyond this contributes relatively little to the total effect.*

However, in well-logging methods the average resistivity is not so important, espececially in the case in which the electrode spacing is very small (2.5 feet.) Since the electrodes are surrounded by a conducting material (i.e., a sandstone bed that is traversed by the bore hole) the resistivity measured would not be an average, as in the case of surface resistivity exploration, but rather would be nearer the actual resistivity of the aforementioned sandstone strata. In well-logging, since the bore hole traverses materials of different resistivities, it is more desirable, and better terminology, to speak of the resistivity of the materials as the "apparent resistivity."

It is simple to calculate the potential due to any current for any electrode configuration in a homogeneous earth of known resistivity. Knowing the current and potential one is therefore able

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* For a detailed mathematical study of average resistivity refer to the following: (1) "The Earth-Resistivity Method of Electrical Prospecting," by E. Landcaster-Jones, Mining Magazine, Vol. XLIII, July, 1930. Pp. 19-29.
(2) "Some Earth Resistivity Measurements," by F. W. Lee, J. W. Joyce, and Phil Boyer, Bureau of Mines, Information Circular No. 6171, October, 1929.

to determine what would have been the resistivity of the earth if it had been homogeneous. This resistivity is spoken of as the "apparent resistivity." Hence knowing the potential and the current through the materials surrounding the bore hole, at various depths, one is able to determine the apparent resistivity of each of the materials.

It should be remembered that the many mathematical formulae developed for resistivity lose their validity because they are developed under the assumption of a homogeneous medium and do not satisfy the conditions in inhomogeneous ground. Inspite of this, these formulae may be used to calculate the apparent resistivity. However, the calculated resistivity changes with the electrode spacing and thus loses its meaning as a strictly defined quantity. It therefore has no fixed physical meaning and is accordingly called the "apparent resistivity."*

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* For a detailed mathematical study of apparent resistivity refer to "A Theoretical Study of Apparent Resistivity in Surface Potential Methods," by J. N. Hummel, A.I.M.E. Geophysical Prospecting, 1932. Pp. 392-422.

SECTION IV

1. Geo-Electrical Measurements in Shot Holes
2. Spontaneous Electrical Phenomena in Drill Holes
3. Use of Electrical Resistivity Logs for Geological Correlation

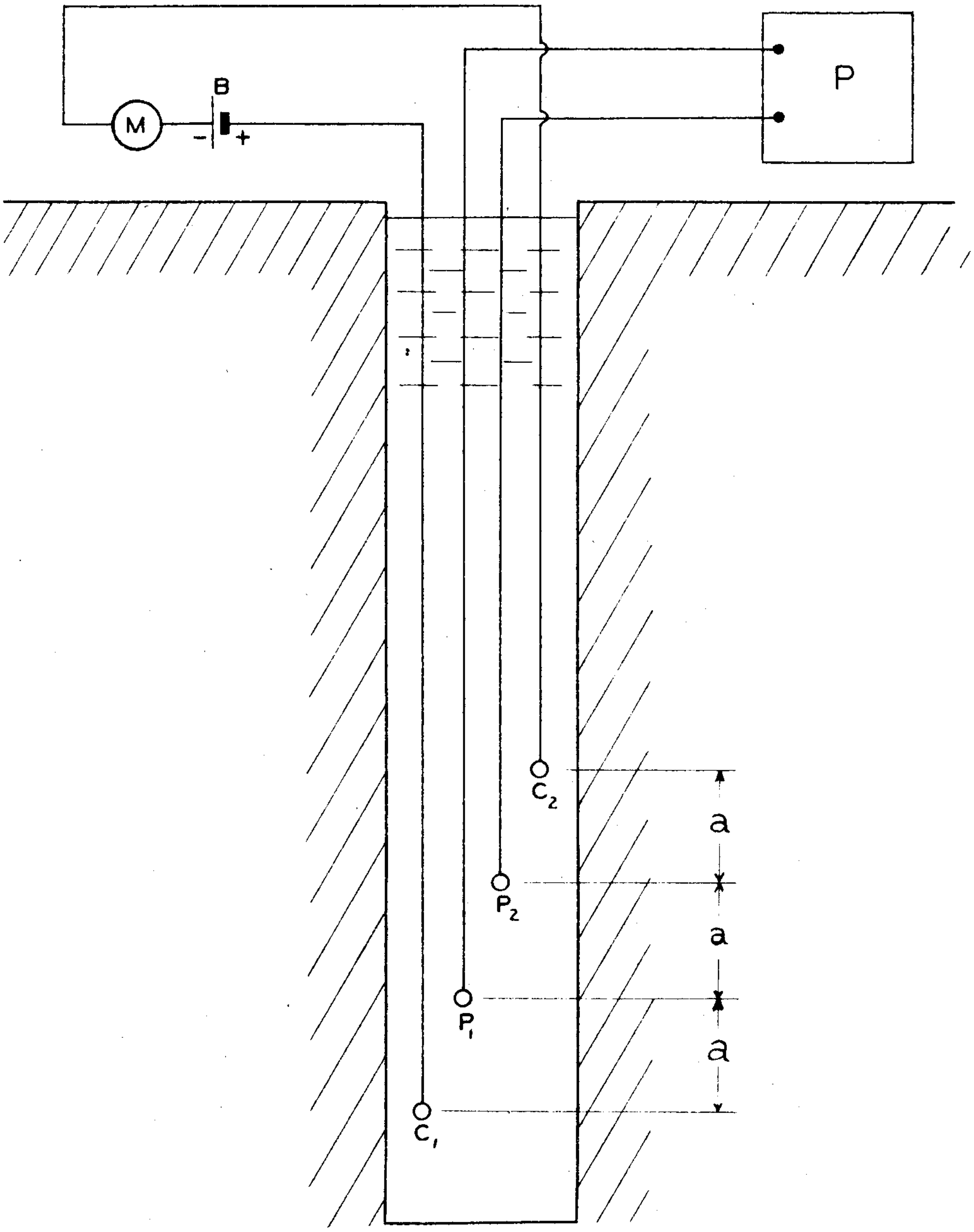
GEO-ELECTRICAL MEASUREMENTS IN SHOT HOLES

For the recording of the electrical properties encountered in a shot hole, a series of resistivity measurements are the same as for similar measurements made at the surface of the ground, the only difference being that the necessary electrodes are lowered into the shot hole by means of insulated cables, the appropriate readings being taken on instruments at the surface as the electrodes are raised or lowered in the hole. The necessary electrode contacts are made through the water and mud in the hole, so that measurements are not possible in dry holes or in the part of a hole above the water level; nor are measurements possible in the cased part of a hole because of the short circuiting action of the casing. (See page 69.)

For the resistivity measurements in shot holes, the diameter usually being 5 1/2 inches, the arrangement of electrodes is shown on the following page. The current, from B batteries, enters the ground at the electrode C_1 and passes through the formations surrounding the shot hole and passes out through electrode C_2. The current then goes through a milliammeter M and back to the minus side of the battery. The difference of potential created by this current is measured from the potential electrode P_1 to the other potential electrode P_2. This e.m.f. is measured by the potentiometer P. The electrode interval a is kept constant, 2.9 feet, and it must be remembered that the electrodes are one beneath the other and not offset as shown in the schematic diagram.

<u>The resistivity is given by</u>

$$\rho = 4 \pi a \times \frac{E}{I},$$



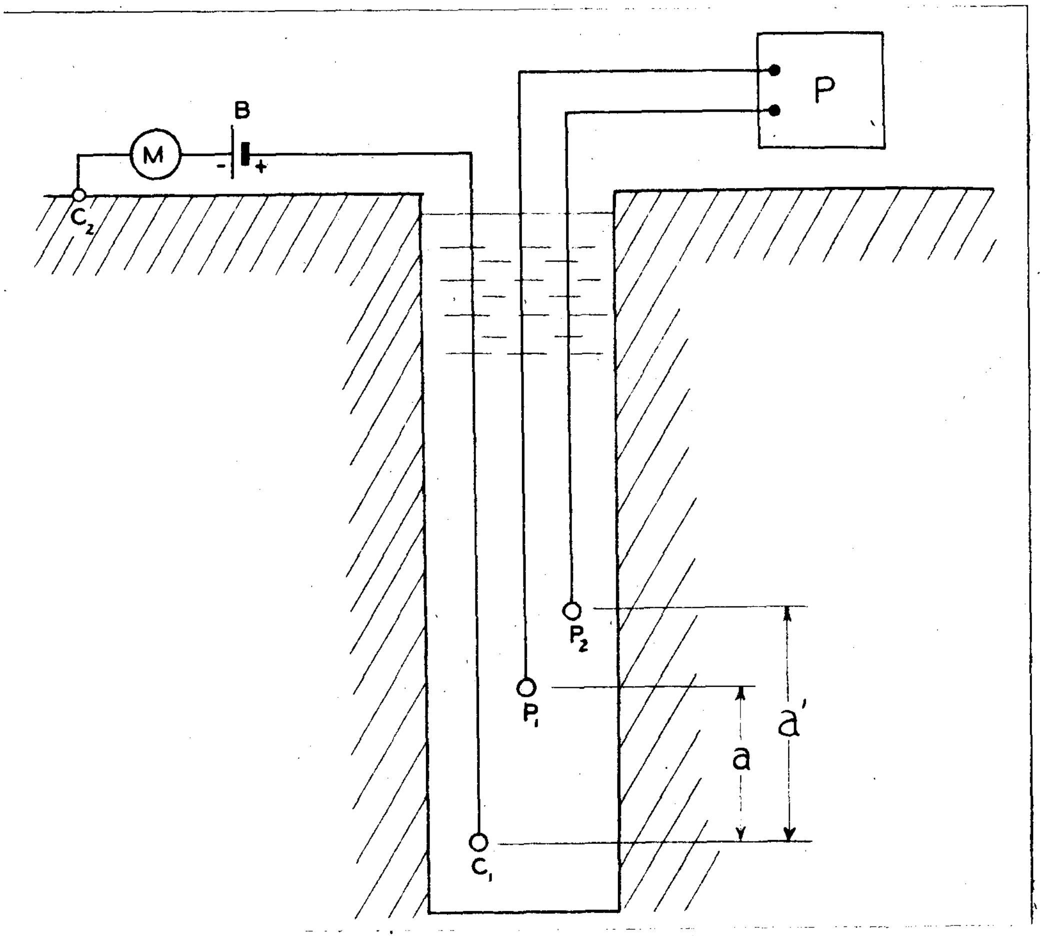
SCHEMATIC DIAGRAM OF CIRCUIT
FOR MEASUREMENT OF
EARTH RESISTIVITY
IN SHOT HOLES

where E is the e.m.f measured by the potentiometer and I the current measured by the milliammeter.

The use of separate contacts for the potential measurements eliminates the effect of contact resistances from the readings and enables the actual resistivity to be determined accurately.

Other electrode configurations.

I. Three electrodes in the shot hole and one on the surface.

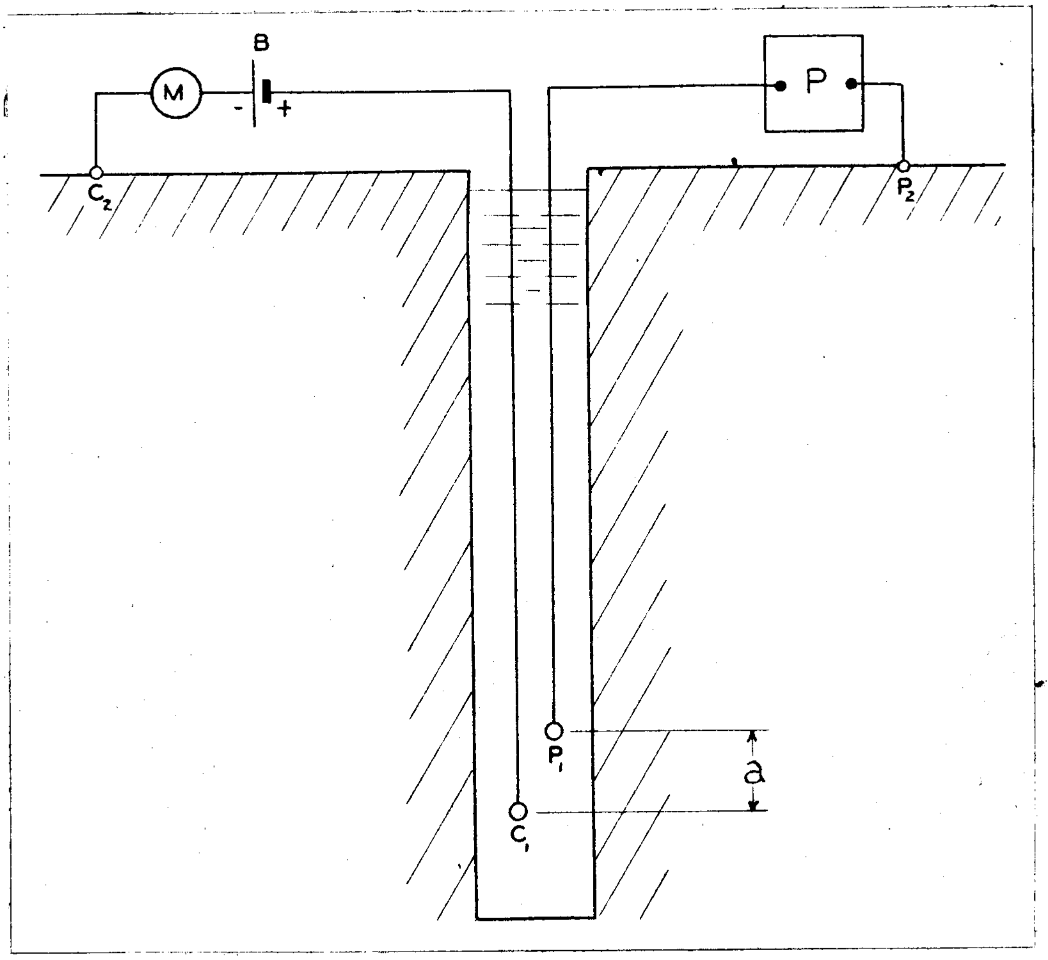


The current enters the ground at C$_1$ and leaves at C$_2$. The potential difference is measured from P$_1$ to P$_2$. a and a' are about 10-20 times the diameter of the shot hole.

The resistivity is given by

$$\rho = 4\pi \times \frac{aa'}{a-a'} \times \frac{E}{I}$$

II. Two electrodes in the shot hole and two on the surface.



The current enters the ground at C_1 and leaves at C_2. The potential difference is measured from P_1 to P_2. The spacing a must be known accurately. It is usually made two or three times the diameter of the hole. P_2 is placed a long way from C_2.

The resistivity is given by

$$\rho = 4\pi a \times \frac{E}{I}.$$

III. One electrode in the drill hole and one on the surface.

For accurate measurements, using one electrode in the drill hole, alternating current should be used.* Since the author did not have access to the use of an A.C. Generator, this method was not tried.

The following references deal with this subject:

(1) Halliburton Oil Well Cementing Company of Duncan, Oklahoma. Catalog No. 10, January, 1939.

(2) "Single Cable Electrical Well-Logging," by W. M. Rust, Jr. and W. D. Mounce, U. S. Patent No. 2,132,807, October 11, 1938.

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* Conrad Schlumberger, in his U. S. Patent No. 1,819,923, August 18, 1931, briefly describes a method of single electrode well-logging using direct current. The present author, however, did not try this method.

SPONTANEOUS ELECTRICAL PHENOMENA IN DRILL HOLES

In the course of resistivity surveys made inside of drill holes, it is found that there are currents spontaneously generated inside these holes. These phenomena are not at all negligible and experience actually shows that over distances of a few feet differences of potentials, ranging from a few millivolts up to 200 millivolts, can be measured.

There are two main causes for these spontaneously generated currents:

I. Electro-filtration

Spontaneous potentials may arise in a drill hole due to the flow of liquid, such as water or oil, into the hole from a porous formation, or by passage, under high pressures, of water or drilling mud from the hole into the porous formation. The production of an electrical potential from the passage of an electrolyte through a porous diaphragm in this way is a phenomenon known as "electric endosmose." The term employed first by Schlumberger is "electro-filtration" and he shows, by the following method, that the potentials occurring are quantitatively related to the porosity of the rock and to the resistivity of the liquid filling its pores. When an electrolyte is caused to flow through a sheet of a pervious, solid dielectric, an electromotive force occurs between the two sides of the sheet. This electromotive force is proportional to the pressure and to the electrical resistivity of the liquid, and is inversely proportional to its viscosity. It is independent of the thickness of the filtering sheet, and of the radii and number of pores of the pervious medium.* It may be expressed by the following formula:

$$E = m \times R/V \times P$$

where
E = the e.m.f. of filtration
P = the pressure of the liquid
R = the electrical resistivity of the liquid
V = the viscosity of the liquid
m = a constant factor which depends on the porous medium.

