

**INDUCED POLARIZATION MEASUREMENTS
THROUGH
FREQUENCY DEPENDENCE OF RESISTIVITY**

A THESIS

Presented to the Graduate Faculty of the

NEW MEXICO INSTITUTE OF MINING AND TECHNOLOGY

supervisor of Dr. Paul H. Hobbinger, whose advice to obtain the
fellowship was appreciated. After Dr. Hobbinger left N. M. I. M. T.,
Dr. Charles A. Fugère accepted advisory responsibility for the
remainder of the work. The invaluable cooperation, suggestions,
and guidance of Dr. Fugère throughout the course of the study
have contributed greatly to its success.

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Abstract

A new technique in prospecting for electrically polarizable material was investigated in the laboratory through application to a number of prepared samples. The measuring technique involves comparison of the percentage differences between the real and imaginary parts of the complex resistivity.

Acknowledgments

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Abbreviations

| | |
|-----------------------------------|---|
| F. G. | Model 202A Hewlett-Packard low-frequency function generator |
| G. O. L. | Function generator output level |
| W. R. | "Wing" resistor(s) whose values are 50 times or more larger than the resistance of the sample. The W. R. are in pairs connected in series with the sample outside either end of the sample. |
| IP | Induced polarization |
| IR | The voltage drop across a resistance (R) when a current (I) passes through |
| ϕ a. 01 | Polarisability (percentage); the subscript indicates the low frequency (in cps) used as equivalent to dc |
| E | The total potential measured across the potential electrodes |
| E 100cps | The total potential measured across the potential electrodes when the frequency employed is 100 cps |
| D log F | Consecutive increments in log F for successive values of frequency. The D stands for the Greek letter Δ meaning increment |
| E ¹ and E ² | First and second potential electrodes respectively |
| dc and ac | Direct and alternating current respectively |

INDUCED POLARIZATION MEASUREMENTS
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Introduction

Interest in the phenomena involved in induced polarization has been shown in the literature for a long time. The earliest accessible publications go back to the work of the Curies, Pellat, Maxwell, and Wagner (Hartshorn, 1926) in the late 19th and early 20th centuries. The field of such early investigation was the behavior and properties of dielectrics. Later, attempts were made to give mathematical formulation to the observed phenomena in terms of a series of relaxation decay expressions.

Schlumberger seems to have been the first to apply the observed gradual decay of potential to prospecting and well logging. While prospecting for sulfide ore deposits he observed anomalous effects from wet soils so great that they masked the response which he was seeking.

A number of explanations have been proposed to account for the gradual growth of potential when an electric field is introduced in a medium, as well as the gradual decay of the potential when the

field is removed. Heiland (1946) explains such behavior as due to the material transportation of ions directed by the electric field, resulting in concentration toward opposite ends of the substance. More recently, investigators explain the phenomenon as an electrode type of polarization within the volume of the substance (Brant and Gilbert, 1952), or as electro-osmosis in porous rocks (Dakhov et al., 1952). Theoretical studies and mathematical tabulations have been presented recently by Frische and von Buttlar (1957), Henkel (1958), and Siegel (1959).

Attempts to apply methods of induced polarization to mining exploration have, in some cases, been complicated greatly by the response from nonmineralized material (without sulfide). In consequence, a detailed study of the behavior of nonmineralized materials (clayey sands) was initiated (Vanquier et al., 1957), which has provided a new geophysical method of exploration for ground water.

Most of the techniques used so far by previous investigators are largely similar to each other. The substance under investigation is energized by an electric current whose direction is reversed at regular intervals of time. The periods during which the current flows in either direction are separated by time intervals during which the current is cut off and the decaying potential signal that persists across the potential electrodes is being measured. A diagram illustrating the voltage wave form is given in Appendix I (app. fig. 1).

Walt (1956) reports on the employment of a variable-frequency sinusoidal waveform of energizing current, using continuous frequency variation between 10^{-1} and 10^3 cps. His analysis of the data obtained is summarized in Appendix I.

A simpler technique than either of these, which would be both direct and diagnostic, is the combination of the ac character of the sine wave with the steady character of direct energizing current of the square wave for a number of discrete frequencies within a limited range. The immediate purpose of the present work has been to

explore the possibility of using this new technique in evaluating the polarizability of materials through frequency dependence of the resistivity, and to develop a suitable procedure for energizing the sample electrically and recording the desired data. The ultimate aim has been to determine whether, by this technique, changes in resistivity can be utilized in detecting ground-water reservoirs.

Experimental Aspects

Experiments were done in the laboratory on a number of samples that were contained in a specially designed sample holder. The polarity of the energizing current was reversed at a number of fixed frequencies with no intermediate step between the positive and negative parts of the cycle. The resistance of the portion of the sample between the potential electrodes was determined for the highest frequency employed (100 cps) through measurement of the current passing through the sample and the potential difference across the potential electrodes. For lower frequencies (down to 0.01 cps) the changes in resistance were measured in terms of changes in the potential difference while keeping the current constant. To measure these small changes, most of the signal across the potential electrodes was cancelled in the measuring instrument (oscilloscope) with a controlled signal of the same shape and frequency. The small fraction that remained was magnified, and its variation with frequency was recorded for study.

Instrumentation

Before discussing the details of instrumentation and sample preparation, it is necessary to describe the sample holder and the electrodes used in the measurements. The sample holder is a cloth-bare plastic tube 10 inches long and 2 inches in diameter, designed for use in a horizontal position. The top quarter inch of the circular section is cut away for accessibility and ease in changing the samples. The tube is plugged at both ends by filter paper and glass wool held in place by blocks of plastic. A central hole of 2-inch diameter is cut out of each end block to allow continuity on both sides.

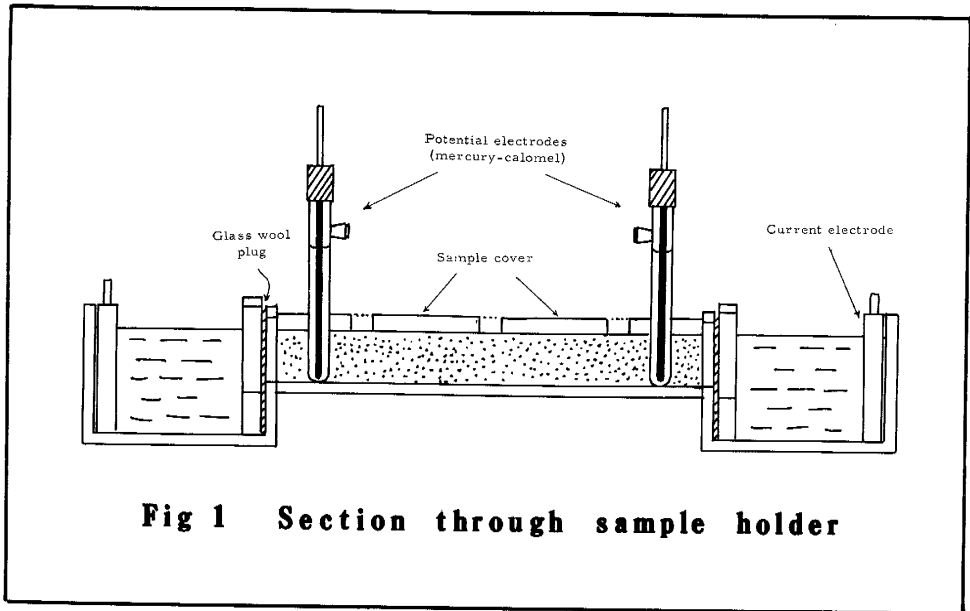


Fig 1 Section through sample holder

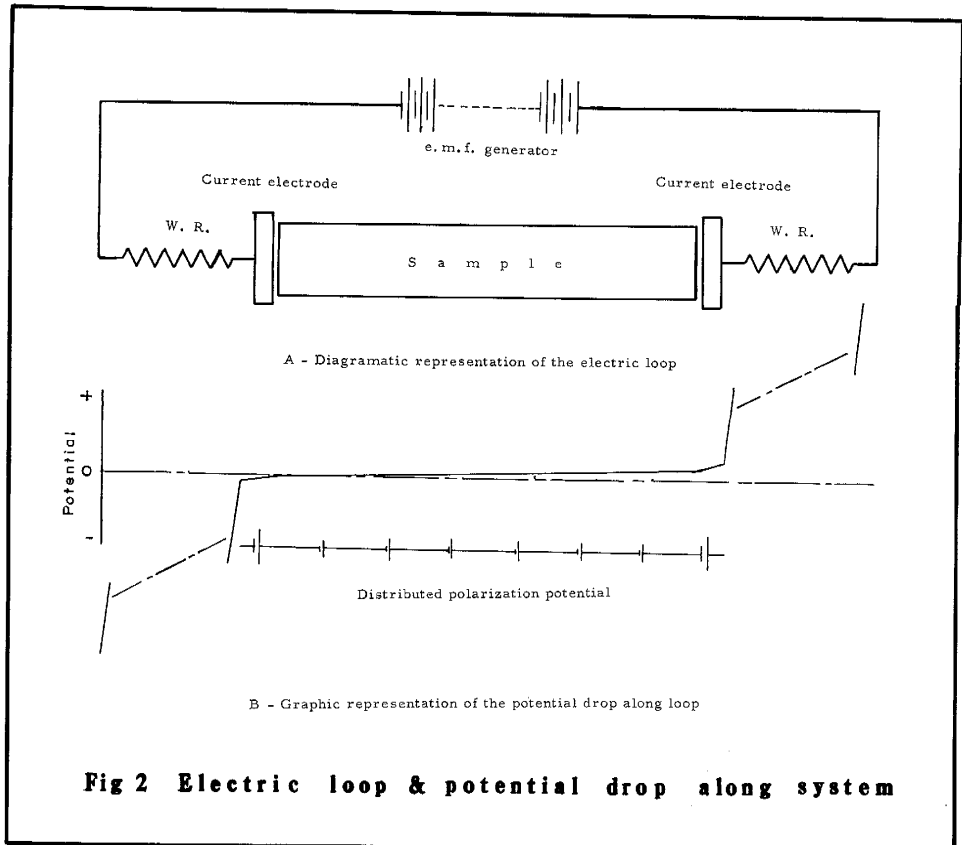


Fig 2 Electric loop & potential drop along system

A removable plastic cover (1/8 inch thick) drilled with five holes (3/64 inch diameter) fixes the potential electrodes upright and spaces them symmetrically about a central position either 6 or 8 inches apart. The fixed electrode positions assure that the same fraction of the total sample is considered every time, thus providing a constant basis for comparison. This eliminates the necessity of including a geometrical factor in the calculation, so that the value of the resistance determined can serve to represent the resistivity of the sample.

Two boxes (4 inches long, 3 inches wide, 3 inches deep) are affixed to the ends of the sample holder to hold the current electrodes at the farther ends of the boxes (see fig. 1). The current electrodes (carbon discs 3 inches diameter) have a large surface area to ensure low current density; this is necessary for minimizing electrode polarization and will be referred to again. The sample holder and current-electrode boxes were cemented together with black roofing cement to prevent water and electrical leaks and then sprayed with a fast-drying lacquer.

The choice of electrodes used for the potential measurements is of great importance. The electrodes should be reversible (i. e., nonpolarizable) and fairly stable (i. e., the drift should be less than 0.5 microvolt per second). The latter requirement, though desirable, is not essential, as the electrodes are used with an alternating signal and any slow drift will not show.

A number of "homemade" electrodes have been tried, all applying the principle of the common ion effect at the silver-silver chloride contact. For the first trial a strip of silver was electrolytically coated with silver chloride (about 4 ma/sq. in. being used for 4 or 5 hours in normal HCl solution). The silver-silver chloride strip was embedded in silver chloride paste in a porous pot. Later,

the coated strip was used alone, protected inside a glass tube with a very narrow opening left at its lower extremity, but was difficult to maintain. The most satisfactory electrode tried, a commercial standard mercury-calomel electrode, was used for making the potential measurements.

Current control unit. The power supply used for energizing the sample is a model 202A Hewlett-Packard low-frequency function generator (F.G.). This source is inherently a constant-amplitude device of 100-ohm internal resistance, which delivers square wave test voltages, 10 volts peak-to-peak, into a 5,000 ohm load. The frequencies available are in five bands from 0.01 to 1,000 cps, with a 20-percent overlap at each end of every band. The values 0.01, 0.1, 1, 10, and 100 cps were arbitrarily chosen and were selected by fixing the dial on the mark 1.0 and changing the decade multiplier switch. The power output was balanced from the two output terminals of the F.G. to its ground (middle terminal) through 470-ohm load resistances in order to minimize pickup of extraneous voltages.

Since the polarization of the sample is proportional to the value of the energizing current, the latter must be kept constant during each excitation period (any half cycle). The two main factors that tend to distort the constancy of the current are electrode and sample polarizations. The use of current electrodes of large surface area to minimize electrode polarization has been mentioned. The most effective way to maintain constant current is to restrict the voltage drop across the sample holder to a small fraction of the supply voltage; the technique employed to meet this requirement is best described by reference to Figure 2.

When a current (I) passes through the electric loop due to the source of emf (represented by the batteries), the current electrodes absorb energy from the source and become polarized (according to

3

the general principle of Le Chatelier) in such a direction as to oppose the flow of current. This behavior is analogous to what happens when a lead storage cell is charged. Employing this analogy, one can replace the two current electrodes by two small batteries in opposition to the emf in the loop. The polarization of the electrodes (i. e., the induced opposing emf) increases with time, and consequently the net emf in the loop gradually decreases. When the next half cycle starts (main emf reversed), the emf on the electrodes will be in the same direction as the impressed emf, and so the current starts with a value higher than normal, decreases to normal as time passes, and, by the end of the half cycle, falls below the normal value. Since the current decreases with time, the polarization of the sample tends to decrease in proportion; unless correction is made for this error, the polarization measured will be smaller than that for the normal value of current. The term "normal" here refers to the case where there is no polarization.

The condition that the electrode polarization be a very small percentage of the total voltage drop through the loop is met by adding in series with the sample a 'wing' resistor (W.R.) of suitable large value outside each end of the sample holder (fig. 4). From three different sets of W.R., one is selected (as required by the resistivity of the sample) to obtain the desired value of current, such that the potential drop across the sample holder was a very small fraction of the source voltage. This fraction was usually less than 2 percent. Thus the amount of distortion of the energizing voltage caused by sample polarization is also kept very small (less than 2 percent). Each W.R. set consists of a single resistor on one side and a combination of a fixed and a variable resistor on the other side of the sample holder. The values of each limb of the W.R. sets are of the order of 150K, 680K, and 2M respectively.

Potential signal and its measurement. The study of the electric loop (fig. 3) will now be extended to determine the shape of the

potential signal that is to be expected. When a current flows through the sample, the emf's of the "incubation batteries" created within the sample start to grow, as explained previously, until they reach a saturation value. The sum of such emf's is very small compared to the total emf in the system, and its sense is opposite to that of the total emf.

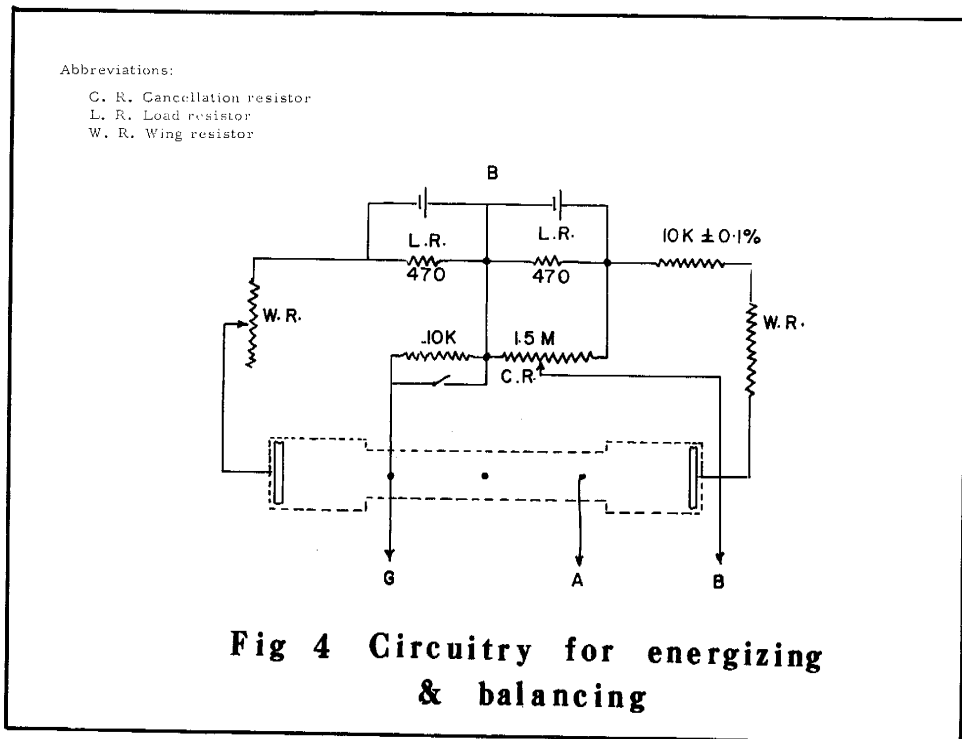
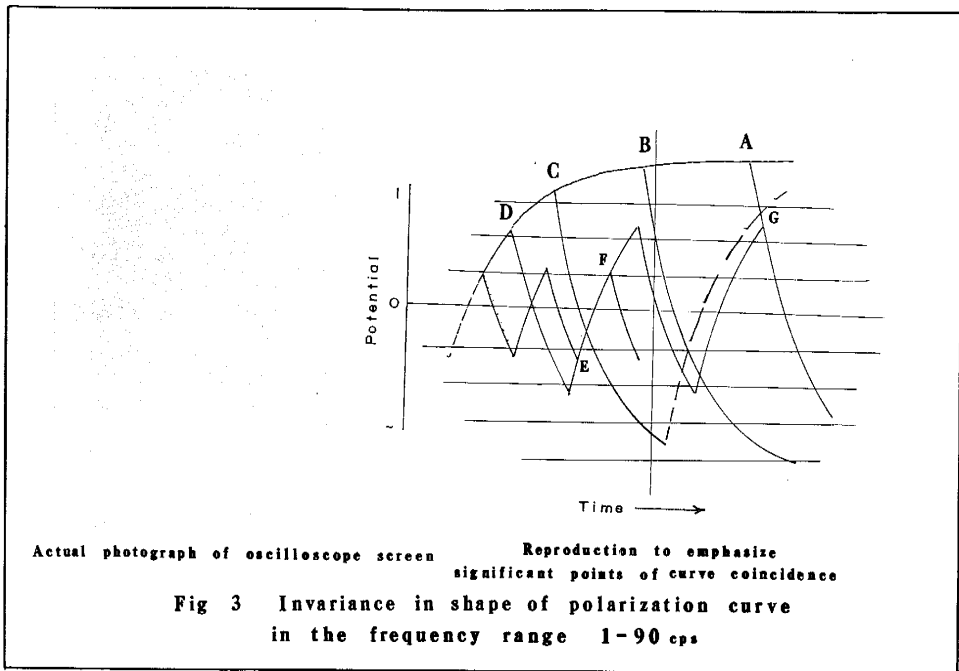
Let the IR drop across the sample be V and the induced emf (I. P.) be $+v$ (i. e., in the same direction as the IR drop). When the current is reversed, the IR drop instantaneously becomes $-V$, but the previously induced emf is still $+v$; so the potential difference now measured will be $-V+v$. In this second period, emf is induced in the reverse direction and increases with time until it cancels the emf initially induced by the positive current. It then continues to grow toward its negative saturation value as long as the current is not reversed again to the positive direction*.