In drill holes the water of the hole plays the part of the electrolyte, and the porous layer is the dielectric. The e.m.f. is then proportional to the resistivity of the mud and to the pressure inside of the layer.

II. Electro-osmosis

Spontaneous potentials may also be produced in drill holes by the diffusion of two liquids of different electrolyte concentrations. They would be produced, for instance, by the contact of water from a fresh water horizon with a brine from a saline horizon. This is an electro-chemical effect and is known as "electro-osmosis."

In drill holes, the electrolytes in contact are the mud and the salt water in the porous layers. In most cases the salt water in the sand is saltier than the mud; the lines of current (see figures on the following page) then enter the layer--and under such conditions the potential profile, as in the case of electro-filtration, will show a negative anomaly. In this instance the two phenomena, electro-filtration and electro-osmosis, have the same sign, and add their action to each other. The reverse case is also possible.

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* Refer to "Electrical Coring; A Method of Determining Bottom-Hole Data by Electrical Measurements," by C. and M. Schlumberger and E. G. Leonardon, A.I.M.E. Geophysical Prospecting, 1934. Pp.237-272

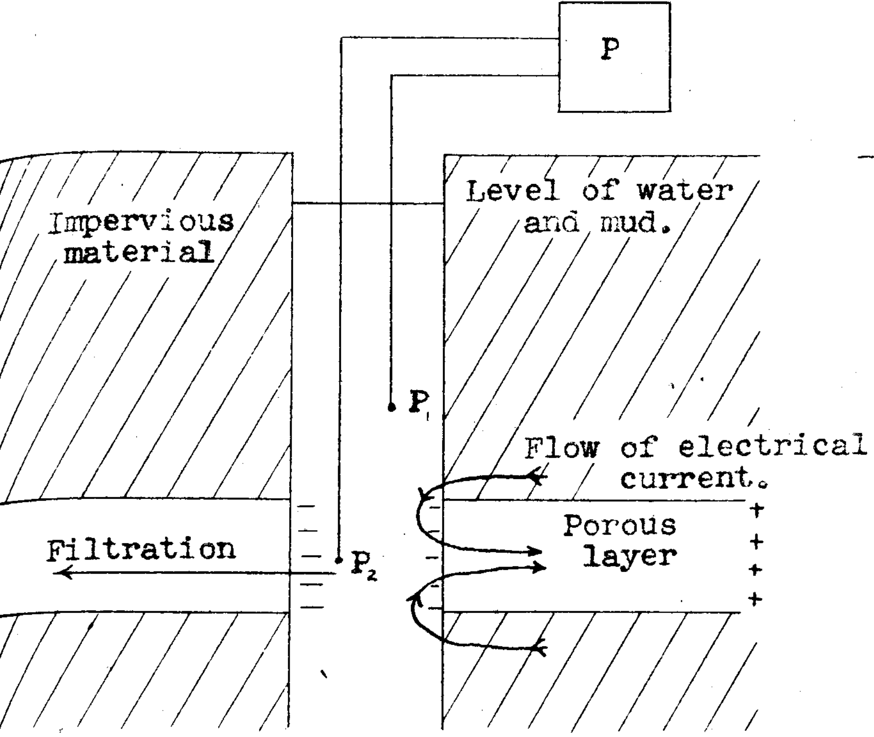

Figure 1.

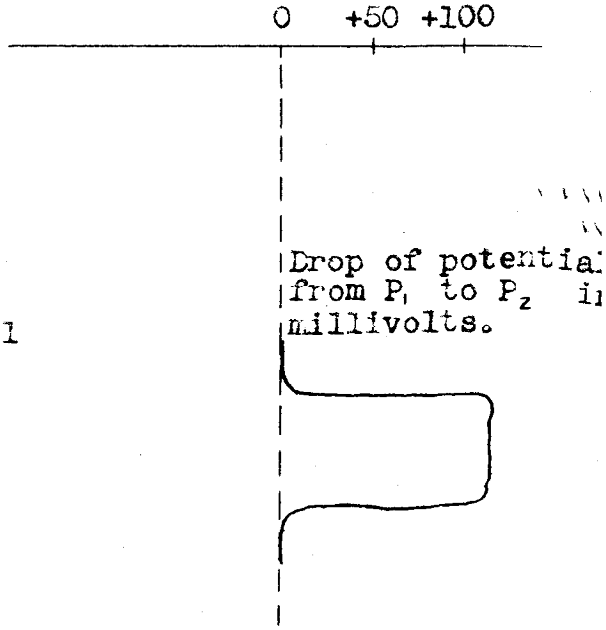

Figure 1a.

P = Potentiometer
P_1 & P_2 = Electrodes

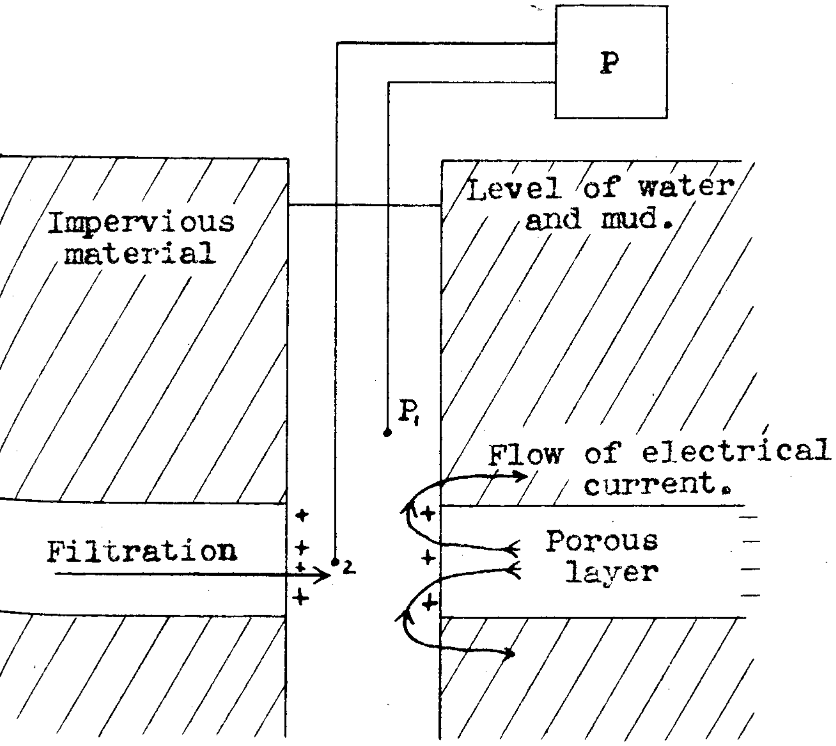

Figure 2.

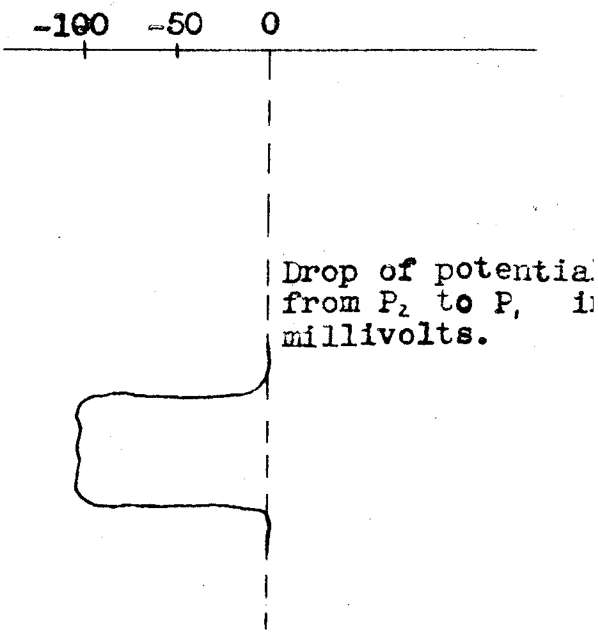

Figure 2a.

SPONTANEOUS POTENTIAL MEASUREMENTS

INSIDE DRILL HOLES.

SPONTANEOUS POTENTIAL MEASUREMENTS INSIDE DRILL HOLES

The spontaneous potentials existing in drill holes can be easily measured.

On the preceding page it is seen that two electrodes connected to a potentiometer are lowered into the drill hole. The potential difference is measured from one to the other and this gives one the spontaneous potential.

The direction of current is the same as the direction of the filtration. In figure 1, preceding page, the water in the hole is filtering into the porous layer. Thus the current flows into the porous layer. In other words, it is as if, in front of a porous layer, the wall of the hole were covered with negative electricity. Thus the potential of P_2 is lower than the potential of P_1. Calling this case a plus drop of potential, one gets the curve as shown by figure 1a.

In figure 2 water is filtering into the hole from the porous layer. Thus the current flows into the hole and the wall of the hole is covered with positive electricity at the porous layer. In this case, the potential of P_2 is higher than the potential of P_1. Calling this case a minus drop of potential, one gets the curve shown by figure 2a.

Another method of measuring the spontaneous potentials is to have one potential electrode on the surface of the ground and to lower the other into the bore hole.

In general, the spontaneous potentials that are observed and measured in a drill hole result from a combination of the electro-filtration and electro-osmosis effects. The electro-osmosis effects are usually not so large as those produced by electro-filtration.

Since both phenomena are always taking place in front of a porous layer, and the spontaneous potentials are quantitatively related to the porosity of the rock, Schlumberger calls these measurements "porosity measurements."

A "porosity log" of the type shown on page 27 is of paramount importance for the detection of porous layers and for the differentiation between impervious resistive formations, such as granite, quartzite, etc., and pervious resistant formations, such as oil or gas sand. As is the case for the resistivity log which shows only apparent resistivities, the "porosity" data do not represent the true porosity. It is merely a qualitative factor depending upon electro-filtration and electro-osmosis.

Schlumberger states that by varying the head of water, or of drilling mud, in a hole, the hydrostatic pressure may be varied and with it the amount of liquid passing into or out of a porous horizon; by measuring the changes in the natural potentials brought about by the changes in the rate of flow, he claims that a quantitative estimate of the hydrostatic pressure in the porous formation may be made.*

Natural potentials cannot be usefully measured in the cased part of a hole since the casing not only acts as a shield, but is

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* Refer to "A New Contribution to Subsurface Studies by Means of Electrical Measurements in Drill Holes, by C. and M. Schlumberger and E. G. Leonardon, A.I.M.E. Geophysical Prospecting, 1934. Pp. 273-289.

usually responsible for large and erratic polarization effects.

It would seem plausible that one could bring about a change in spontaneous potentials by pumping water out of a hole, thus causing a more rapid movement of ground water in the vicinity of the drill hole.

ELIMINATION OF SPONTANEOUS POTENTIALS

In the customary commercial practice the effect of spontaneous potentials on resistivity measurements may be neglected and the results obtained will still be well within the limits of the required accuracy. However, in cases where the resistivity values are to be measured with greater accuracy, it is desirable that the spontaneous potentials be eliminated from the induced potential readings taken. Schlumberger has recently developed a technique that accomplishes this purpose.*

He shows that by making the spacing between the electrode supplying the current to the ground and one potential electrode, C_1 and P_1 in the figures on pages 17, 18, 19, of the order of the bore hole diameter, the effects of spontaneous potentials are negligible. (This applies to either two, three, or four electrodes in the hole.) The current must be of sufficiently high value for the potential difference produced by it between points of measurement to be always large in comparison with the spontaneous potential existing between the said points.

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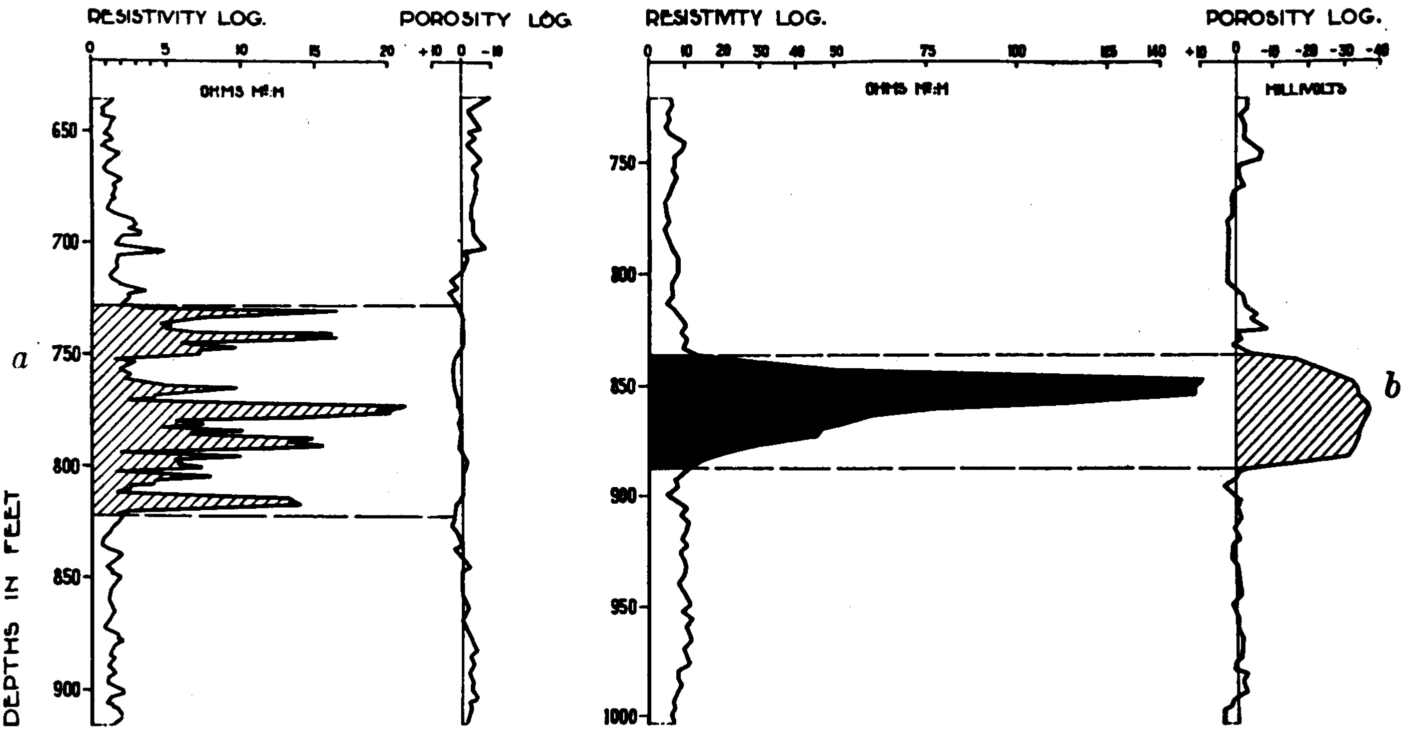
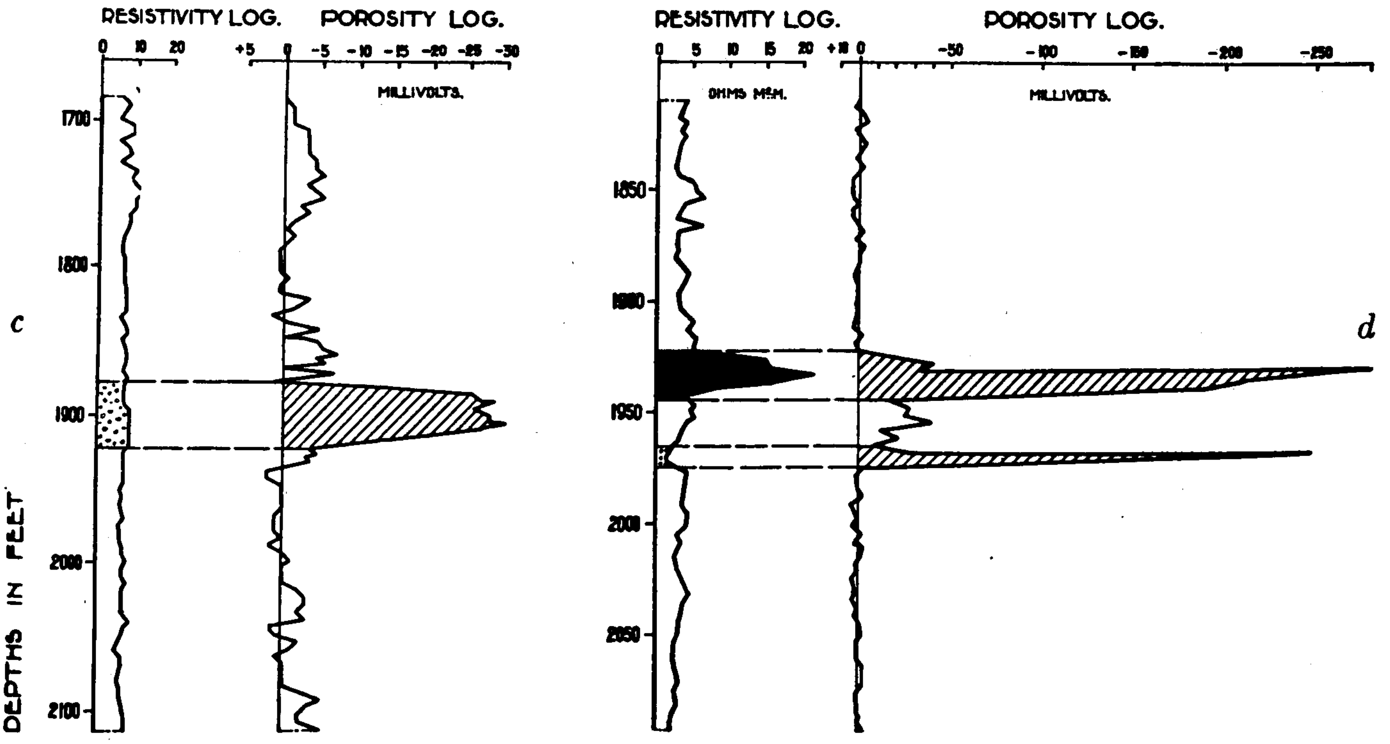
* Refer to "Method and Arrangement for the Electrical Survey of the Strata Traversed by a Bore Hole," by Conrad Schlumberger, U. S. Patent No. 2,141,826, December 27, 1938.



SCHLUMBERGER RESISTIVITY AND POROSITY DIAGRAMS.



a. Impervious and resistant formation, gypsum.
b. Pervious and resistant formation, oil sand.
c. Pervious and conductive formation, water sand.
d. Pervious formation resistant at top—oil. Conductive at bottom—salt water.

THE USE OF ELECTRICAL RESISTIVITY LOGS FOR GEOLOGICAL CORRELATION

Since the resistivity parameter generally varies widely from one layer to another, and is relatively constant for a given layer, this makes it possible to differentiate between various formations. On the other hand, the mere numerical value of the resistivity is not necessarily a distinguishing characteristic of a given formation, except under particular circumstances, since two formations of very different age, or even of lithologic facies, may show the same resistivities. Thus a single resistivity figure does not yield accurate information.

However, the comparison of two resistivity profiles on the same series of sedimentary formations will give, in a reliable manner, the relative depths to the various strata. Therefore, to obtain numerous and reliable correlations between several holes in a given area, it is no longer necessary to core all of them mechanically. It will suffice to perform the operation for the first hole drilled, and, subsequently, to take advantage of the electrical resistivity diagrams to deduce the geological columns in the new holes and to establish stratigraphical correlations in the whole district.

An important point is whether or not it will be possible to discover numerous and reliable electrical horizon markers. In this connection it must be pointed out that any given geological horizon characterized by a precise lithological change, for instance the passage from a sandstone or a limestone to a marl, will constitute also a good electrical marker. The number of electrical horizon markers, therefore, will be nearly proportional to the number of definite lithological alternations.

Generally, electrical markers are not lacking, and the resistivity graphs have a saw-tooth silhouette showing numerous characteristic beds. The figures on the following page show nicely the results that may be expected in the case of a regular sedimentation. Due to the wide range or variation in the resistivities (variations from 1 to 100) they are shown on a logarithmic scale. The beds with a saw-tooth profile are limestones or sandy shales. The two zones with a fairly regular resistivity I and III correspond to two characteristic layers of homogeneous shales; the resistive region II corresponds to limestones, and the depressions A, B, and C indicate three water sands. Sand C, of which the resistivity is very low, is a very salty one.

The reliability of the electrical markers depends on the regularity of the formations. In numerous cases, the sediments maintain their lithological facies over large areas. The consequence of this is that the diagrams possess remarkable similar silhouettes. Schlumberger shows examples of excellent correlations between a series of wells over a distance of 45 miles.* He also shows that faults can be very accurately located by correlation between adjacent wells.

Correlations may also be based on electro-filtration and electro-osmosis effects between adjacent holes.

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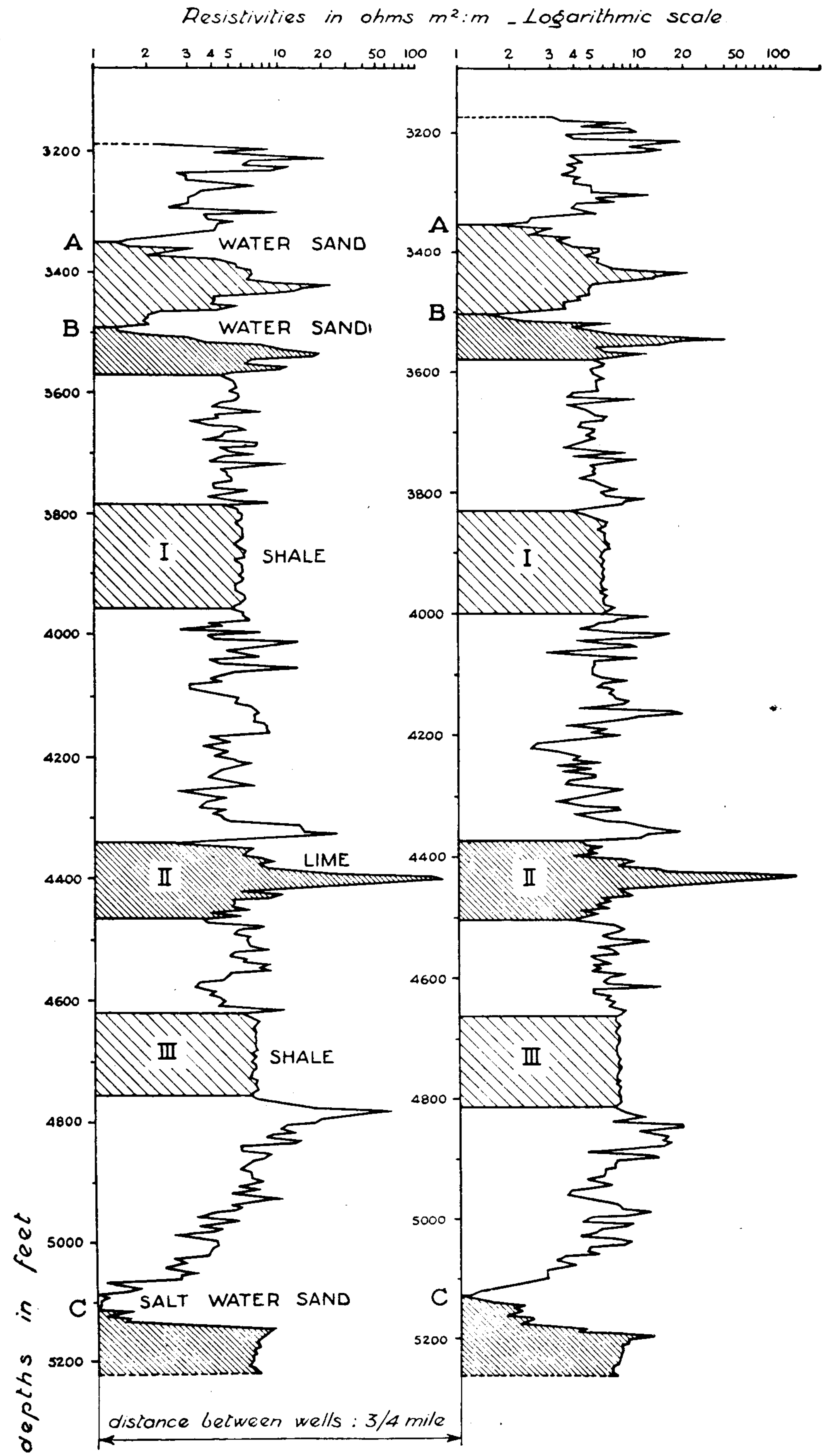
* Refer to "Electrical Coring; a Method of Determining Bottom-Hole Data by Electrical Measurements," by C. and M. Schlumberger and E. G. Leonardon, A.I.M.E. Geophysical Prospecting, 1934. Pp. 237-272.

ELECTRICAL CORRELATIONS BETWEEN TWO WELLS*



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* After Schlumberger.

SECTION V

Results of Field Experimentation

RESULTS OF FIELD EXPERIMENTATION

Two shot holes were logged, April 19, 1939, using the four electrode configuration shown on page 17. These holes were about 6 inches in diameter, uncased, drilled to a depth of approximately 200 feet, and one hole was about 1/4 mile north-east of the other. They were located about 4 miles east of Delano, California. These holes were the property of the Honolulu Oil Company, who very kindly consented to the holes being used by the author, and were drilled by the United Geophysical Company of Pasadena, California.

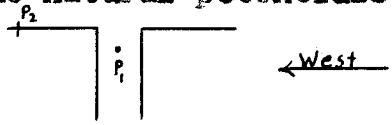
I. Shot Hole No. M-14-9

In the first hole logged, M-14-9, readings were taken every 20 feet from a depth of 65 feet down to 180 feet.* The results taken in this hole were qualitative in that this was the first time in the field with the equipment and many minor difficulties, both instrumental and manual, had to be overcome.

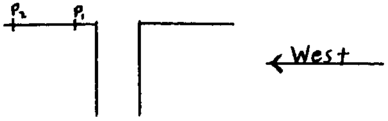
The drilling of this hole was finished at 8:30 A.M., April 19, 1939, and the well logging began at 9:00 A.M. At 10:14 A.M. the top of the water in the hole was 19 feet below the surface, and at 11:15 it was 25 feet below the surface. The logging of this hole was completed at 4:00 P.M.

Measurement of Natural Potentials

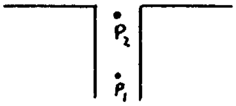
The natural potentials were measured in the following three ways:



Case I.



Case II.



Case III.

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* This depth given is measured from the surface to the middle of the electrode configuration.

Case I.

When the electrodes were at a depth of 50 feet, the potential difference due to natural potentials was measured from the potential electrode P_1 in the hole to a porous pot P_2 on the surface of the ground about 10 feet west of the hole. This potential difference was found to be 0.013 volts.

Case II.

Using two porous pots on the surface, P_1 about 35 feet of the hole and P_2 10 feet west of the hole, the natural potential difference from P_1 to P_2 was found to be 0.013 volts.

It is noted that the natural potentials measured in Case I and Case II are in opposite directions. That they are of the same value is merely coincidental. In Case I, if P_1 had been at a different depth, the value of the natural potential difference would undoubtedly have been different.

Case III.

In this case the natural potentials were measured from one metal electrode in the shot hole to the other.

Tabulation of Results.

I = current sent through the ground.

Measured e.m.f. = voltage measured from one potential electrode to the other.

R = ratio of measured e.m.f./ I. R_{Av} = Average R.

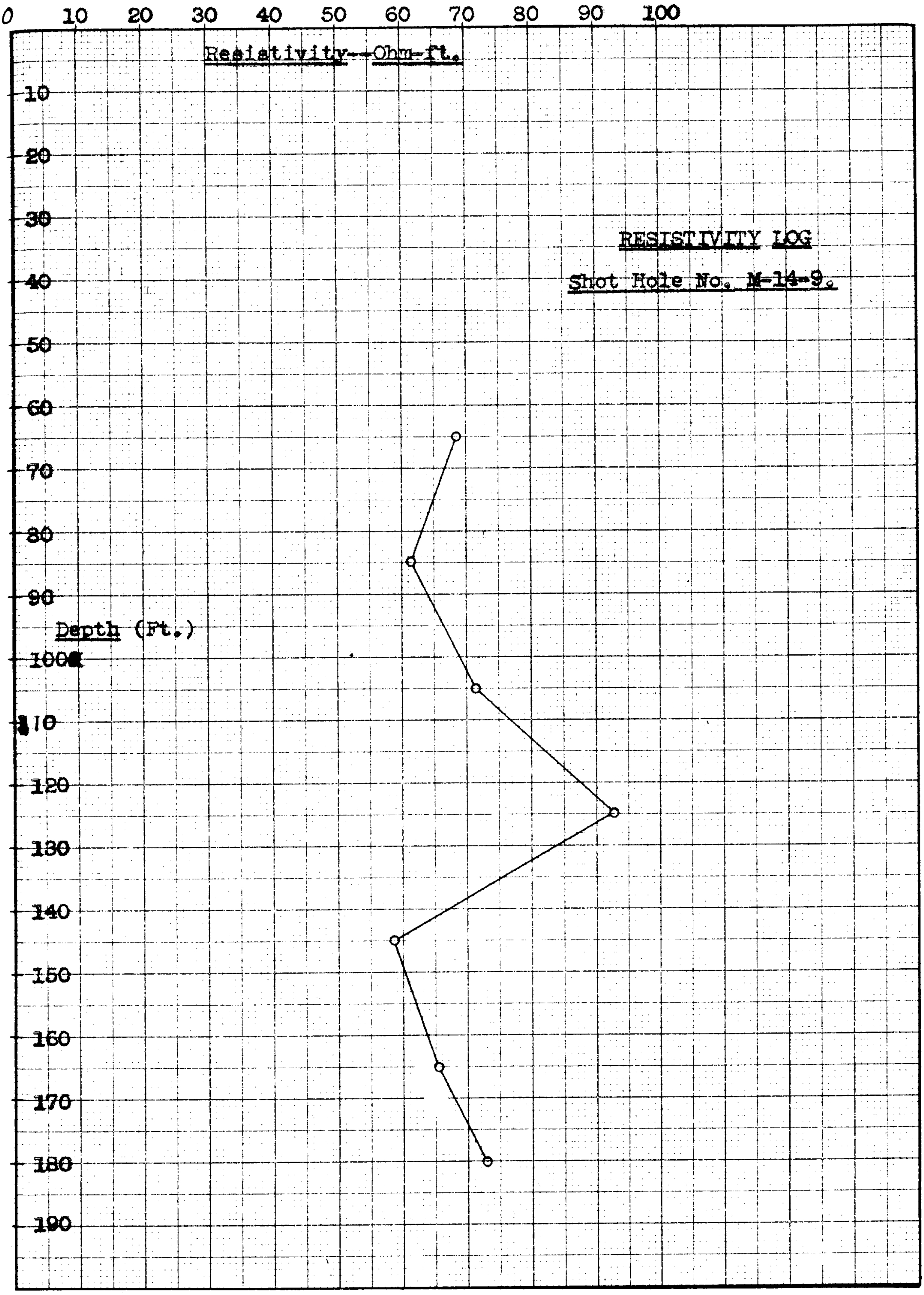
ρ = resistivity = $4\pi a \times R_{Av}$ = ohm-ft. where a = 2.9 ft.

Configuration: The symbol "$C_1 - C_2$" is used to indicate that the current is entering C_1 and leaving through C_2 and thus the potential difference is measured from P_1 to P_2.
The symbol "$C_2 - C_1$" is used to indicate that the current is entering C_2 and leaving through C_1 and thus the potential difference is measured from P_2 to P_1. $P_1 - P_2$ = Natural potential from P_1 to P_2.

Shot Hole No. M-14-9

Depth (Ft.)	Configuration	I (Amps.)	Measured e.m.f. (Volts.)	R	R_{Av}	ρ (Ohm-ft.)
65	$C_1 - C_2$	0.0790	0.155	1.96	1.88	68.5
	$C_2 - C_1$	0.0785	0.1495	1.88		
	$C_1 - C_2$	0.0790	0.1696			
	$C_2 - C_1$	0.0795	0.143	1.80		
85	$C_1 - C_2$	0.0805	0.160	1.99	1.68	61.1
	$C_2 - C_1$	0.0800	0.111	1.39		
	$C_1 - C_2$	0.0800	0.157	1.96		
	$C_2 - C_1$	0.0795	0.108	1.36		
105	$C_1 - C_2$	0.0803	0.170	2.12	1.96	71.4
	$C_2 - C_1$	0.0795	0.149	1.87		
	$C_1 - C_2$	0.0795	0.164	2.06		
	$C_2 - C_1$	0.0800	0.143	1.79		
	$P_1 - P_2$		0.011			
125	$C_1 - C_2$	0.0815	0.231	2.84	2.55	92.9
	$C_2 - C_1$	0.0810	0.183	2.26		
	$C_1 - C_2$	0.0810	0.228	2.82		
	$C_2 - C_1$	0.0815	0.186	2.28		
	$P_1 - P_2$		0.023			
145	$C_1 - C_2$	0.0825	0.156	1.89	1.61	58.7
	$C_2 - C_1$	0.0825	0.108	1.31		
	$C_1 - C_2$	0.0825	0.148	1.80		
	$C_2 - C_1$	0.0820	0.119	1.45		
	$P_1 - P_2$		0.017			
165	$C_1 - C_2$	0.0825	0.176	2.14	1.80	65.6
	$C_2 - C_1$	0.0825	0.126	1.53		
	$C_1 - C_2$	0.0825	0.172	2.08		
	$C_2 - C_1$	0.0825	0.119	1.45		
	$P_1 - P_2$					
180	$C_1 - C_2$	0.0815	0.155	1.90	1.70	61.9
	$C_2 - C_1$	0.0815	0.122	1.50		
	$C_1 - C_2$	0.0815	0.154	1.89		
	$C_2 - C_1$	0.0820	0.123	1.50		
	$P_1 - P_2$					
	$(C_1 - C_2)$*	0.0795	0.186	2.50	2.00	72.9
	$(C_2 - C_1)$	0.0795	0.088	1.19		
	$(C_1 - C_2)$	0.0795	0.172	2.31		

* See page35 .