The general shape of the potential signal can be divided into three portions: the IR contribution, a steeply curved part, and a gently sloping part. At the suggestion of Dr. Holmes, the character of the induced fraction of the potential signal was investigated as a function of frequency to ascertain whether the growth curve of the signal could serve as a guide to further study.

The photograph shown in Figure 3 displays an interesting effect that proved to be very useful in designing the measuring technique. The lower multiple exposure was taken for frequencies between 1 and 30 cps; the time scale was 20 ms/cm, and the sensitivity was 100 mv/cm. The upper multiple exposure was taken for the three frequencies 25, 35, and 90 cps respectively; the time scale was 5 ms/cm, and the sensitivity was 50 mv/cm.

The lower picture shows clearly that the growth of the potential signal is completely independent of the frequency of alternation.

* See Appendix III for mathematical analysis of the problem.



No matter where the charging starts, the induced signal still traces exactly the same growth curve. The superposition of sections of curves corresponding to different frequencies is an advantageous coincidence. The outermost curve (for lowest frequencies) contains, except for a slight 60-cycle ripple, all three points A, B, and C that mark different instants of reversal corresponding to different frequencies. This characteristic shows the invariance of both the curved part and the gently increasing part. The invariance of the steeply curved part is seen clearly from the coincidence of the curves for 15 cps and 30 cps at the points D and E. The upper multiple exposure emphasizes the invariance of the curve within the time range from 0.04 second to 0.01 second.

Once the fact is established that the signal will continue to trace the same growth curve until the time comes for reversal, it is not necessary to observe the growth curve for every frequency.

It is important to note that it is sufficient to record the total growth curve over an adequate period and then take the necessary readings off that single curve for all desired frequencies. In practice, however, it is impossible to have on the screen of the scope the whole of the desired curve, if a conveniently small scale is used, and at the same time to trust it for reliable accuracy along its entire path. A much simpler approach is to switch off the horizontal sweep of the oscilloscope and watch the spot as it travels vertically for each frequency used. The procedure finally followed was to record the separation between the maximum and minimum vertical positions of the vertical trace of the spot, corresponding to each frequency. The frequencies can easily be converted into time intervals to provide a basis for plotting the time-dependent polarization signal. This method measures the total potential signal, which includes both the IR drop and the induced emf of the sample.

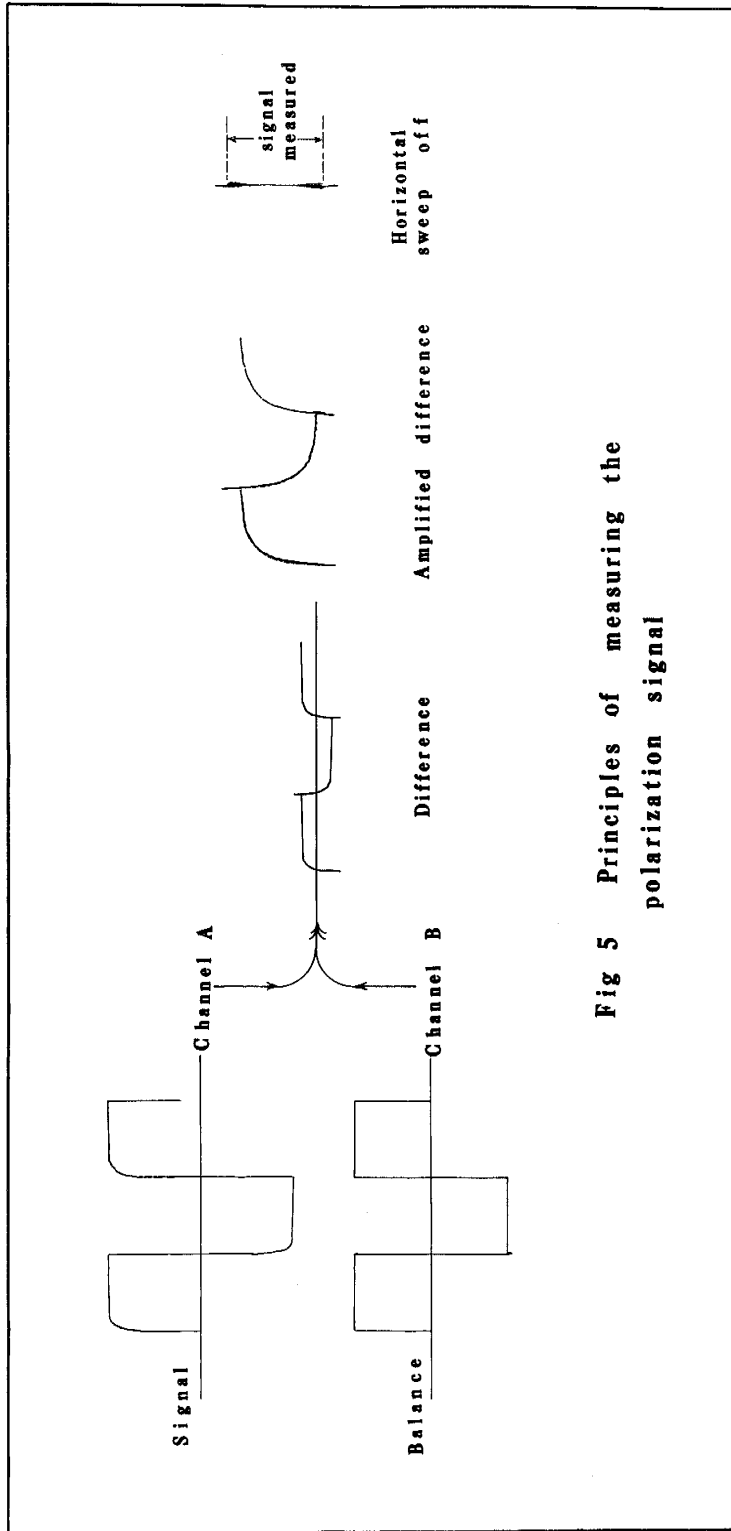


Fig 5 Principles of measuring the polarization signal

The early procedure of taking measurements of the potential signal was to use the maximum sensitivity of the oscilloscope to magnify the total signal and then displace the whole trace up or down until either end could be viewed on the screen of the oscilloscope. The L. F. variations were taken as the changes in the maximum or minimum position of the peak of the signal. The variations on both sides were then added to a low sensitivity reading of the total signal.

With that technique the actual zero of the oscilloscope was indeterminate. There was no way of making sure that the dc level of the zero signal on the instrument was the same for all frequencies. The oscilloscope amplifier responds linearly to potential signals only within a limited range. The size of the signal recorded at the most sensitive gain setting is much larger than this limited range; consequently the shape of the signal is distorted.

A more advantageous modification of the procedure provided cancellation of more than 90 percent of the potential signal, so that the remaining signal could be amplified without distortion. Such cancellation without distortion cannot be effected directly on the potential electrodes but must be done in the measuring instrument. The canceling signal, by necessity, had to be derived from the same F. C. to insure synchronization. It also had to be purely resistive.

A potentiometer of about 1 megohm range, connected between the ground and one terminal of the F. C., was used to supply the required cancellation signal (fig. 4). This signal was taken between ground and the center tap of the potentiometer. The requirement that the potential signal be handled away from the electrodes necessitates the use of a differential amplifier intermediate between the potential electrodes and the measuring instrument (oscilloscope).

The oscilloscope used is a Tektronix, model 313. It has a double-channel input and built-in differential amplifier. One channel (A) receives the potential signal from the sample, and the other channel (B) receives the canceling signal directly from the F. C.

The oscilloscope has a switch for selecting channel A, channel B, or the difference between the two. With the selector switch on the "DIFF" position, the cancelling signal is increased until the difference between the two signals observed on the screen is almost nullified, and the sensitivity can be increased to the maximum (1 rev/cm). When such differences are recorded for all frequencies, the oscilloscope is switched to channel B at a lower sensitivity setting. The sum of the two readings (B and DIFF) gives the total value of the potential signal. Such a procedure allows the use of much greater sensitivity in measuring the most important part of the signal, the I.P. fraction. The limit to the accuracy imposed by the 60-cps pickup is about 300 microvolts. The minimum difference that can be read with the oscilloscope is one-third of a mm, corresponding to 0.5 percent in case the signal to be measured occupies the full screen (7 cm).

The total signal measured in any half cycle is a combination of a large IR drop and a relatively small, changing induced-polarization potential. Two points should be emphasized in this connection. The cancelling signal is not necessarily the same as the IR drop in magnitude. In fact, the magnitude of the former is a matter of personal judgment. Likewise, the remainder recorded through the differential amplifier cannot be considered representative of the induced-polarization signal. All that can be said about the difference between the reading at 100 cps and that at 0.01 cps is that it is the maximum I.P. signal detectable within the limited range of frequencies employed.

There are a number of advantages in using the cancelling signal. One can always observe the entire induced component of the signal unaffected by possible drift of the zero position of the oscilloscope, which would be caused by feeding the total signal amplified into the amplifier. In addition, the setting for the cancelling signal does not require much adjustment with change in

emerging current since both are derived from the same source. Thirdly, the important part of the signal, the I. F. variation, can be measured with much greater sensitivity.