Resistivity--Ohm-ft.
0
10
20
30
40
50
60
70
80
90
100
RESISTIVITY LOG
Shot Hole No. M-14-9.
Depth (Ft.)
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190

THE RECIPROCITY THEOREM*

According to the Reciprocity Theorem, when applied to electrical resistivity methods, the ratio "measured e.m.f./I" should be the same when the current and potential electrodes of the standard Wenner Configuration are interchanged. However, the author did not find this to be the case in the shot holes surveyed.

On page 33 it is noted that the second set of readings taken at 180 feet are very much larger than the first set of readings taken at this depth. The second set of readings was taken by sending the current through P_1 and having it leave through P_2. The potential was measured from C_1 to C_2. (This procedure is indicated by $(C_1 - C_2)$.) The symbol $(C_2 - C_1)$ indicates that the current was reversed and entered through P_2 and left through P_1. The potential difference was measured from C_2 to C_1.

Also as indicated on page 37 the reciprocity theorem did not hold. It is noted that in both these cases, pages 33 and 37, the ratio "measured e.m.f./I" is much higher after the current and potential electrodes have been interchanged. It was found that by moving the electrodes up and down in the mud several times, waiting about fifteen minutes and then returning to the standard Wenner Configuration, the aforementioned ratio was once again of the correct order of magnitude.

The author does not know why the Reciprocity Theorem is not valid, except that in all probability polarization effects at the original Wenner Configuration current electrodes caused the erratic results obtained. This subject bears further investigation.

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* Refer to "Communication Engineering," by W. L. Everitt. (1937) Pp. 52-53.

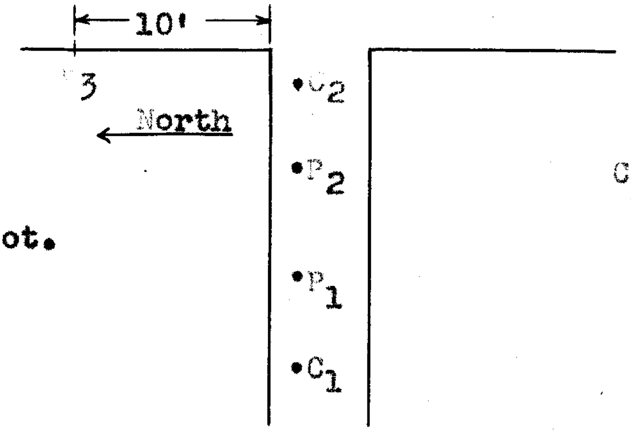
II. Shot Hole No. M13 - 13

In the second shot hole logged, M13-13, on April 19, 1939, readings were taken every ten feet from a depth of 55 feet to 125 feet; then the readings were taken every 5 feet from 125 feet down to 155 feet; and every ten feet from 155 feet down to 180 feet. The results obtained from this hole are quantitative.

The drilling of this hole was finished in the early afternoon and the well logging began at 4:30 P.M. The logging was completed at 6:30 P.M. at which time the top of the water in the hole was 45 feet from the surface.

Measurement of Natural Potentials

The following arrangement of potential electrodes was used to measure the natural potentials:



P_3 = Porous pot.

C_1 and C_2 = current electrodes that were also used for potential electrodes

At a depth of 105 feet:

Natural Potential difference from P_3 to P_2 = 0.425 volts.
" " " " P_3 to P_1 = 0.434 volts.
" " " " P_2 to P_1 = 0.007 volts.

At a depth of 155 feet:

Natural Potential difference from P_3 to P_2 = 0.440 volts.
" " " " P_3 to P_1 = 0.433 volts.
" " " " P_2 to P_1 = 0.005 volts.

At a depth of 180 feet:

(At 4:35 P.M.)
Natural Potential difference from P_3 to P_2 = 0.120 volts.
" " " " P_3 to P_1 = 0.473 volts.
" " " " P_3 to C_1 = 0.421 volts.
" " " " P_3 to C_2 = 0.092 volts.
" " " " P_2 to P_1 = 0.041 volts.

(At 4:45 P.M.)
Natural Potential difference from P_3 to P_2 = 0.134 volts.
" " " " P_3 to P_1 = 0.455 volts.

(At 4:55 P.M.)
Natural Potential difference from P_3 to P_2 = 0.385 volts.
" " " " P_3 to P_1 = 0.140 volts.
" " " " P_2 to P_1 = 0.031 volts.

The following results were obtained, at a depth of 180 feet in trying to verify the Reciprocity Theorem:

1. Using the standard Wenner Configuration.
(At 5:00 P.M.)

Amps.	Configuration	Measured volts.	R	R_{Av}	ρ (Ohm-ft.)
0.730	$C_1 - C_2$	0.937	1.29	1.25	45.7
0.715	$C_2 - C_1$	0.881	1.23		
0.730	$C_1 - C_2$	0.921	1.26		
0.735	$C_2 - C_1$	0.913	1.24		

2. Interchanging the Potential and Current Electrodes of the Wenner Configuration as described on page 35.
(At 5:05 P.M.)

0.545	$(C_1 - C_2)$	0.854	1.57	1.33	48.6
0.530	$(C_2 - C_1)$	0.571	1.08		

3. Returning to the standard Wenner Configuration.
(At 5:10 P.M.)

0.710	$C_1 - C_2$	1.400	1.97	1.96	71.5
0.710	$C_2 - C_1$	1.457	2.05		
0.690	$C_2 - C_1$	1.285	1.87		

It is noted that the Reciprocity Theorem does not hold here, although the results are much better than for the first shot hole.

One also notes that the value of R_{Av}, and consequently the value of ρ increased after returning to the standard Wenner Configuration.

Tabulation of Results.

The symbols are the same as indicated on page 32.

At depths of 105, 115, 125, 135, 145, and 155 feet there is more than one set of readings. At these depths the value of the resistivity, ρ, that is plotted on the resistivity log is underlined.

Correlation of Resistivity Logs of Shot Holes M-14-9 and M13-13.

It is hard to correlate in this case because hole M-14-9 was not logged at small enough intervals. However, there is a definite break of smaller resistivity in each curve at 145 feet. This is probably the bottom of the weathered layer since it is known to be at approximately that depth in this region.

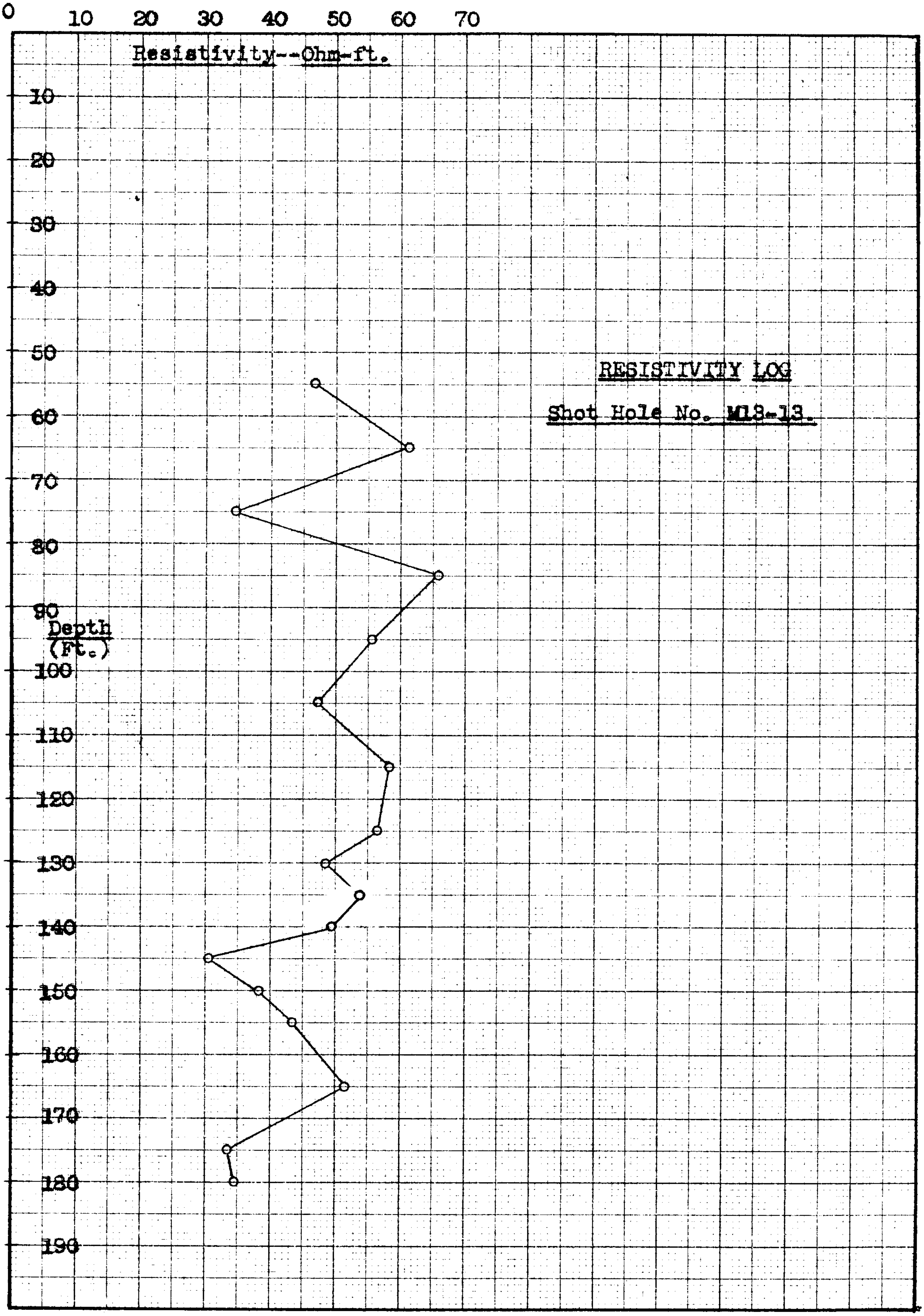
Apparantly these two holes were not drilled deep enough to locate the top of the water table.

Shot Hole No. M13-13

Depth (Ft.)	Configuration	I (Amps)	Measured e.m.f. (Volts)	R	R_{Av}	ρ (Ohm-ft.)
55	$C_1 - C_2$	0.720	0.916	1.27	1.28	46.6
	$C_2 - C_1$	0.730	0.950	1.30		
	$C_1 - C_2$	0.725	0.920	1.27		
	$C_2 - C_1$	0.730	0.935	1.28		
65	$C_1 - C_2$	0.710	1.198	1.69	1.68	61.2
	$C_2 - C_1$	0.720	1.190	1.66		
	$C_1 - C_2$	0.715	1.190	1.68		
	$C_2 - C_1$	0.720	1.209	1.68		
75	$C_1 - C_2$	0.730	0.686	0.940	0.948	34.5
	$C_2 - C_1$	0.745	0.713	0.960		
	$C_1 - C_2$	0.725	0.680	0.940		
	$C_2 - C_1$	0.740	0.706	0.955		
85	$C_1 - C_2$	0.695	1.254	1.81	1.81	65.9
	$C_2 - C_1$	0.710	1.290	1.82		
	$C_1 - C_2$	0.690	1.245	1.81		
	$C_2 - C_1$	0.710	1.265	1.78		
	$C_2 - C_1$	0.720	1.814	1.83		
95	$C_1 - C_2$	0.690	1.043	1.51	1.53	55.7
	$C_2 - C_1$	0.710	1.077	1.52		
	$C_1 - C_2$	0.690	1.045	1.52		
	$C_2 - C_1$	0.705	1.076	1.53		
	$C_2 - C_1$	0.720	1.130	1.57		
105	$C_1 - C_2$	0.690	0.922	1.34	1.34	47.3
	$C_2 - C_1$	0.685	0.925	1.35		
	$C_1 - C_2$	0.685	0.904	1.32		
	$C_2 - C_1$	0.700	0.950	1.36		
	$C_1 - C_2$	0.710	0.900	1.27	1.26	
	$C_2 - C_1$	0.730	0.910	1.25		
	$C_1 - C_2$	0.710	0.890	1.25		
	$C_2 - C_1$	0.725	0.911	1.26		
115	$C_1 - C_2$	0.725	1.141	1.58	1.61	58.1
	$C_2 - C_1$	0.720	1.145	1.59		
	$C_1 - C_2$	0.710	1.175	1.66		
	$C_2 - C_1$	0.725	1.177	1.63		
	$C_1 - C_2$	0.680	1.078	1.59	1.58	
	$C_2 - C_1$	0.690	1.093	1.58		
	$C_1 - C_2$	0.675	1.059	1.57		
	$C_2 - C_1$	0.685	1.085	1.58		

Depth (Ft.)	Configuration	I (Amps)	Measured e.m.f. (Volts)	R	R_{Av}	ρ (Ohm-ft.)
125	$C_1 - C_2$	0.705	1.185	1.68	1.49	56.5
	$C_2 - C_1$	0.710	1.000	1.41		
	$C_1 - C_2$	0.695	1.000	1.44		
	$C_2 - C_1$	0.700	0.995	1.42		
	$C_1 - C_2$	0.685	1.115	1.63	1.62	
	$C_2 - C_1$	0.705	1.122	1.60		
	$C_1 - C_2$	0.690	1.110	1.61		
	$C_2 - C_1$	0.695	1.133	1.63		
130	$C_1 - C_2$	0.710	0.949	1.34	1.34	48.8
	$C_2 - C_1$	0.725	0.973	1.34		
	$C_1 - C_2$	0.700	0.942	1.34		
	$C_2 - C_1$	0.720	0.970	1.34		
135	$C_1 - C_2$	0.730	1.105	1.52	1.52	53.9
	$C_2 - C_1$	0.715	1.100	1.54		
	$C_1 - C_2$	0.705	1.095	1.55		
	$C_2 - C_1$	0.715	1.044	1.46		
	$C_1 - C_2$	0.710	1.035	1.46	1.44	
	$C_2 - C_1$	0.725	1.030	1.42		
	$C_1 - C_2$	0.710	1.026	1.45		
	$C_2 - C_1$	0.720	1.038	1.44		
140	$C_1 - C_2$	0.730	1.004	1.38	1.36	49.5
	$C_2 - C_1$	0.740	1.000	1.35		
	$C_1 - C_2$	0.730	0.992	1.36		
	$C_2 - C_1$	0.740	1.000	1.35		
145	$C_1 - C_2$	0.725	0.656	0.905	0.89	30.5
	$C_2 - C_1$	0.730	0.638	0.88		
	$C_1 - C_2$	0.720	0.631	0.88		
	$C_2 - C_1$	0.715	0.644	0.90		
	$C_1 - C_2$	0.710	0.567	0.80	0.79	
	$C_2 - C_1$	0.730	0.565	0.78		
	$C_1 - C_2$	0.710	0.566	0.80		
	$C_2 - C_1$	0.725	0.567	0.78		
150	$C_1 - C_2$	0.730	0.807	1.11	1.10	38.1
	$C_2 - C_1$	0.750	0.814	1.09		
	$C_1 - C_2$	0.720	0.794	1.10		
	$C_2 - C_1$	0.740	0.808	1.09		

Depth (Ft.)	Configuration	I (Amps)	Measured e.m.f. (Volts)	R	R_{Av}	ρ (Ohm-ft.)
155	$C_1 - C_2$	0.715	0.842	1.18	1.19	43.4
	$C_2 - C_1$	0.705	0.842	1.19		
	$C_1 - C_2$	0.695	0.819	1.18		
	$C_2 - C_1$	0.725	0.874	1.21		
	$C_1 - C_2$	0.725	0.879	1.21	1.20	
	$C_2 - C_1$	0.735	0.875	1.19		
	$C_1 - C_2$	0.725	0.863	1.19		
	$C_2 - C_1$	0.725	0.876	1.21		
	$C_1 - C_2$	0.720	0.860	1.19		
	$C_1 - C_2$	0.715	0.852	1.19	1.17	
	$C_2 - C_1$	0.725	0.842	1.16		
	$C_1 - C_2$	0.710	0.838	1.18		
	$C_2 - C_1$	0.720	0.839	1.17		
165	$C_1 - C_2$	0.730	1.012	1.52	1.41	51.4
	$C_2 - C_1$	0.710	0.997	1.41		
	$C_1 - C_2$	0.710	0.978	1.38		
	$C_2 - C_1$	0.720	0.960	1.33		
175	$C_1 - C_2$	0.740	0.688	0.93	0.92	33.5
	$C_2 - C_1$	0.750	0.675	0.90		
	$C_1 - C_2$	0.730	0.678	0.93		
	$C_2 - C_1$	0.740	0.680	0.92		
180	$C_1 - C_2$	0.730	0.689	0.95	0.95	34.5
	$C_2 - C_1$	0.730	0.700	0.96		
	$C_1 - C_2$	0.735	0.678	0.92		
	$C_2 - C_1$	0.720	0.691	0.96		



RESISTIVITY LOG

Shot Hole No. M13-13.