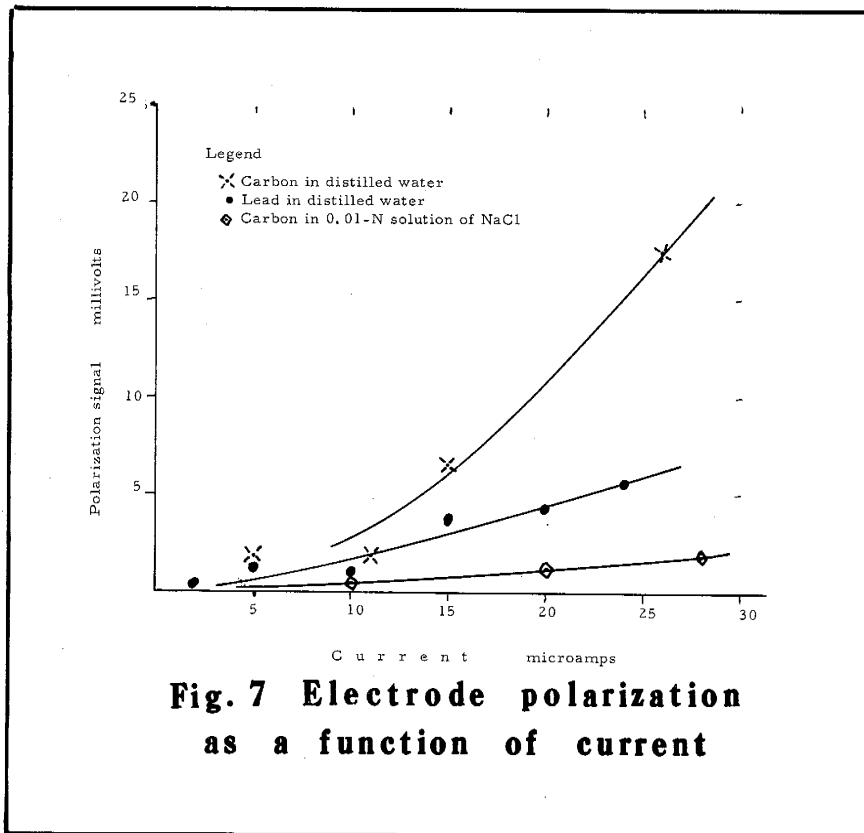
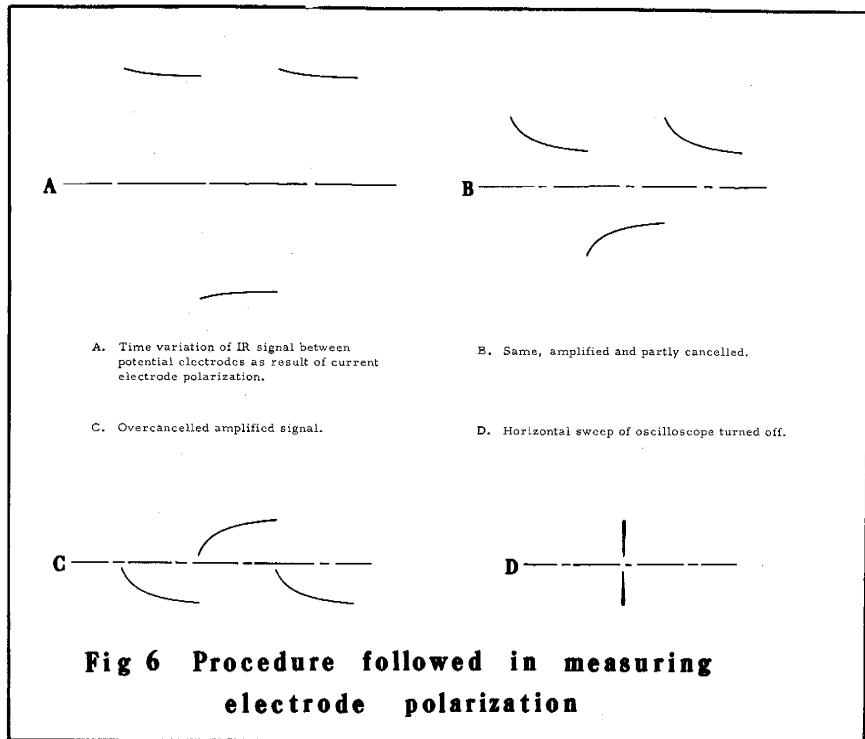
The polarizability of the current electrode tends to set a limit to the accuracy of the potential signals recorded. According to the considerations discussed in connection with Figure 3, the polarization of these electrodes would oppose the impedance drop from the P. G. and give it a time-dependent character, as shown in Figure 5d. This would be the characteristic slope of the IR drop recorded at the potential electrode that results from the polarization of the current electrode.

The time dependence of the sample polarization and of the current-electrode polarization are in opposition. The signal detected at the potential electrode is actually the algebraic sum of the two effects. The resultant signals, from which the polarizabilities are calculated*, would therefore be lower by an amount dependent on the current-electrode polarization. The amount by which the signal is decreased depends also on the value of the wing resistor (W.R.) used and is inversely proportional to this value**.

A number of experiments were carried out to investigate current-electrode polarization as a function of time, intensity of current, and salinity of the water. Since lead electrodes of an replaced the original carbon disc electrodes, both types had to be investigated in the calibration study. The sample used for such a study was pure silica sand (St. Peter sand, 20-30 mesh) and was assumed to be practically nonpolarizable. Three different salinities were used: distilled water, tap water, and a 0.01-N solution of sodium chloride. The times of excitation were selected from the full range between 2 milliseconds and 100 sec. The specific values were chosen by means of the decade

*See section on Calculations.

**The W.R. constitutes about 70 percent of the load across the emf created by polarization of the current electrode.



multiplier switch of the P.D. Three fixed points on the dial, namely 1, 2, and 3, were combined with every position of the decade switch. The differential cancellation procedure previously described* was applied in this series of measurements (see fig. 6). It was found more convenient to use a cancelling signal that is larger than the observed signal. Thus we get an "overcancelled" potential signal. The convenience of this overcanceling lies in the fact that the final position of the spot on the screen of the oscilloscope is very sharply defined, whereas the starting position is indeterminate, owing to the steepness of the trace.

Figure 7 summarizes the data for current densities ranging from 2 to 25 microamp. The values plotted are those observed at the end of 100 seconds, 250 K being used as the W.R. This value of W.R. sets an upper limit to the corrections that are to be added to the potential signals.

These experiments show that the lead electrodes exhibit a very small amount of polarization when used with distilled water. The polarization is negligible with tap water. With a 0.01-N solution of NaCl, the polarization is still smaller and undetectable at low current densities. The lead electrode seems to behave somewhat reversibly in salt solution. The carbon electrode shows consistently higher polarization. Apparently the hydrogen ions that are neutralized on its surface accumulate and form a hydrogen electrode. For current densities of less than 15 microamp, the polarization with 250-K W.R. is less than 5 mV; with higher W.R., the polarization is correspondingly smaller.

Sample preparation

The main purpose of this research is to study the electrical response of certain soil samples when an alternating current of square form is impressed on them, and to relate such response to

*See page 13.

problems of geophysical interpretation. With this in mind, some samples were studied without change of their natural composition, and others were studied for the effects of the individual components. In addition, many samples were prepared in the laboratory by synthesis of purified sand, as the matrix, and a desired "impurity," such as pyrite and magnetite. These synthetic samples served to determine the background noise level that was expected to complicate the observation of the normal signal from water saturated sands.

The first natural material studied was dune sand, collected from the dunes north of Sorocco, which contained an appreciable amount of magnetite. Experiments were performed on the original material, with the use of different current densities, as well as on the portion that remained after removal of some of the magnetic components.

The second type of material was arroyo sand, which exhibited a wide range of grain sizes from fine gravel to very fine sand (finer than 100 mesh). The sizes studied were between 10 and 50 mesh, since these are the sizes ordinarily present in a beach region. The arroyo sand was sampled twice. The first time, it was separated into two sizes, 20-30 mesh, and 30-50 mesh. These two size ranges were used to indicate qualitatively the effect of grain size on the I. P. characteristics of the material. The second time, the sampling was made following a short rainy period, and the sample was differentiated into 10-25 and 25-50 mesh. It was expected that the large grains would get a natural coating of clay material after contact with muddy water and subsequent drying. Only distilled water was used with this material.

The third type of material was sand used for preparing concrete mix for building, which had been on the N. S. I. M. E. campus for almost 2 years. This was indurated quartz sand, consisting mainly of quartz and feldspar, with minor amounts of mica,

black biotite, amphibole, and garnet. It showed an appreciable percentage of magnetite.

The builders' sand was purified by magnetic separation. The magnetite was removed first, by using a strong magnetron magnet several times until practically all the magnetite was removed. The rest of the strongly magnetic material was removed by passing the sand several times over a belt magnetic separator. The final purification was done by induction magnetic separator, with utilization of the strongest field. This presumably removed the weakly magnetic fraction as well. The effectiveness of magnetic purification of the sand was checked with the microscope. The purified sand was used as matrix for subsequent studies. Both the original and the non-magnetic fraction of the builders' sand were studied. For the purpose of comparison, experiments were also performed on a mixture of the magnetically purified builders' sand and pure magnetite (5 percent mixture).

A number of experiments were performed on mixtures of the nonmagnetic fraction of builders' sand and different sizes of pyrite. Three different proportions were used; namely, 10, 20, and 40 grams of pyrite in 400 grams of sand each. Another variable was the water salinity. The different salinities used were a 0.01-M solution of NaCl, tap water, and distilled water, with conductivities in the approximate proportion of 100:3:1 respectively.