Surface Resistivity Profile at Shot Hole No. M13-13

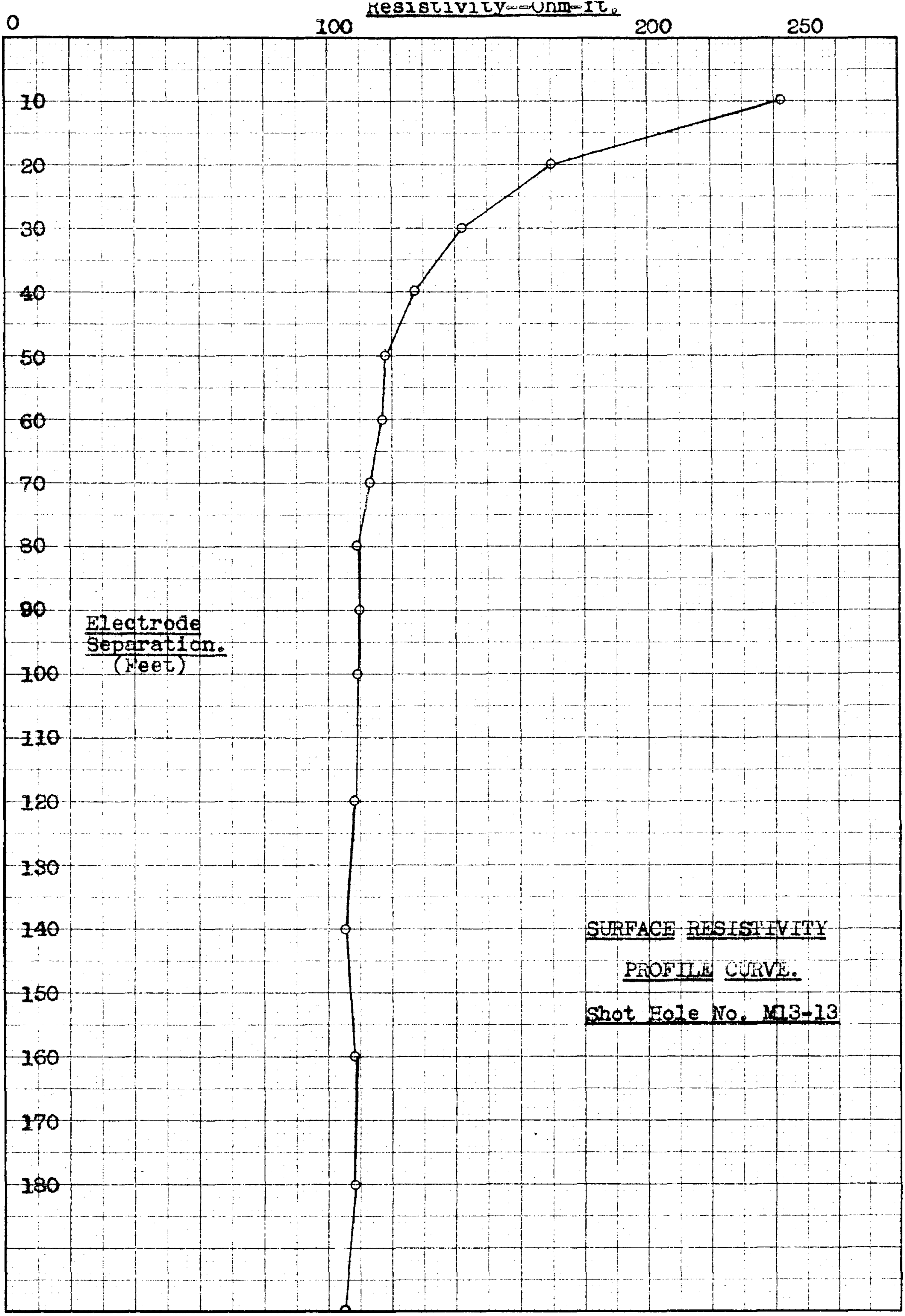
On April 20, 1939, a surface resistivity profile was run, north and south, to supplement the resistivity log obtained in this hole. The shot hole was used as the center of a Wenner Configuration and the electrode spacing was increased by 10 foot intervals up to an interval of 100 feet. From a 100 foot interval to a 200 foot interval, the interval spacing was increased every 20 feet. Thus with an interval between electrodes of 200 feet, the resistivity of the ground, surrounding the shot hole, was determined to a depth of 200 feet.

A resistivity curve, electrode separation or depth plotted against resistivity, is found on page 45. This curve should correlate with the resistivity log plotted on the preceding page. It is noted that the resistivity log shows a much greater variation in detail than the surface resistivity profile curve. Thus one sees that a resistivity log is of much more value, than the surface resistivity profile curve, in obtaining a detailed study of the structure of the ground.

Data For Surface Resistivity Profile Curve

Electrode Separation (Feet.)	Resistivity (Ohm-ft.)				
10	242.1	60 Ft.	117.2	120	97.9
20	170.0	70	112.9	140	94.6
30	142.0	80	108.6	160	97.9
40	126.9	90	109.7	180	97.9
50	118.3	100	108.6	200	94.6

It is noted that the values of resistivity found from the surface are much greater than those found by logging the shot hole. This is probably due to the fact that the surface resistivity values are an average, whereas the values found by logging are more nearly the actual values of the resistivity. (See page 14). The surface resistivity profile curve, found on the following page, also indicates a high resistivity value near the surface of the earth.



SURFACE RESISTIVITY PROFILE CURVE.

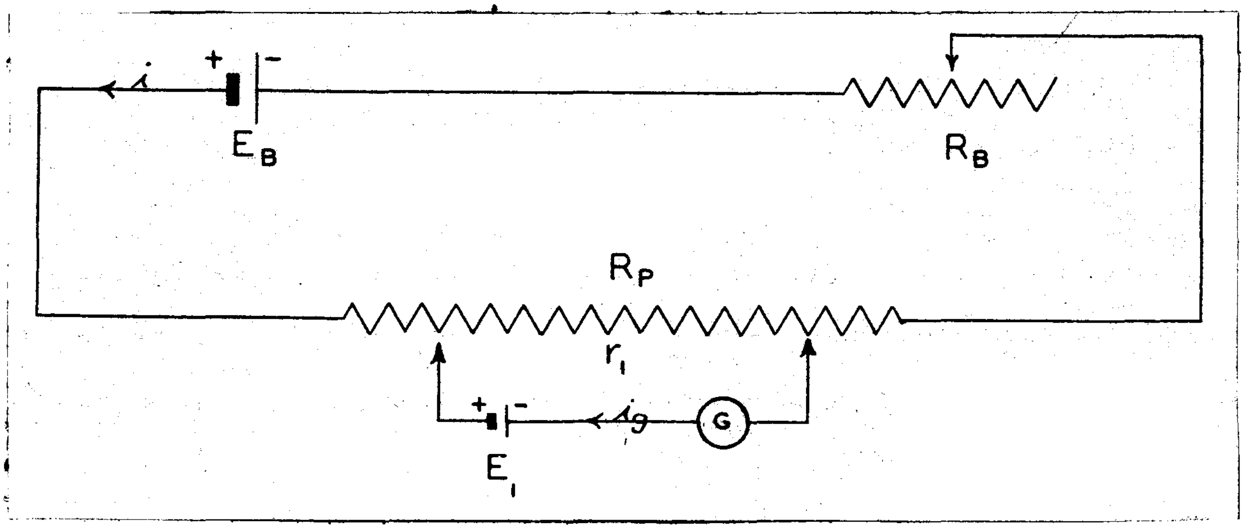
Shot Hole No. M13-13

SECTION VI

1. The Potentiometer
2. High Gain Amplifier
3. Circuit for Measuring Earth-Resistivity
4. Description of Apparatus
5. Commutator
6. Megger Ground Tester
7. Field Difficulties Encountered in Resistivity Measurements

THE POTENTIOMETER

Let there be given an electrical circuit in which E, R, and i are known. Then the electrical condition of the circuit is completely specified. It is desired to measure an e.m.f., or potential difference, in the circuit. When the measuring instruments are inserted in the circuit it is essential that they draw no current, otherwise the measured e.m.f. may differ appreciably from the true value which exists in the absence of the measuring instruments. This rigid requirement is met by a resistance network device known as a "Potentiometer." The main features of such a network are shown in the following figure:



A battery E_B causes a current i to flow through a resistance R_P. The adjustable resistance R_B, in series with R_P, is used to vary the magnitude of current i. Across a certain portion, r_1, of R_P is bridged a source of e.m.f. E_1 and a galvanometer G in series. Now suppose that r_1 is chosen so that $i_g = 0$. Then evidently $r_1 = E_1$, for by Kirchhoff's second law $r_1(i + i_g) + R_g i_g = E_1$, R_g being the galvanometer resistance. Therefore to balance the potentiometer one must adjust r_1 until the galvanometer shows no deflection. Note that this cannot be done unless E_1 is connected with the proper polarity. Now keeping i constant and replacing E_1 by another e.m.f. E_2, a new balance is obtained with r_2. Therefore

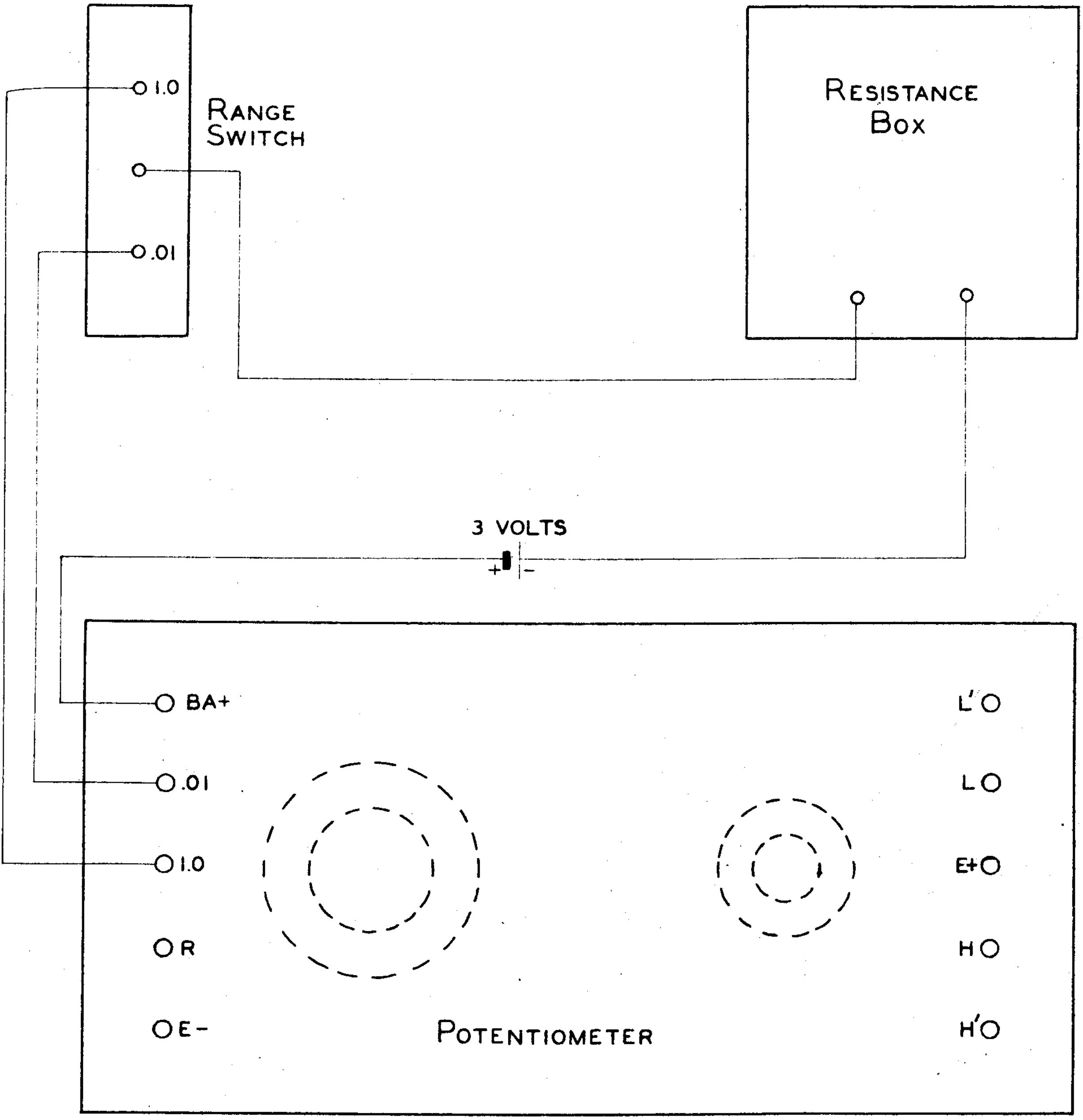
$$\frac{E_1}{E_2} = \frac{r_1}{r_2} .$$

<u>That is, the potentiometer compares e.m.f.'s in terms of resistances.</u> Now supposing that E_1 is due to a standard cell E_s, and that E_2 refers to any unknown e.m.f. E, then the above equation becomes

$$E = E_s \times r/r_s .$$

Keeping the current through R_p constant, the elements of which R_p is composed may be calibrated to read directly in volts. Thus it is noted that in a potentiometer the standard cell is applied to a fixed portion of R_p only, and the balance effected by adjustment of R_B. This establishes a definite current in R_p and consequently a definite potential drop across each resistance element, so that when the unknown E is balanced by varying r the desired magnitude is indicated directly.

The Leeds and Northrup Student Potentiometer used in this thesis employs the above principle. This instrument has two ranges; 0 to 16 millivolts and 0 to 1.6 volts. A detailed description of this potentiometer may be found in the Leeds and Northrup Catalog E-50B (1), 1937. The potentiometer circuit is seen on the following page.



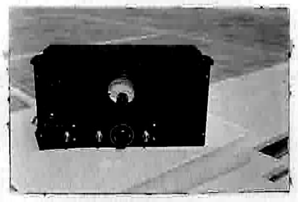
POTENTIOMETER CIRCUIT

Procedure Followed in Using the Potentiometer

The instrument is so designed that when 0.01 ampere is flowing through the resistance R_p the voltage read is $0.01 \times r_1 = E$. However, if 0.01 ampere __is not__ flowing through R_p then the voltage read, E, is not the actual e.m.f. across the terminals of the instrument. To get the desired current, 0.01 ampere, one must balance the potentiometer against a standard cell. This is done as follows: Place the standard cell across the potentiometer and also fix the dials on the potentiometer to read the same voltage as the standard cell. If 0.01 ampere is flowing through the potentiometer then there will be no deflection of the galvanometer* and the potentiometer is in balance. However, if 0.01 ampere __is not__ flowing through the potentiometer the galvanometer will deflect thus indicating the potentiometer is not balanced. By varying the resistance, using the resistance box indicated on the preceding page, the galvanometer may be brought to zero position and hence the potentiometer is balanced because 0.01 amperes are now flowing through it. The standard cell is then removed and the potentiometer is ready to be used to determine an unknown voltage. The potentiometer should be balanced against the standard cell at least every one-half hour for accurate results.

* In the work of this thesis an amplifier was used in place of the galvanometer. (See following pages)

HIGH GAIN AMPLIFIER



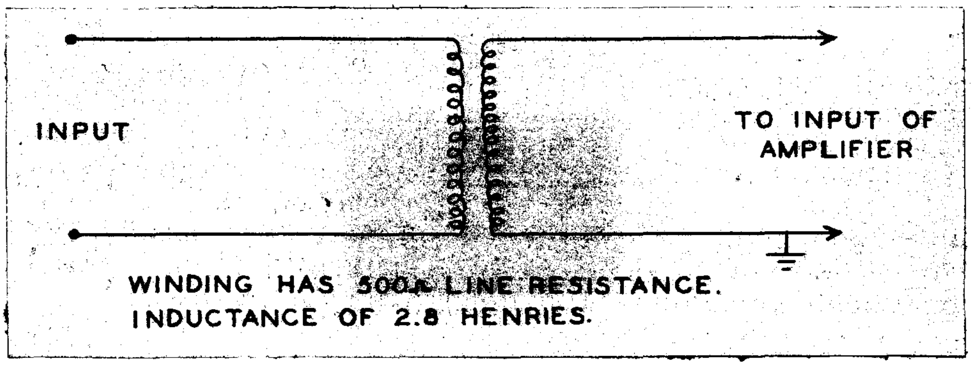
The usual procedure in using a galvanometer with a potentiometer is described on the preceding page. This author, however, for reasons of economy and greater rapidity of measurements, has used an amplifier in the place of the highly sensitive galvanometer.

The use of the amplifier is very simple: When the potentiometer is in balance with the unknown e.m.f. and when the potential circuit is made and broken with the telegraph key, the needle of the milliammeter of the amplifier is deflected. The needle "kicks" every time the key is closed. As the potentiometer is gradually brought to balance with the unknown e.m.f., the amplifier needle "kicks" less and less until, when a balance is reached, there is no kick of the needle. As the balance is approached, the sensitivity or gain of the amplifier is increased by turning the "volume" knob. This gradually cuts out the 0.5 megohm that is across the input of the amplifier.

Design of the Amplifier. (See page 52.)

The amplifier is three stage resistance-coupled with an input transformer, whose characteristics are as follows: (see next page)

Input Transformer

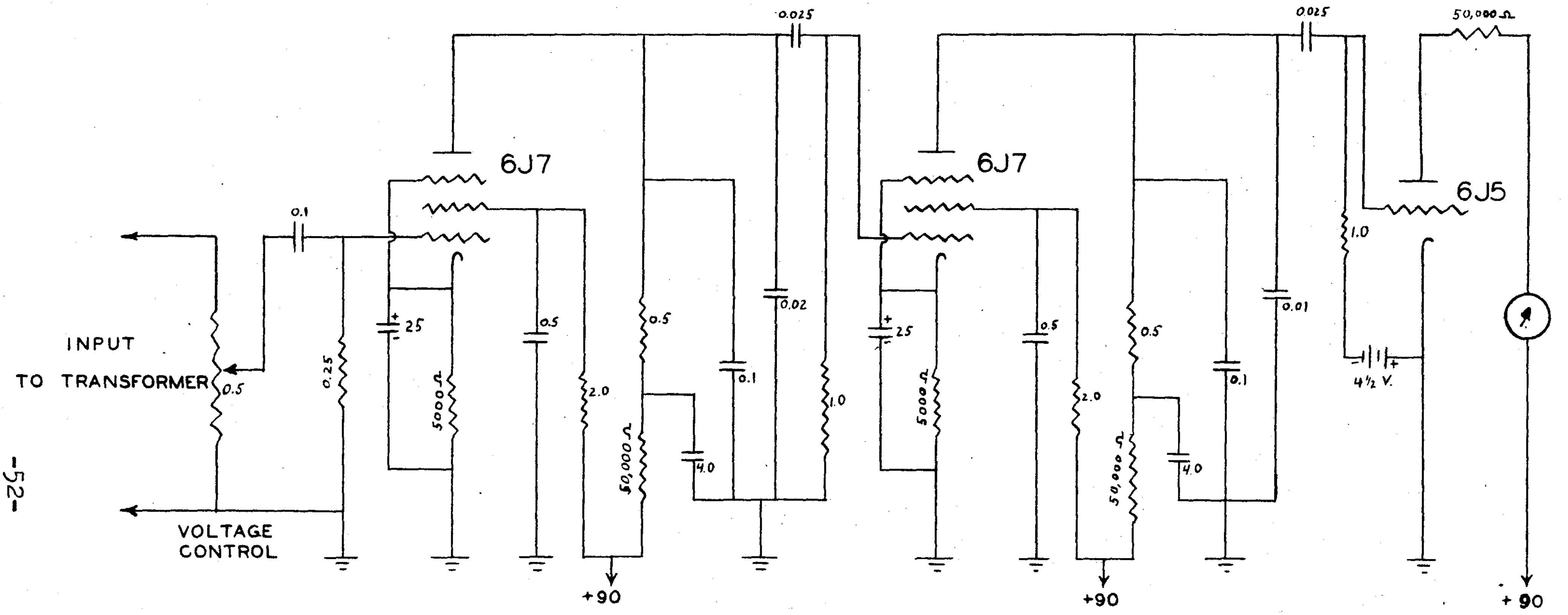


The gain of the amplifier is about 90 d.b. and the frequency response falls off at around 15 cycles. The response is good up to 1000 cycles.

There are no feed-back pentodes and a 0.5 megohm voltage control is used across the input to control the sensitivity. The 0.1 micro-farad condenser in the grid circuit of the first tube is to protect this grid from any stray direct currents that may enter the amplifier. A 50,000 ohm resistor is used in the plate circuit of the last tube for stability. It stops oscillation, if any occurs, when the 0.5 megohm is cut out entirely. The 50,000 ohms is not usually needed.

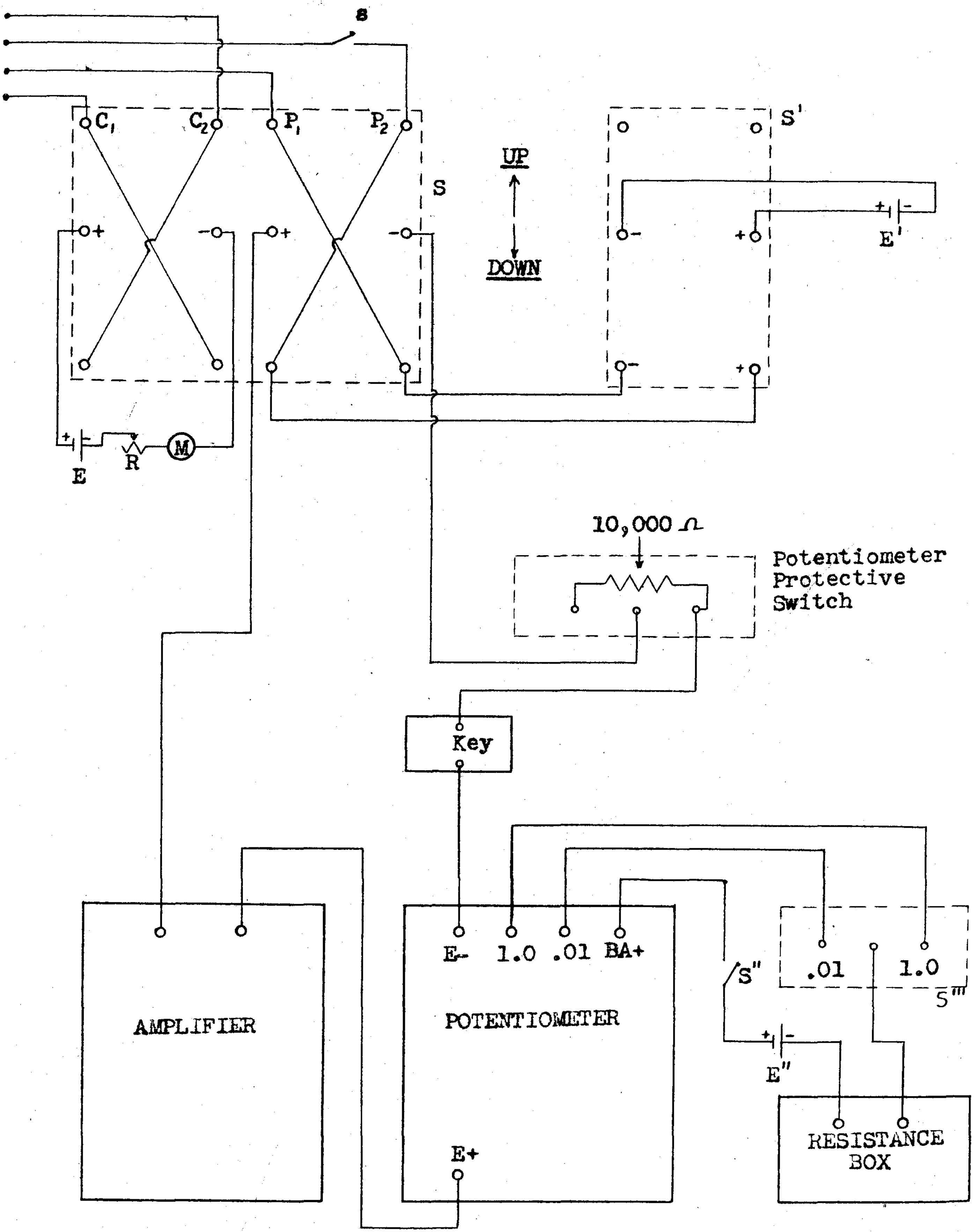
The plate current of the last tube is about 0.3 milliamperes, and the meter indicated is a one milliampere milliammeter. When the voltage transient is sent through the amplifier, by making and breaking the potential circuit of the measuring apparatus, the needle of this meter "kicks" as previously described.

A 4 1/2 volt C battery is used for the grid bias of the last tube and two 45 volt B batteries are used to supply the 90 volts to the amplifier. A 6 volt A battery is used to heat the filaments of the three tubes.



HIGH GAIN AMPLIFIER

ALL CONDENSERS IN MICRO-FARADS
RESISTANCES IN MEGOHMS



CIRCUIT FOR MEASURING EARTH-RESISTIVITY

ELEMENTS OF CIRCUIT FOR MEASURING EARTH-RESISTIVITY

(See preceding page)

E = Voltage of B batteries that produce the current that is sent through the ground.

M = Milliammeter to measure the current through the ground.

R = 500 ohm rheostat to control the current.

S = Four pole, double-throw, reversing switch. This switch serves to reverse the current and the e.m.f. in the ground, and at the same time keeps the current through the milliammeter and the potential applied to the potentiometer always in the same direction. For example, when the switch S is thrown "up" the current enters the ground through C_1 and leaves through C_2. The potential is measured from P_1 to P_2. Now when the switch S is thrown "down" the current enters the ground through C_2 and leaves through C_1 and yet the current is still in the same direction through the milliammeter as it was when the switch was thrown "up." Also when the switch is "down" P_2 is at a higher potential than P_1 and thus the potential is measured from P_2 to P_1. And yet the potential applied to the potentiometer is in the same direction as it was when the switch was "up."

E' = Standard cell.

S' = Double pole, double-throw switch. This switch is used to put the standard cell across the potentiometer. When the resistivity measurements are being made this switch must be thrown "up." To put the standard cell across the potentiometer, turn off the current due to E and then throw both S and S' "down" and the switch s must be open.

Key = Telegraph key to make and break the potential circuit. Sometimes this key does not make good contact. It might be desirable, although not tried by the author, to use a relay to make and break the potential circuit.

S" = Switch to open potentiometer circuit.

E" = Three volts from dry cells for the potentiometer circuit.

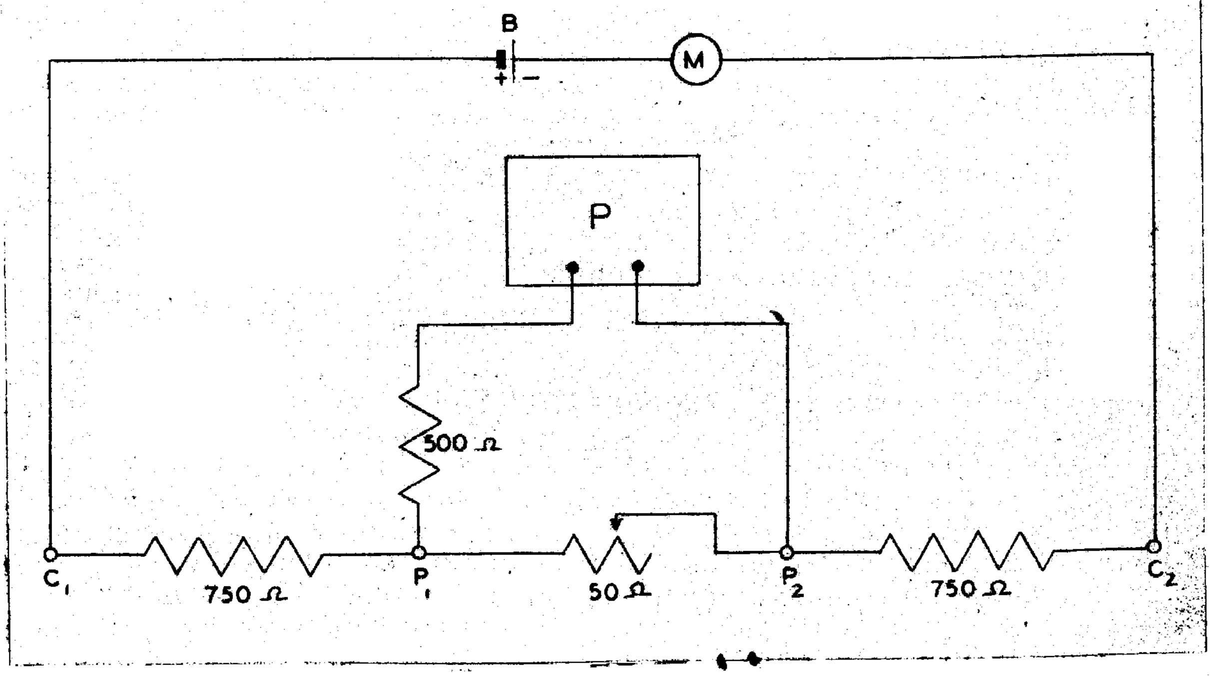
S"' = Potentiometer Range Switch. When the switch is thrown to the 1.0 side the potentiometer reads directly the voltage across its terminals. The range of the potentiometer is then 0 to 1.6 volts. When the switch is thrown to the 0.01 side the potentiometer readings must be multiplied by 0.01. The range of the potentiometer is then 0 to 16 millivolts.

s = Switch that, when it is open, prevents any natural potentials that may be present from being across S when E' is in the circuit. s is closed when making resistivity measurements.

Potentiometer Protective Switch

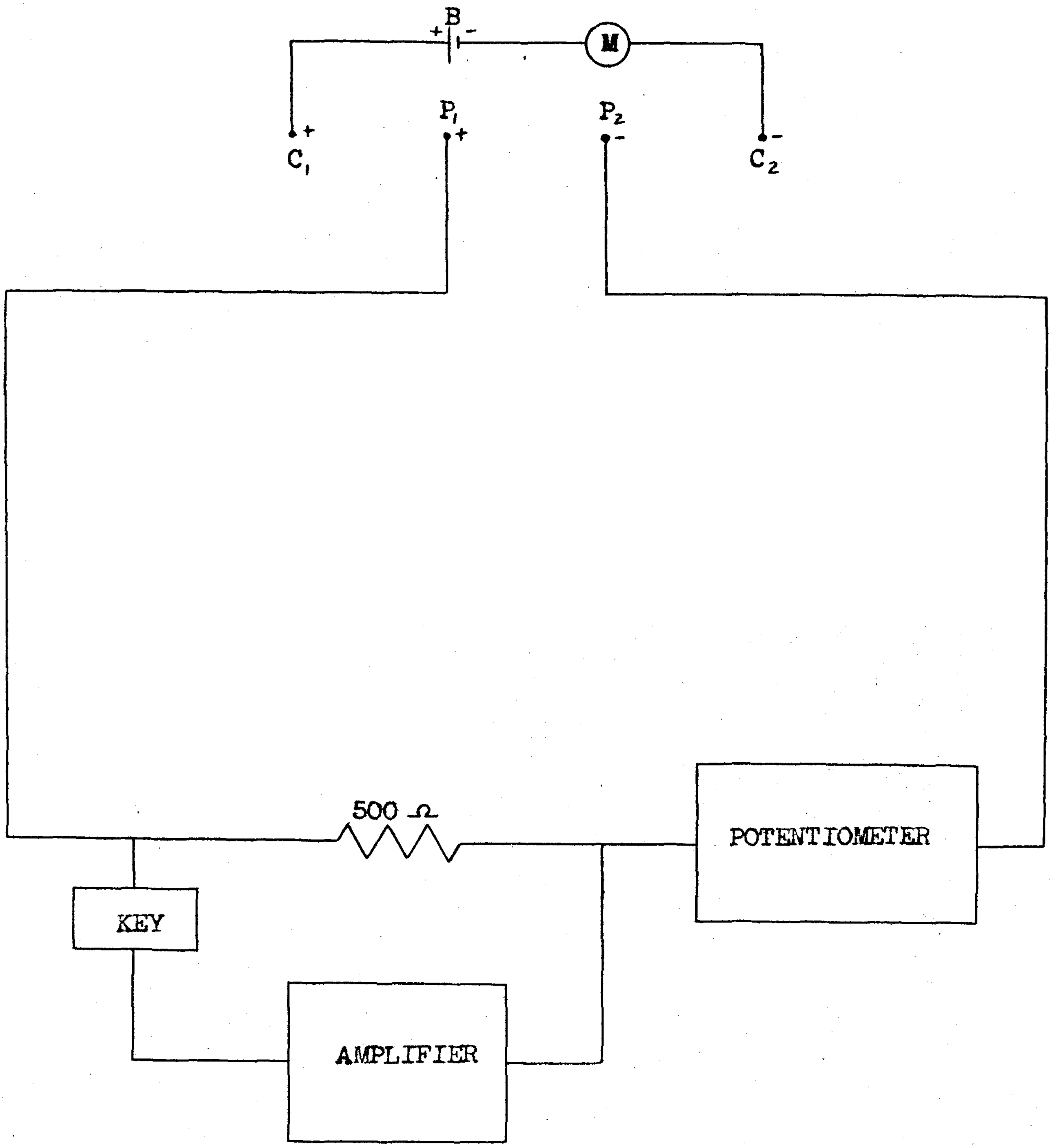
The 10,000 ohm resistance is thrown in series with the potentiometer to prevent any large currents from going through the potentiometer. When the potentiometer is about balanced with the unknown e.m.f. the 10,000 ohms is taken out of the circuit. This tends to make the measurements more delicate.