Procedure and experimental results

Measurements. The measurement procedure employed in this study requires that the total potential developed across the sample holder be small compared with the voltage supplied by the P.C. As a direct result, the very small signal available for measurement must be free of extraneous electrical noise. Sixty-decibel pickup noise can be minimized most simply by placing the

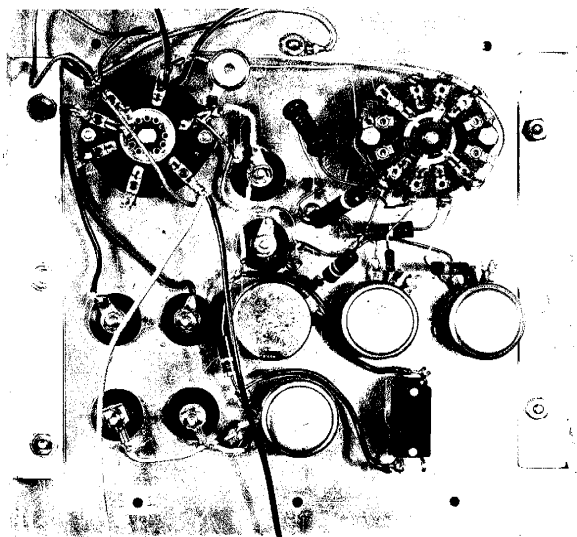
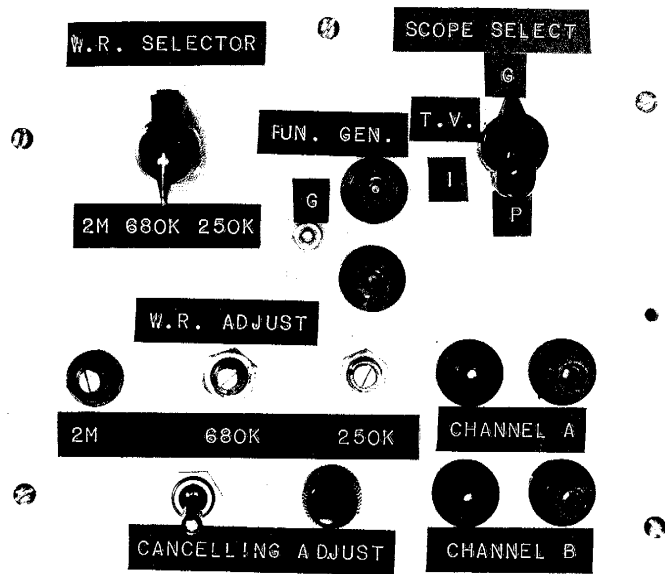


Fig. 8 Control panel - Face & Back

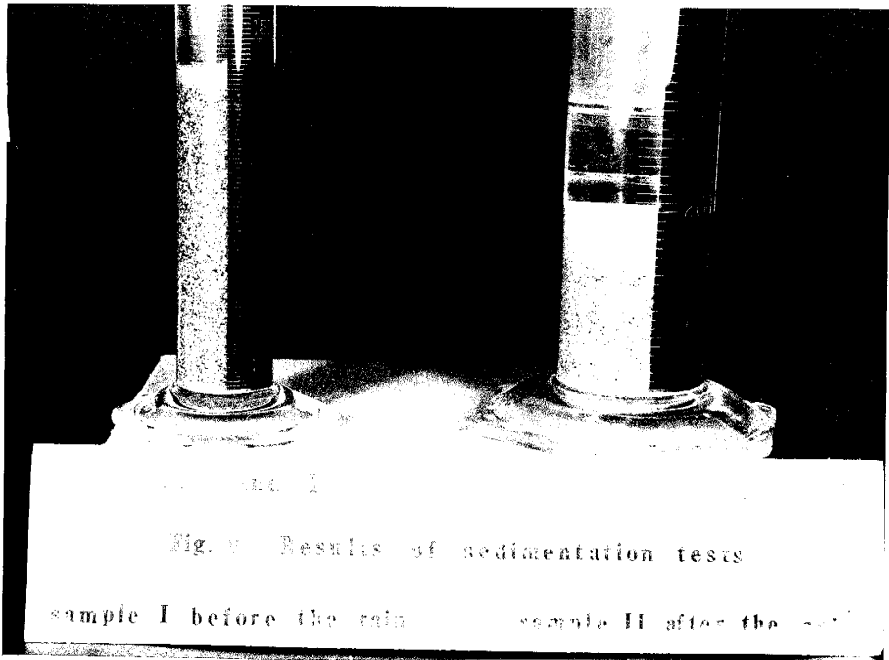
oscilloscope ground (on one potential electrode) at the same potential as the F.G. ground.

The condition given above is satisfied by the circuit shown in Figure 4. The adjustment of the resistors used to balance the circuit and oscilloscope ground is made with a control panel on one end of the metal box that contained the sample holder. On that panel are fixed all the terminal leads in and out. Shielded wire connects these leads to the F.G. and the oscilloscope. On the panel also are the W.R., and the necessary selector rotary switches (fig. 4). One rotary switch is used for selecting the suitable W.R. set, the other (scopeselect) connects the oscilloscope to different points of the circuit. The oscilloscope, being the only measuring instrument used, needs a selector switch to connect it for measurement of current and potential signal, as well as for grounding adjustment.

The ground level of one of the electrodes (fig. 4) is adjusted with the scope ground connected between this electrode and the common ground. If the potential of this electrode is different from zero, the current through the resistor will produce a square wave on the oscilloscope. The potential of the electrode is nullified to less than 30 microvolts by varying the W.R. potentiometer, ensuring that the current through the grounded electrode is less than 1×10^{-9} amp. This adjustment must be checked whenever the F.G. output level (G. O. L.) is changed. Once the adjustment is complete, the electrode is shorted to the F.G. ground.

For current measurement, a precision 10-K resistor (accuracy 0.1 percent) is included in series between the W.R. and the F.G. terminal. The potential difference across the resistance as measured by the oscilloscope in units of 10 mv represents the current passing through the sample in microamperes.

Calculations. From the data recorded, one can calculate the resistance of the material included between the potential elec-



sample I

Fig. 7 Results of sedimentation tests

sample I before the rain

sample II after the rain

Presentation of Data

The results of measuring the changes in the resistance of the various samples in response to the different frequencies are briefly summarized in Tables I-IV at the end of this section. The information given consists of the current intensity in microamperes, the resistance of the sample in kilo-ohms, and the polarizability ϕ both as a fraction and as a percentage. The fractional form of ϕ shows the actual values of potential measured. Generally the values given are $\phi_{0.1}$, corresponding to the differences between potential signals for the 100 cps and 0.1 cps. In some cases, the values for $\phi_{0.01}$ are also included.

The first sample of arroyo sand (photographed in the narrow cylinder (fig. 9) gave a high value of polarizability (table I-A, column 5). A larger effect (close to 10 percent) was observed when the second sample (photographed in the wide cylinder) was studied (table I-B). The latter was left to dry overnight and was set up again in the morning and retasted (section 3, table I-B). The polarizability was only slightly decreased. It was expected that since the wetting and mixing removed some of the clay coating of the large grains, a decrease in the polarizability would result. Most of the coating, however, was still there and was not much affected by the treatment that it received. The same sample was then subjected several times to the action of 0.01-N HCl, Calgon (a commercial detergent), and heat, then washed freely in running water, and finally washed in the sample holder with distilled water. The subsequent measurements (section 4, table I-B) showed a definite decrease in polarizability to less than half the original value, whereas the resistivity was increased almost threefold, as expected.

A number of tests were carried out on the builders' sand (table II) to discover the possible cause of polarizability and to check the effect of sample resistivity on the polarizability of the material. The changes observed could probably be tolerated within the limit of experimental error.

The results obtained with clay contamination were weighed against the results obtained in the case of contamination with metallic minerals. Pyrite and magnetite were the minerals chosen for that purpose. The study served to evaluate the effect of grain size of the mineral* and the percentage of mineralization, as well as the effect of the nature of mineral present. Distilled water was used in all these experiments to increase the polarizability of the sample.

The information shown in Table III presents the effect of adding pyrite particles to the previously prepared matrix. Within the limits of the percentages used, the polarizability apparently decreases with increasing pyrite content. The resistivity of the sample decreases as well. Pyrite grains almost five times as large give higher polarizability to the sample, as indicated in Table III-B.

Table IV shows the response of 5-percent magnetite contamination. Magnetite shows a relatively higher polarizability than the pyrite. By comparing both materials on the basis of the same mineral grain size and percentage by weight we get a more satisfactory confirmation that more polarizability would be expected from magnetite than from pyrite.

Tables A-F in Appendix IV present in more detail a number of examples that have been selected from the original tables. The tables in the appendix include the potential signals obtained for the various frequencies, as well as the step changes in the logarithm to base ten of these signals. The differences between consecutive

*This is a measure of the degree of dissemination or scatter.

values of $\log P$ are given under the heading $D \log P$. A graphical representation of the potential signals contained in these tables of selected data is given as a plot of $\log P/P_{100 \text{ cps}}$ against the logarithm of time of excitation, $\log T$ (fig. 11).

TABLES I - IV*

Summary of Results of Measuring the Frequency Dependence of
the Electrical Resistance of the Various Samples

*For a description of the contents of these tables, see p. 18.