When working in the laboratory it was found necessary to devise a circuit that would simulate field conditions. The author found that the following circuit served this purpose very well:



P is the potentiometer and M the milliammeter. The 50 ohm rheostat varies the e.m.f. from P_1 to P_2.

On the following page is seen an alternative earth-resistivity measurement circuit. The 500 ohms matches the line resistance of the transformer in the amplifier. This circuit operates very well but it seems to have no advantages over the circuit already described.



SCHEMATIC DIAGRAM OF AN ALTERNATIVE EARTH-RESISTIVITY CIRCUIT.

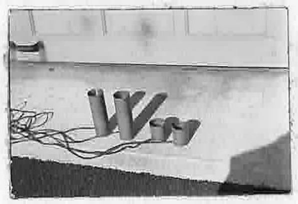
DESCRIPTION OF THE APPARATUS

The important factor in building the apparatus is to have everything as compact as possible so that the equipment may be carried about conveniently. It is also essential that the instruments are so arranged that very few connections have to be made when the apparatus is moved about. A great deal of time and effort is saved if one has only to connect up a very few instruments at each set up.

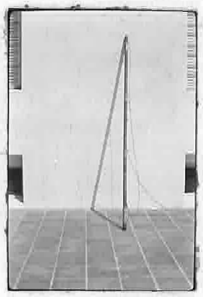
All the apparatus, except that which had to be machined, was made by the author.

Apparatus for lowering the electrodes into the shot hole.

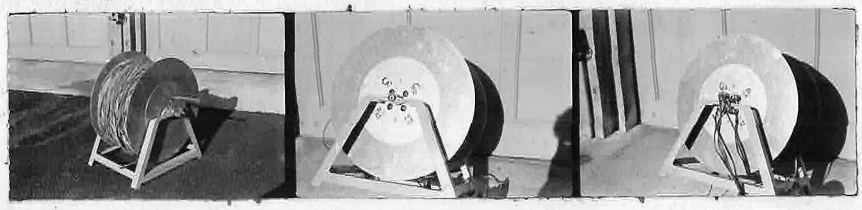
The electrodes were cut from a sheet of copper. The current electrodes are six inches long and the potential electrodes are two and one half inches long. They are then made into the form of hollow cylinders.



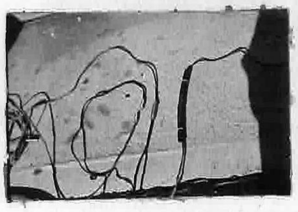
The electrodes are slipped over the end of a hard rubber pipe that is ten feet long, inside diameter of 1.43 inches, and an outside diameter of 1.90 inches. The electrodes are evenly spaced over the length of the pipe, 2.9 feet between them, and are taped in place.



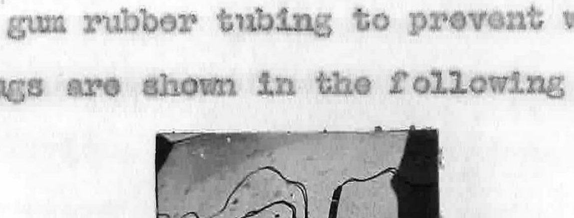
One rubber insulated copper wire is soldered to each of the electrodes. These copper wires, that go to the surface to the measuring apparatus, are taped together and wound around a metal reel. There are four plug sockets in the side of the reel into which are plugged the leads from the measuring instruments.



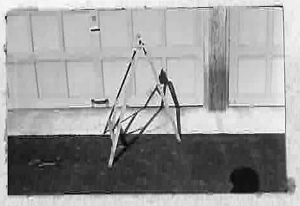
Since the electrodes are taped to the rubber pipe, some arrangement must be made to remove the wires from the electrodes when moving the apparatus about. Instead of taking them off the electrodes, they are sent through a special type of plug. Each wire has a plug and is unplugged just above the top of the rubber pipe. These plugs screw together and are then covered with a piece of pure gum rubber tubing to prevent water from touching them. These plugs are shown in the following figure:

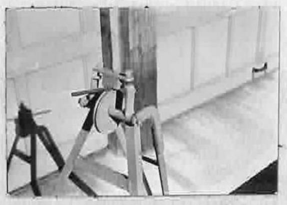


A large lead weight is bolted to the lower end of the rubber pipe. This weight pulls the electrodes down the hole and has four springs on it that keep the weight and the pipe more or less in the center of the hole. The weight should be about 150 pounds.

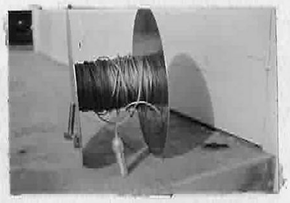


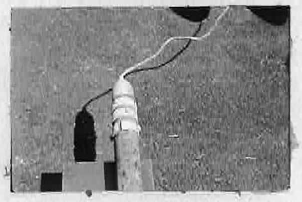
The pipe is lowered into the hole over a pulley, setting on a tripod, by means of a 3/16 inch wire rope cable. On top of the pulley is a device that allows the electrodes to be stopped at any depth desired.





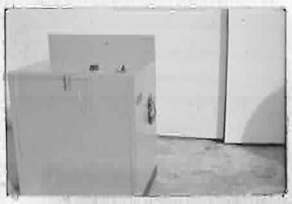
The wire rope is wound around a large metal reel that fits on the side of a truck. The wire is attached to the top of the rubber pipe by means of a metal spinner that is attached to the end of the wire rope.



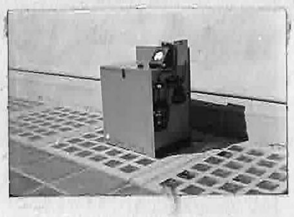


Measuring Apparatus

Eight B batteries, heavy duty, are kept in a heavy wooden box made of 3/4 inch white pine. The box is held together with screws and is reinforced around the base by a metal band. The box and batteries are very heavy and must be carried around by means of two strong and large handles screwed on the side of the box.

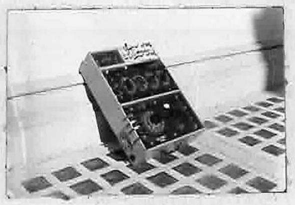


On top of this box is a small box that contains the standard cell. This cell is delicate and the box that holds it is lined with sponge rubber. The milliammeter is also screwed to the top of the battery box. A rheostat to adjust the current from the batteries and a seventeen point Yaxley Selector Switch are also situated on top of this box. The selector switch selects the voltage that is to be used.



On the side of the battery box are two plug sockets, plus and minus, going to the batteries. Also a double-pole, double-throw switch for the standard cell, and a four-pole, double-throw, reversing switch for the four electrodes that go into the well, are screwed on the side of the battery box.

The potentiometer, potentiometer protective switch, potentiometer range switch, resistance box, dry cell batteries, and the telegraph key are all placed in another box.



COMMUTATOR

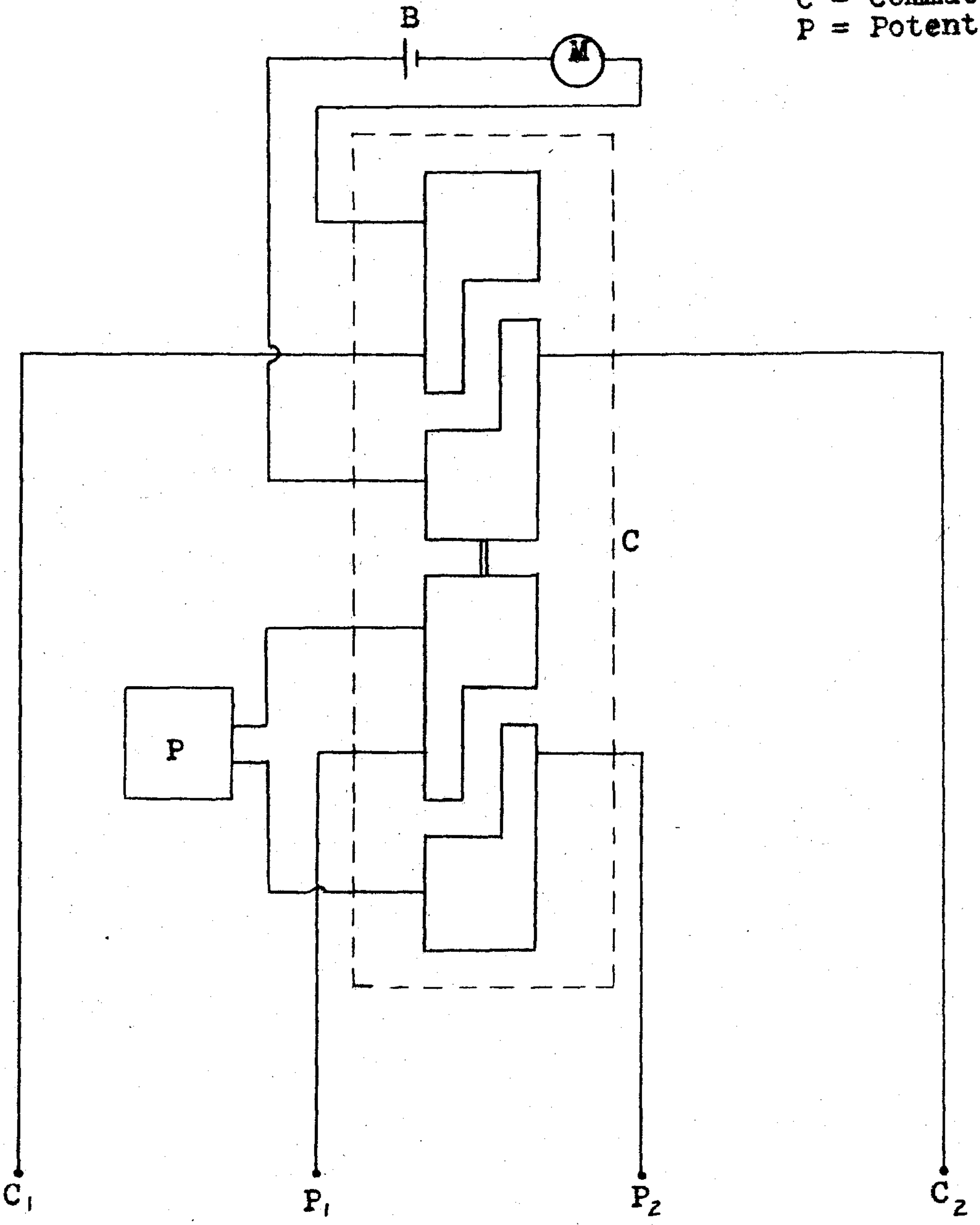
Many of the errors in the surface resistivity measurements, especially the effect of earth currents and the effect of polarization or galvanic action when iron stakes are driven into the ground and used as electrodes, may be eliminated by the use of a commutator. This instrument is so designed that it has the following effect (when used with a Wenner or Lee Partitioning electrode configuration): The applied direct current in the ground and the potential from one potential electrode to the other are alternating, while the current through the milliammeter and the potential applied to the potentiometer are both uni-directional. (See pages 63 and 64.) The applied direct current is reversed by the commutator about twenty times per second; hence the current may be called an alternating direct current. The commutator may be run either by hand or by an electric motor.

The commutator that was at the disposal of this author did not function satisfactorily when using an amplifier, of the type used in this thesis, in the place of a galvanometer. This was due to the fact that a galvanometer used in resistivity work, in connection with a commutator, must be a long period instrument that is not disturbed by the wave form due to the commutator. The amplifier does not act as a long period instrument and is greatly disturbed by this wave form. The high frequency commutator transients and poor brush contacts in the commutator also disturb the amplifier. Putting the commutator on an oscilloscope, it was found that the wave form was very bad. Perhaps if the commutator were specially designed to be used with an amplifier, satisfactory results could be obtained. However, a direct coupled amplifier would undoubtedly take the place of a long period galvanometer and would function properly when using a commutator.

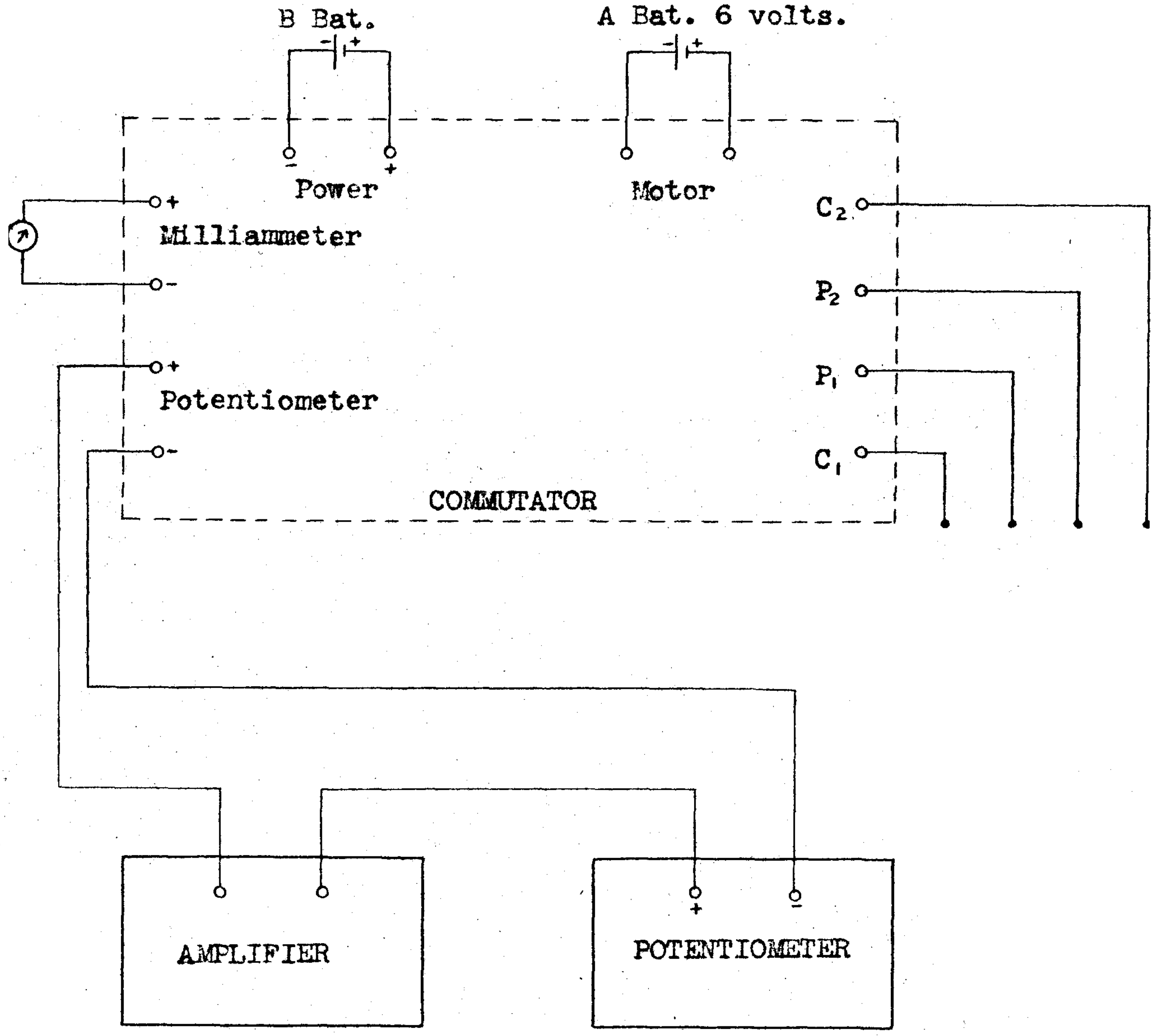
In the preceding paragraph it is stated that a commutator could not be used, when using the amplifier, in surface resistivity methods. This was also found to be true in well logging methods. However, on the surface of the ground, by using porous pots for the potential electrodes the amplifier functioned excellently. Obviously this type of porous pot could not be used in drill holes, since the change in pressure from point to point in the hole must be accompanied by a passage of liquid through the porous cup of the electrode and such passage would give rise to electro-filtration potentials and, possibly, electro-chemical potentials that would be inseparable from the potentials being measured. As far as can be ascertained from the work done by this author, the large and erratic polarization potentials commonly experienced in surface measurements when metal contact is used in direct contact with the soil do not occur when the contact is with the water and mud of a shot hole and ordinary metallic electrodes may be used.

Thus it has been shown that a commutator is not necessary for the well logging methods used in this thesis.

M = Milliammeter
B = Battery
C = Commutator
P = Potentiometer



SCHEMATIC DIAGRAM OF COMMUTATOR IN EARTH-RESISTIVITY CIRCUIT



Schematic Diagram of Earth-Resistivity Circuit when the Commutator is used.

MEGGER GROUND TESTER*

Although the author was unable to obtain use of a Megger, it seems well worth while to give a brief summary of the principles involved in this instrument.

The Megger Ground Tester, see page 67, allows one to carry out simple surface reconnaissance electrical surveys and the unique thing about it is its simplicity of operation. The four binding posts of the instrument are connected by insulated wires to four stakes driven into the ground at appropriate points. The crank of the Megger is then turned and the resistance of the ground between the two inside stakes is read directly, in ohms, by the deflection of a pointer over a scale.

When the crank is turned, it drives a self-contained, direct current generator. The current thus generated passes first through the current coil, or ammeter element, of an ohmmeter. Thence it goes to a commutator mounted on the same shaft with the generator, where it is changed into alternating current of about 50 cycles per second. Finally, it is lead from the two current binding posts, C_1 and C_2, of the instrument to the two appropriate field stakes. The other two field stakes are connected to the two potential binding posts, P_1 and P_2, of the instrument. The potential drop across these two stakes is measured by leading the current picked up by them through a second commutator, run synchronously with the first, where it is converted back into direct current. It then goes to the potential coil of the ohmmeter.

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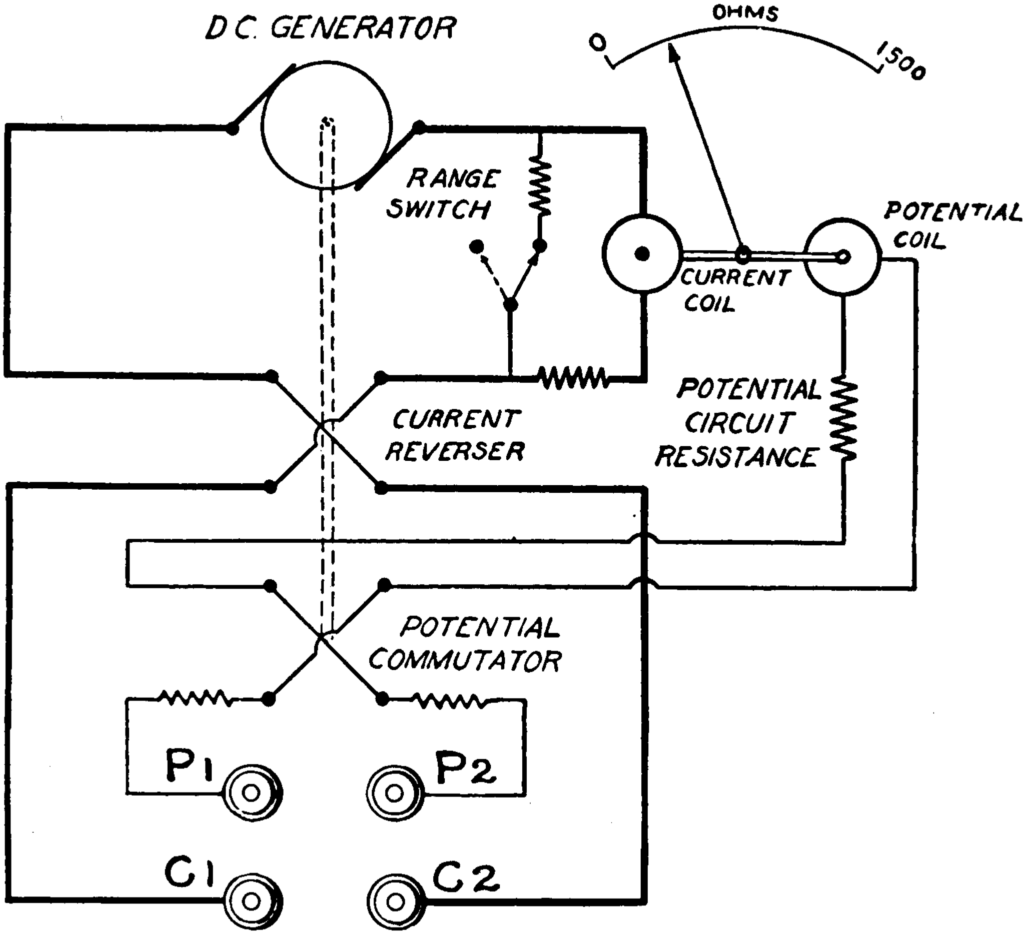
* For a detailed study of the Megger refer to: "Applying the Megger Ground Tester in Electrical Exploration," by B. Low, S. F. Kelly, and W. B. Creagmile, A.I.M.E. Geophysical Prospecting, 1932. Pp. 114-126.

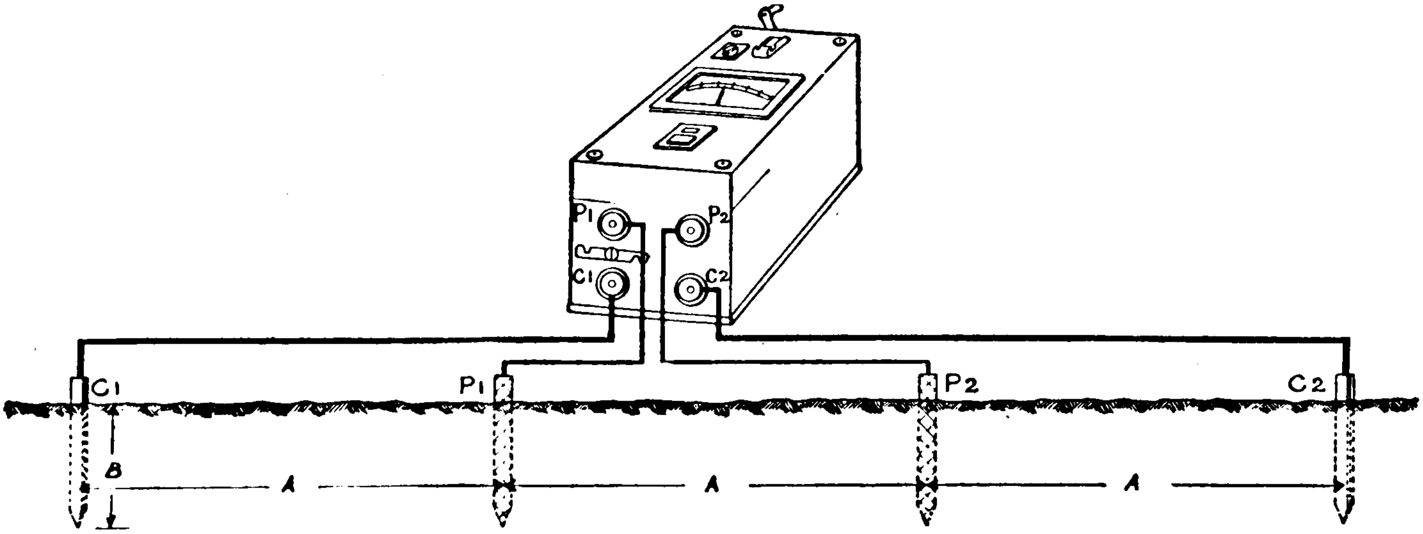
The current coil and the potential coil of the ohmmeter are mounted on a common spindle, so that their torques oppose each other. Thus they automatically perform the division of volts by amperes. According to Ohm's law, resistance equals volts divided by amperes, so the scale of the ohmmeter is calibrated to read directly in ohms.

The arrangement described is doubly advantageous. It retains the sensitiveness and accuracy of the direct current ohmmeter. By using alternating current in the ground circuits, moreover, the errors that would be introduced in a direct current circuit by polarization and electrolysis at the ground stakes, or by stray direct current, are eliminated. Thus the use of non-polarizing electrodes is avoided, and copper or iron stakes can be employed without having to introduce any device to compensate for the unwanted currents. Stray alternating currents are not bothersome, as by changing the speed with which the generator commutator shaft is turned, the Megger Ground Tester circuits may be thrown out of phase with the strays, and so are no longer affected by them.

Thus it is seen that the Megger could probably be used in well logging except that, as in the case of the commutator, it is not needed. (See page 62.)



INTERNAL CONNECTIONS OF MEGGER GROUND TESTER.



MEGGER GROUND TESTER CONNECTIONS TO FIELD STAKES.
Note, *A* must be at least 20 × *B*.

FIELD DIFFICULTIES ENCOUNTERED IN RESISTIVITY METHODS

1. The effect of earth currnets.
   Natural earth currents are always present and these will set up natural potentials between the potential electrodes. These natural potentials were found to be small in comparison with the potentials induced in the ground. The effect of earth currents can be greatly reduced by inducing large currents into the ground.

2. The effect of natural currents due to the electrolysis of local ore-bodies.
   As far as is known by the author there were no ore-bodies in the areas surveyed.

3. The effect of strays due to direct currents leaking from dynamos, street railways, and power lines.
   The holes surveyed by this author were not near any of the above sources of stray currents.

4. The effect of polarization or galvanic action when iron stakes are driven into the ground.
   As stated on page 62 , there were no polarization effects present.

5. The possible effect of inductance between the wires leading to the current and to the potential stakes.
   Since all the wires coming from the electrodes in the hole are taped together, the inductance should be at a minimum.

6. The effect of wet ground on the insulation of the long wires leading to the electrodes. This may be called wire leakage.
   The author had no trouble with this effect and it may be eliminated by the use of good insulation.

7. The effect of dampness on the instruments used, particularly on the instrument that separates the battery leads from the potential leads. This may be called instrument leakage.
   As in number 6 there was no trouble from this effect and it should be eliminated by the use of good insulation and good switches. The instruments were kept dry at all times.

8. In the field the effect of tilt of the instruments vitiating small readings.
   This effect may be neglected if one is careful to place the instruments as level as possible.

SECTION VII

1. Geo-Electric Measurements Inside of Cased Drill Holes
2. Comparison of the Resistivity Values from a Hole with the Drill Logs.

GEO-ELECTRIC MEASUREMENTS INSIDE OF CASED DRILL HOLES

Since measurements taken inside cased drill holes are rather difficult and delicate, and the equipment available was not suitable, the author did not attempt to log cased shot holes. However, the following section from a paper by S. H. Shaw* is of interest in this respect:

"Schlumberger has stated (A.I.M.E. Technical Publication 462, 1932) that electrical measurements can only be made in the uncased part of the hole since the casing acts as a screen that completely masks the properties of the surrounding rocks and that inside the casing the resistivities are equal to zero. Experimental results do not bear out this statement. In one hole in particular, measurements were made both before and after inserting the casing. The two sets of resistivity readings agreed very closely, thus showing that the casing was exerting no screening effect. On theoretical grounds also it is doubtful whether Schlumberger's contention is correct; he is careful to show (A.I.M.E. Technical Publication 503, 1933) that the conducting mud in the hole has little effect in modifying the measured resistivity; by the same argument it might be shown that the thin shell of casing need not necessarily prevent passage of current to the surrounding rock.

"Even if the casing should exercise a partial screening effect this would not prevent determination of the relative resistivities of the formations and the relative values may be as useful as absolute

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* Refer to "Geo-Electrical Measurements in Drill Holes," by S. H. Shaw, Mining Magazine, Vol. LVI, January, 1937. Pp. 17-23. Continued in Vol. LVI, April, 1937 Pp.201-208.

ones in many cases. Certain precautions should be adopted, however, if measurements are to be made inside the cased part of the hole and the readings should always be carefully watched for possible erratic results. First, the casing itself should not be used as the upper or surface electrode for passing current into the ground; a separate stake at some distance from the collar of the hole would insure a distribution of the current to the ground and minimize any short-circuiting effect the casing might have. Secondly, precautions should be taken to prevent any of the electrodes inside the hole from coming into actual contact with the casing, as such a contact would certainly prevent reliable results being obtained. An alternating current instrument such as the Megger should be used in preference to a potentiometer that is used for direct current measurements, because large and erratic polarization potentials may be caused by the casing and these might interfere with or even prevent the reading of the potentiometer. In deep or crooked drill holes the second precaution mentioned may be difficult or impossible to apply, in which case measurements may not be possible."

In conclusion it might be stated that the Lane-Wells Company of Los Angeles, California, have made many attempts to log cased drill holes and have been somewhat successful.

COMPARISON OF THE RESISTIVITY VALUES FROM A HOLE WITH THE DRILL-LOGS

Since no core samples are taken of shot holes, the author has had no opportunity to compare the resistivity values of a hole with the drill-logs. However, such a relation undoubtedly exists and the following section from an article by S. H. Shaw* is of interest in this respect:

"This comparison shows a satisfactory agreement between changes in lithology and changes in resistivity. A few instances of this are: the low resistivity at 87 feet corresponding to the 9 feet of marl between 85 feet, and 94 feet; the high resistivity at 157 feet corresponding with 2 1/2 feet of coarse cemented sandstone at 158 feet; and the generally lower values from 207 feet onwards corresponding with the finer character of the sandstones from that depth. As the electrode separation was 10 feet and slight changes of lithology occured every foot or so, an exact agreement between resistivity values and the ligholog is not to be expected and some of the peaks and troughs on the curve cannot be definitely correlated with any noticeable feature in the drill record. It will be seen that, in general, the resistivity values decrease with increasing fineness in the grade of the sandstones; this result in in accordance with theoretical expectations. As far as can be seen, however, no simple relationship exists between the resistivities and the porosities determined from the core samples."

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* Refer to "Geo-Electrical Measurements in Drill Holes," by S. H. Shaw, Mining Magazine, Vol. LVI, January, 1937. Pp. 17-23. Continued in Vol. LVI, April, 1937. Pp.201-208.

SECTION VIII

Conclusions

CONCLUSIONS

An endeavor has been made in this thesis to give the principles applied in electrical surveys of shot and drill holes and to outline the principal applications thereof. The author believes that the method tried, and those that will be suggested later in this section, have excellent possibilities as to practical application of logging shot holes.

As a result of this work the following conclusions may be made:

1. The large and erratic polarization potentials commonly experienced in surface measurements, using the standard Wenner Configuration, when metal contact is used in direct contact with the soil do not occur when the contact is with the water and mud of a shot hole and ordinary metallic electrodes may be used.

2. It follows from 1 that neither a Commutator nor a Megger Ground Tester are needed for well-logging measurements.

3. The Reciprocity Theorem does not hold very well in logging methods due to natural potentials and small polarization effects.

4. By using a series of shot holes in a line, it seems probable that one could determine accurately the thickness of the weathered layer.

5. Although no quantitative proof is available, it seems likely that one could locate the top of the water table.

6. A surface resistivity profile curve does not give the desired variation in detail that is given by resistivity logs. It would be difficult to correlate surface resistivity profile curves from one shot hole to another and the process is entirely too slow to keep up with the rapid work carried on by the present day seismograph crew.

Due to lact of time, and the inability to obtain a mast and a winch to lower the electrodes into the holes, the author was unable to complete all the research that he desired on the logging of shot holes. In the future, the author hopes to work on the following problems:

1. Run three separate logs in a deep shot holes with the three different configurations indicated on pages 17, 18 and 19. By comparing the logs thus obtained one should be able to determine the best configuration applicable to logging of shot holes.

2. Try different electrode spacings of the configurations indicated in 1.

3. Take the electrical logs of a line of shot holes and compare and correlate the resistivity logs thus obtained. It would be of interest to correlate the natural potentials obtained from these holes. One should also be able to determine the top of the water table by this correlation.

4. Determine the possibility of taking electrical logs inside cased shot holes.

5. Determine the validity of the Reciprocity Theorem when using alternating current and determine why the theorem does not hold when using direct current.

6. Determine the possibility of using the Megger Ground Tester for logging shot holes.

7. Determine the resistivity of the drilling mud in the shot holes.

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