Table I-A: Arroyo Sand I

20-30 mesh in distilled water

| W. R. | 250 K | 250 K | 680 K | 2 M | 2 M |
|--------------|--------------------------------------|--|--|---------------------------------------|---------------------------------------|
| I μ a | 18.1 | 17.7 | 6.7 | 3.9 | 2.4 |
| Φ { | $\frac{9.5}{204}$ $\frac{11.3}{204}$ | $\frac{8.0}{191.8}$ $\frac{10.0}{191.8}$ | $\frac{3.85}{74.4}$ $\frac{4.4}{74.4}$ | $\frac{2.2}{40.5}$ $\frac{3.1}{40.5}$ | $\frac{1.4}{25.1}$ $\frac{1.9}{25.1}$ |
| | 3.96 5.45 | 4.2 5.2 | 5.2 5.9 | 5.4 7.25 | 5.5 7.5 |
| R K Ω | 11.3 | 10.8 | 11.1 | 10.4 | 11.3 |

Table I-B: Arroyo Sand II

10-35 Mesh, in distilled water

| | 1. Moistened by capillary action | | | | | | 2. Saturated | | | | | |
|--------------|---|---------------------------------------|---------------------------------------|--|--|---------------------------------------|--------------|--|-------|--|------|--|
| W. R. | 250 K | | 680 K | | 2 M | | 250 K | | 680 K | | 2 M | |
| I μ a | 28.1 | | 6.9 | | 2.4 | | 29.5 | | 11.8 | | 3.85 | |
| Φ { | $\frac{15.0}{150.5}$ $\frac{21.0}{150.5}$ | $\frac{3.6}{33.7}$ $\frac{5.0}{33.7}$ | $\frac{1.2}{11.5}$ $\frac{1.8}{11.5}$ | $\frac{15.9}{150.6}$ $\frac{23.65}{150.6}$ | $\frac{6.6}{56.3}$ $\frac{10.6}{56.3}$ | $\frac{2.0}{19.1}$ $\frac{2.8}{19.1}$ | | | | | | |
| | 9.95 13.95 | 10.4 14.8 | 10.4 15.6 | 10.6 15.8 | 11.7 18.8 | 10.5 14.7 | | | | | | |
| R K Ω | 5.4 | | 4.9 | | 4.8 | | 5.1 | | 4.7 | | 4.96 | |

| | 3. Dried and reused | | | | | | 4. Washed thoroughly | | | | | |
|--------------|---|---------------------------------|--|---|---------------------------------------|--|----------------------|--|------|--|--|--|
| W. R. | 250 K | | 680 K | | 680 K | | 680 K | | 2 M | | | |
| I μ a | 30 | | 12 | | 11.6 | | 7.2 | | 3.9 | | | |
| Φ { | $\frac{29.5}{206.5}$ $\frac{32.5}{206.5}$ | $\frac{11}{82}$ $\frac{14}{82}$ | $\frac{8.25}{189}$ $\frac{13.75}{189}$ | $\frac{4.5}{105.7}$ $\frac{7.4}{105.7}$ | $\frac{2.6}{57.9}$ $\frac{5.7}{57.9}$ | | | | | | | |
| | 14.3 15.7 | 13.4 17.1 | 4.35 7.3 | 4.75 7.0 | 4.5 9.85 | | | | | | | |
| R K Ω | 6.9 | | 6.8 | | 16.3 | | 14.7 | | 14.8 | | | |

5. 35 - to 65 - Mesh, in distilled water

| W. R. | 250 K | 250 K | 680 K | 680 K | 2 M |
|--------------|-------------------------------------|---|---------------------------------------|---------------------------------------|---------------------------------------|
| I μ a | 29.5 | 18.5 | 11.8 | 7.3 | 3.8 |
| Φ { | $\frac{17}{12.2}$ $\frac{19}{12.2}$ | $\frac{11.6}{71.0}$ $\frac{12.2}{71.0}$ | $\frac{7.6}{47.6}$ $\frac{8.4}{47.6}$ | $\frac{4.4}{28.3}$ $\frac{5.1}{28.3}$ | $\frac{2.5}{15.3}$ $\frac{3.0}{15.3}$ |
| | 13.9 15.6 | 16.3 17.2 | 15.9 17.6 | 15.6 18. | 16.3 19.6 |
| R K Ω | 4.1 | 4.5 | 4.1 | 3.9 | 4.0 |

Table II: Builders' Sand

| | | 1a. Original material, in tap water | | | | | 1b. Same, in fresh tap water | | |
|--------------|---|-------------------------------------|-------------------|---------------------|------------------|---------------------|------------------------------|-------------------|------------------|
| W. R. | | 250 K | | | | | 250K | | |
| I μ a | | 33.5 | 26 | 17 | 6.5 | 3.1 | 30.5 | 15 | 6.3 |
| Φ | } | $\frac{7.5}{340}$ | $\frac{6}{254.5}$ | $\frac{3.8}{158.8}$ | $\frac{1.4}{62}$ | $\frac{0.75}{31.5}$ | $\frac{7.9}{288.1}$ | $\frac{3.5}{141}$ | $\frac{1.4}{56}$ |
| | | 2.2 | 2.36 | 2.4 | 2.26 | 2.38 | 2.7 | 2.48 | 2.5 |
| R K Ω | | 10.2 | 9.8 | 9.4 | 9.5 | 10.2 | 9.4 | 9.4 | 9.7 |

2. Magnetic fraction, in distilled water

3. Nonmagnetic fraction, in distilled water

| | | 15 hours later | | | 680 K | | | 250 K | | |
|--------------|---|--------------------|-------------------|----------------------|----------------------|---------------------|--------------------|---------------------|---------------------|-------------------|
| W. R. | | 2.7 M | 680 K | 2 M | | | | | | |
| I μ a | | 2.9 | 10 | 3.3 | 11.35 | 6.7 | 1.18 | 28.75 | 17.5 | 4.2 |
| Φ | } | $\frac{0.9}{21.5}$ | $\frac{1.85}{63}$ | $\frac{0.65}{21.65}$ | $\frac{5.25}{216.1}$ | $\frac{3.1}{132.4}$ | $\frac{0.5}{21.7}$ | $\frac{9.7}{524.3}$ | $\frac{6.2}{320.3}$ | $\frac{0.92}{52}$ |
| | | 4.2 | 2.94 | 3.0 | 2.42 | 2.34 | 2.31 | 1.85 | 1.93 | 1.77 |
| R K Ω | | 7.4 | 6.3 | 6.5 | 19 | 19.7 | 18.4 | 18.2 | 18.3 | 12.6 |

4. Nonmagnetic fraction, tap water

5. Nonmagnetic fraction, in 0.01-N solution

| | | 680 K | | | 250 K | | | 680 K | | 250 K | |
|--------------|---|---------------------|---------------------|--------------------|---------------------|---------------------|--------------------|------------------|--------------------|---------------------|--------------------|
| I μ a | | 11.8 | 6.6 | 1.8 | 30.5 | 12.3 | 4.8 | 12 | 5.2 | 30.5 | 14 |
| Φ | } | $\frac{1.8}{126.8}$ | $\frac{0.65}{48.8}$ | $\frac{0.3}{19.5}$ | $\frac{2.9}{331.9}$ | $\frac{1.3}{130.7}$ | $\frac{0.5}{50.9}$ | $\frac{0.8}{64}$ | $\frac{0.3}{29.2}$ | $\frac{1.8}{175.9}$ | $\frac{0.8}{75.6}$ |
| | | 1.42 | 1.33 | 1.5 | 0.87 | 0.99 | 0.98 | 1.25 | 1.03 | 1.05 | 1.06 |
| R K Ω | | 10.7 | 7.3 | 10.5 | 10.8 | 10.6 | 10.6 | 5.3 | 5.6 | 5.8 | 5.4 |

Table III-A: Sand-Pyrite Mixture

Pyrite finer than 100 mesh

| | | 1a. 2.5% pyrite, in tap water | | | 1b. 9 hours later | | | 2a. 2.5% pyrite, in distilled water | | | 2b. 11 hrs. later | | |
|-------------|---|----------------------------------|--------------------|----------------------|---------------------|--------------------|--------------------|--|---------------------|-----|-------------------|-------|--|
| W. R. | | 2 M | 680 K | 2 M | 680 K | 680 K | 2 M | 2 M | 680 K | 2 M | 2 M | 680 K | |
| $I_{\mu a}$ | | 3.9 | 12 | 4 | 12 | 5.7 | 3.6 | 2.25 | 6.7 | | | | |
| Φ | } | $\frac{0.32}{28.6}$ | $\frac{1.0}{89.1}$ | $\frac{0.25}{28.65}$ | $\frac{0.65}{84.7}$ | $\frac{0.3}{39.6}$ | $\frac{0.5}{40.9}$ | $\frac{0.3}{24.8}$ | $\frac{0.45}{62.0}$ | | | | |
| | | 1.12 | 1.2 | 0.87 | 0.77 | 0.76 | 1.22 | 1.21 | 0.73 | | | | |
| R $K\Omega$ | | 7.4 | 7.5 | 7.2 | 7.1 | 7.0 | 11.5 | 11.2 | 9.3 | | | | |

| | | 3. 5% pyrite, in distilled water | | | | 4. 10% pyrite, in distilled water | | |
|-------------|---|----------------------------------|--------------------|---------------------|----------------------|-----------------------------------|----------------------|--------------------|
| W. R. | | 680 K | 2 M | 2 M | 2 M | 250 | 680 | 2 M |
| $I_{\mu a}$ | | 9.6 | 3.6 | 2.3 | 2.5 | 18.5 | 7.6 | 2.5 |
| Φ | } | $\frac{0.3}{86}$ | $\frac{0.3}{32.7}$ | $\frac{0.2}{20.36}$ | $\frac{0.25}{19.55}$ | $\frac{0.3}{79.2}$ | $\frac{0.25}{31.25}$ | $\frac{0.1}{10.7}$ |
| | | 0.35 | 0.91 | 0.98 | 1.27 | 0.38 | 0.8 | 0.93 |
| R $K\Omega$ | | 8.9 | 9.2 | 8.9 | 7.9 | 4.3 | 4.1 | 4.3 |

Table III-B: Sand-Pyrite Mixture

20- to 30- mesh pyrite in distilled water

| | | 1. 2.5%-pyrite | | | | 2. 5%-pyrite | | 3. 10%-pyrite | |
|-------------|---|---------------------|---------------------|---------------------|---------------------|---------------------|----------------------|---------------------|---------------------|
| W. R. | | 680 K | | 2 M | | 680 K | 2 M | 680 K | 2 M |
| $I_{\mu a}$ | | 12 | 5.3 | 3.9 | 0.4 | 10.8 | 3.3 | 11.6 | 3.9 |
| Φ | } | $\frac{3.0}{137.2}$ | $\frac{1.35}{60.8}$ | $\frac{0.9}{43.65}$ | $\frac{0.46}{20.0}$ | $\frac{1.9}{108.7}$ | $\frac{0.65}{32.75}$ | $\frac{2.2}{107.2}$ | $\frac{0.63}{33.9}$ |
| | | 2.18 | 2.22 | 2.08 | 2.3 | 1.75 | 2.0 | 2.05 | 1.86 |
| R $K\Omega$ | | 11.7 | 11.7 | 11.4 | 11.2 | 10.3 | 10.1 | 9.4 | 8.8 |

Table IV: Sand (95%)--Magnetite (5%) Mixture

20- to 30- mesh magnetite in distilled water

5 days later

| | | 680 K | | 2 M | | 680 K | | 680 K | | 680 K | | 2 M | | 2 M | |
|-------------|---|-------------------|-------------------|--------------------|---------------------|---------------------|----------------------|---------------------|----------------------|--------------------|---------------------|--------------------|---------------------|--------------------|---------------------|
| $I_{\mu a}$ | | 7.4 | | 2.45 | | 11.4 | | 11.6 | | 7.2 | | 3.9 | | 2.4 | |
| Φ | } | $\frac{3.4}{141}$ | $\frac{4.3}{141}$ | $\frac{1.2}{48.1}$ | $\frac{1.42}{48.1}$ | $\frac{5.8}{226.2}$ | $\frac{13.1}{226.2}$ | $\frac{2.4}{152.8}$ | $\frac{3.15}{152.8}$ | $\frac{1.5}{94.7}$ | $\frac{1.95}{94.7}$ | $\frac{0.7}{50.6}$ | $\frac{0.95}{50.6}$ | $\frac{0.4}{30.2}$ | $\frac{0.65}{30.2}$ |
| | | 2.4 | 3.05 | 2.5 | 2.96 | 2.56 | 5.8 | 1.57 | 2.07 | 1.58 | 2.06 | 1.38 | 1.88 | 1.32 | 2.16 |
| R $K\Omega$ | | 19 | | 20.2 | | 21 | | 13 | | 13 | | 13 | | 12.6 | |

Analysis and Discussion

The purpose of this study, an investigation of the frequency dependence of the resistivity of earth materials for a spectrum of discrete frequencies, includes specifically the determination of the feasibility of application to the problem of detecting ground water. As a result, the frequency dependence of the resistivity of various samples was studied in the laboratory in terms of the response in the potential signal to different frequencies ranging from 0.01 cps to 100 cps, but is reported in Tables I to IV in the section on presentation of data as a ratio of the difference between the ac and dc readings to the ac reading. This ratio provides a direct indication of the magnitude of polarisability of the sample under study, which can be interpreted in terms of likelihood of water detection in field measurements. It hopes that additional information could be gained from a study of the response of polarization to variation of frequency in the spectrum, the logarithm of a normalized value ($P/P_{100 \text{ cps}}$) of the potential signal is plotted against the logarithm of time as illustrated by Figure 11. The potential signal was normalized in this fashion in order to remove the IM contribution.

This presentation serves to demonstrate the polarization saturation with time as well as its functional dependence. Thus from a study of curve shape it was hoped that some method of discrimination between different types of earth materials could be found out for field application.

The analysis of the data taken on the samples and presented in Figure 11 and the tables will be made in view of these considerations and will then be related to the ground water problem.

The first samples to be considered are those of the arroyo sand. It is interesting to note that after thorough washing in the laboratory, the polarizability of the sample of arroyo sand, taken after the rain, was reduced to almost the same value as that of the sample taken prior to the rain. The possible cause of such behavior was investigated. X-ray diffraction analysis of the clay-size fraction (less than 2 microns) showed that both samples contained montmorillonite and illite. No difference was detectable in the mineralogy of the clay or its relative abundance. So the type and amount of clay could not be taken as criteria to explain the large difference in polarizability observed between the first and second arroyo sand samples. This was followed by a size analysis, by sedimentation, of the highly polarizable sample and the one studied earlier. The results of sedimentation tests are shown in the photograph (fig. 9).

As shown in Figure 9, the early sample (in the narrow cylinder) is well sorted with a sharply defined zone of transition between two grain sizes. The finer fraction was 5 percent of the total volume of the sample. On the other hand, the second sample (in the wide cylinder) can be differentiated into three size ranges. In this case, the gradation from one size range to the other is not so sharply defined. Moreover, the finer grain size fraction constitutes almost 40 percent of the total. These two observations suggest that the clay coating was effectively washed from the early sample in situ by natural processes before being brought into the laboratory.

According to studies by Vacquier et al. (1957) on the effect of percolating the sample with two different solutions in alternation, it might be expected that washing the arroyo sand with dilute HCl might have had some effect on the polarizability of the sample, and could have partly changed the clay coating of the sand grains into an acid clay. The HCl solution, however, was very dilute (0.01-N),

the decrease in resistivity. The first is the addition of a solid component of very low resistivity. The second, possibly, is the contamination of the water by ions dissolved from the mineral. The polarizability depends on the potential difference between the extremities of any one particle. For larger sizes, the potential is larger for the same current density. If the mineral is very conductive, most of the potential difference impressed across the solid-liquid interface causes a current to flow through the grain boundary unimpeded by resistive drop in the particle itself. This current, which passes through, causes polarization.

Experiments by Collett (Wait, 1959) to determine the effect of varying the size and percentage of pyrite on the decay curves gave the following results: (1) Increase of the volume percentage of pyrite increases the response. (2) The decay rate is greater for the smaller particles. (3) For a fixed decay time, the response is maximized for a certain particle size. The results of the present work seem to be in good agreement with Collett's observations (cf. Wait, 1959, p. 69; curves for percentages 1.92%, 4.5% and 8.3%).

A characteristic difference was observed in the response of pyrite (conductive mineral) and magnetite (resistive mineral) at very low frequencies; i. e., for long times of excitation (10 and 100 sec). In spite of the fact that polarization starts with almost the same rate of growth for both minerals (somewhat faster for pyrite), the polarization signal for magnetite is increasingly greater for longer periods.

This behavior stimulated a study of the variations in the logarithm of the potential signal. The logarithm of the total potential signal ($\log P$), was chosen as a basis for normalization. The $\log P$'s for such a study are tabulated as $D \log P$ in Tables A to F, Appendix IV for fixed increments of time. None of the $D \log P$ columns shows constant increments. Such a fact revealed by the behavior of

all samples seems sufficient to prove that the polarization curve does not follow an exponential dependence on time. The dependence of the polarization on time has been expressed as a sum of exponential functions (refer to page 49, app. I).

These data are also represented graphically in Figure 11. This method of representation was chosen because the slope of the plot of the logarithm of the potential signal as a function of the logarithm of the excitation time ($\log T$) provides an indication of the polarizability of the sample and a means of distinguishing the type of polarizable material.

The curvature of the plot of $\log P$ is useful as another criterion for deciding whether the polarizability that is being detected is due to mineralization or to wet clayey material. With very few exceptions the plots in Figure 11 show a negative curvature for all the samples mineralized with pyrite, whereas for clays the plots show a positive curvature. Differentiation between effects due to clays and those due to pyrite could be based on comparison of the change in resistivity and polarizability. In the case of pyrite, both decrease, whereas for clays, the resistivity drops considerably and the polarizability is more than doubled.

The plot of the data for magnetite has a definitely positive curvature, and this differentiates its polarization response from that of pyrite. There are two other criteria, besides the curvature of the $\log P$ curve as a function of time, by which one can also easily differentiate the response of magnetite from that of clay. For one thing, magnetite causes an increase in resistivity, whereas clay remarkably decreases the resistivity. Secondly, magnetite and clay increase the polarizability of the material, but the effect of clay is much bigger (compare section 3, table II with table IV; and section 2 of table I-B with section 4 of the same table).

The time constant of decay of the polarization provides another criterion for differentiating clayey sand from mineralized sand. By referring to the graphic representation of the selected data one can compare the curves for magnetite and clay. Members of the magnetite-curve family show a small time constant and reach their saturation values very fast. The arroyo sand shows a very long time decay constant, as indicated by the continued large increase in the signal until a hundred seconds and probably beyond that.

Frequency analysis of the data presented graphically gives a criterion for differentiating in the field the response of wet sand-clay from the response of mineralized earth. In nearly all the mineralized samples the polarization reached almost saturation values within 10 seconds. In the case of sand-clay mixture, however, saturation was not reached even at the end of 100 seconds of excitation time. Thus a procedure is provided that can be used for direct prospecting for sand-clay material; namely, the comparison of response for long times of excitation (100 sec.) with that for times comparable to the saturation response for pyrite (about 10 sec). It seems that the applicability of induced-polarization techniques in prospecting for sulfide mineralization is unlikely because of the very small polarization effect that such mineralization shows in the laboratory experiments. In the field, the noise-to-signal ratio is expected to be even greater and more difficult to control.

Semi-infinite two-layer medium. The frequency dependence of resistivity of a wet polarizable earth provides the basis for field detection of such a layer under certain conditions. The following analytical considerations are based on an article by Henkel (1958). Let us have the following simplifying assumptions:

1. The upper medium is nonpolarizable or has negligible polarizability.

2. The lower infinite medium is highly polarizable.
3. The top layer has a constant resistivity $\rho_1 = 2 \Omega \text{ m}$, but the bottom layer has a frequency-dependent resistivity*, the value of which for 1 cps is $3 \Omega \text{ m}$.
4. The polarizability of the bottom layer is as high as 8 percent for every multiple-of-10 change in the frequency (corresponding to the sample of arroyo sand).

In the problem of detecting a lower polarizable layer under the conditions stated, one can make direct use of the theoretical considerations that Menkel (1956) presents in his article to obtain an idea of the magnitude of the results to be expected in the field.

Menkel based his analysis on the equation that Irwin Roman derived through his multiple-reflection technique,

$$V = \frac{I \rho_1}{2\pi a} \left[1 + 4 \sum_{j=1}^{\infty} \Omega^j \left(\frac{1}{\sqrt{1 + \frac{(2jh)^2}{\rho_2}}} - \frac{1}{\sqrt{4 + \frac{(2jh)^2}{\rho_2}}} \right) \right] \quad (1)$$

in which (1) a is the distance between the potential electrodes in the equispaced, collinear, four-electrode configuration; (2) ρ_1 and ρ_2 are the resistivities of the top and the bottom layers respectively; (3) Ω is a reflection coefficient represented as a fraction; viz., $\Omega = (\rho_2 - \rho_1) / (\rho_2 + \rho_1)$; and (4) h is the thickness of the top layer.

Menkel obtained the following relation for the ratio (V_p/V) of the polarization signal to the total potential signal:

$$\frac{V_p}{V} = \frac{\rho_1}{\rho_2} - \frac{2}{V} \frac{\partial V}{\partial \Omega} \frac{\rho_2 \rho_1 - \rho_1 \rho_2}{(\rho_1 + \rho_2)^2} \quad (2)$$

where ρ_1 and ρ_2 bear some relation to the polarizabilities of the two media, and V_p is the difference between V_p and V_0 . V_p is

*Although the resistivities quoted are arbitrary, they have been chosen so that one can easily find tabulated values of resistivity and polarizability curves.

obtained by substituting the effective resistivities into equation (1), and V_0 is obtained by substituting the resistivities for zero polarization in the same equation.

For the case of a nonpolarizable top layer (i. e., $p_1 = 0$),

$$\frac{V}{P} = \frac{1}{V} \frac{\partial V}{\partial Q} \frac{2 \rho_1 \rho_2}{(\rho_1 + \rho_2)^2} \quad (3)$$

The changes in the resistivity of the bottom layer for different frequencies will give different values of Q . From assumptions 3 and 4, and the relation

$$Q = (\rho_2 - \rho_1) / (\rho_2 + \rho_1),$$

one can make up the following table:

| Freq. | 0.001 | 0.1 | 1 | 10 | 100 |
|-----------------|-----------------|------------------|---------------|------------------|------------------|
| ρ_2/ρ_1 | $\frac{2.7}{7}$ | $\frac{2.85}{7}$ | $\frac{3}{7}$ | $\frac{3.15}{7}$ | $\frac{3.30}{7}$ |
| Q | -0.443 | -0.421 | -0.4 | -0.379 | -0.359 |

By definition, $p_2 = 0.20 \rho_2$. So the fraction in terms of ρ_1 , ρ_2 and p_2 can be evaluated by substitution to be

$$\frac{2 \rho_1 p_2}{(\rho_1 + \rho_2)^2} = \frac{2 \times 7 \times 0.20 \times 3}{(7 + 3)^2} = 8.4\%$$

The values for $\frac{1}{V} \frac{\partial V}{\partial Q}$ corresponding to the different Q 's would be obtained from Henkel's table at the end of his article. Only three values of Q will be considered; namely, those for the two extremes of frequency and the middle one. The abridged data for $Q = -0.4$ are taken directly from the table, but for other Q 's the values are obtained by interpolation.

| $\frac{\rho}{a}$ | .1 | .3 | .7 | 1 | 1.5 | 2 |
|------------------|------|------|-------|-------|-------|-------|
| -0.44 | 2.44 | 2.05 | 0.759 | 0.376 | 0.147 | 0.070 |
| -0.40 | 2.36 | 1.99 | 0.753 | 0.376 | 0.147 | 0.070 |
| -0.36 | 2.33 | 1.96 | 0.749 | 0.376 | 0.147 | 0.070 |

Substituting these values in the equation for

$$\frac{V}{V} = 8.4\% \frac{1}{V} \frac{\partial V}{\partial \frac{\rho}{a}}$$

one finds that the range of signal to be detected is between 0.588 percent and 19.8 percent of the total potential observed across the potential electrodes.

For purposes of simple calculation, let the current passing be 1 amp for a spacing of 4 meters (the thickness of the top layer being, say, 5 meters). The apparent resistivity will be between 3 and 7 ohm meters; let it be 6.3. The voltage measured would be in the vicinity of

$$V = \frac{I \rho_a}{2 \pi a} = 250 \text{ mv.}$$

For larger values of electrode spacing, (a), the apparent resistivity, (ρ_a), will decrease, and there will be a twofold decrease in V below 250. Moreover, there will be a smaller percentage to be measured. These few considerations give an idea of the size of the polarization signal to be expected.

It is believed that a technique such as that employed in the present study for cancelling out most of the potential signal should be very efficient and of practical use in the field, because it gets rid of the undesirable major part of the signal and leaves only the small percentage necessary for polarizability measurements.

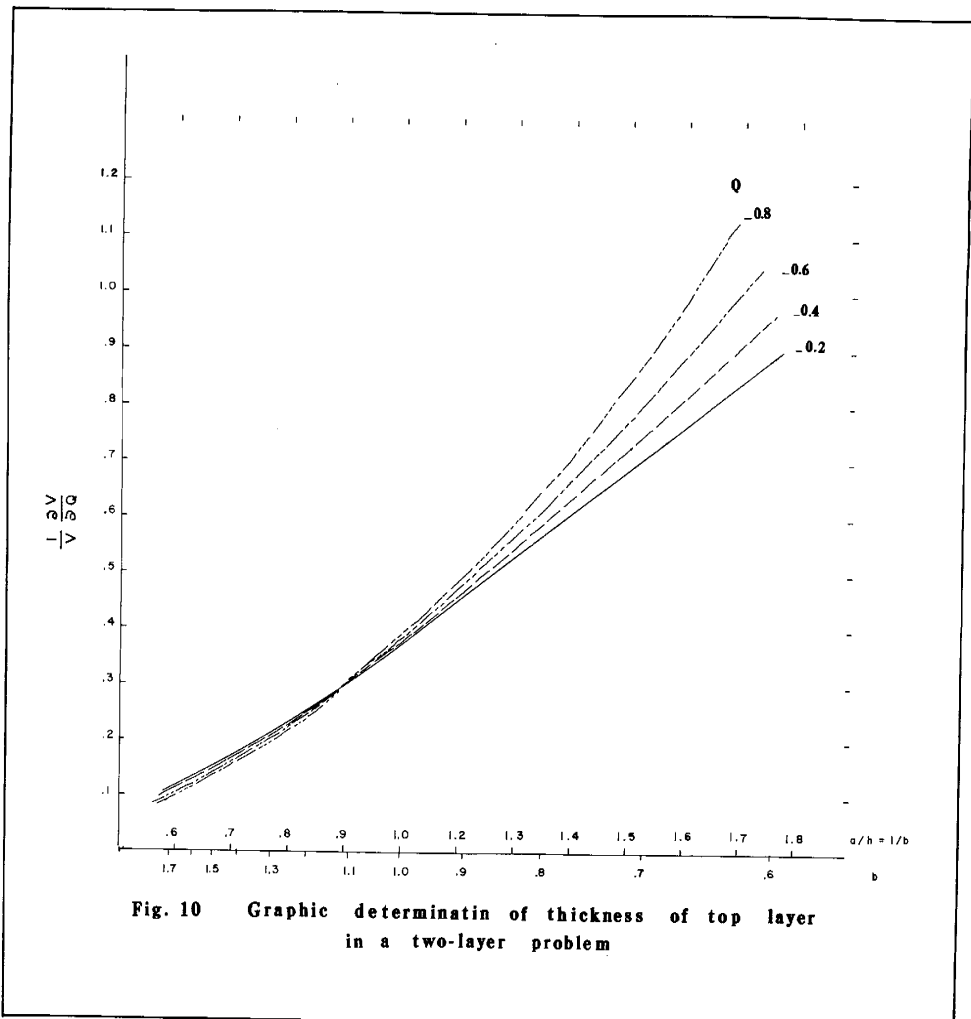
The table given above (extract from Hankel's article) needs a

bit more consideration. The three sets of values of polarizability versus electrode spacing, corresponding to frequencies 100, 1 and 0.01 cps respectively, seem to be concurrent around the value unity for the ratio of thickness to spacing. In the original table, one finds as a general feature for negative values of Q that, in moving to the right the values in the upper section decrease, but in the lower section they increase. The values almost always increase for positive values of Q .

Data for plotting the four curves in Figure 10 (for values of Q between -0.2 and -0.8) were chosen from the tables published by Henkel (1958). The abscissa is the ratio of electrode spacing to thickness of top layer (a/h). The ordinate is $\frac{1}{V} \frac{\partial V}{\partial Q}$, as given in the table. The relation between this quantity and the polarizability (ϕ , as defined on page 22) is the coefficient $\frac{2h\rho}{(\rho_1 + \rho_2)^2}$, since ϕ in the present work represents the same quantity that is represented by $\frac{V}{V_0}$ (eq. 3, p. 25). Differences in the value of Q exemplified in Figure 10 cannot be expected in field measurements of polarizability. They are only used as an illustration of the graphical method.

In practice, variation in Q is a consequence of the changes in resistivity of the lower layer in response to different frequencies of energizing. Such variations usually do not exceed ± 10 percent. Figure 10 shows that all the curves cross over at the point whose abscissa is $a/h = 0.9$. Regardless of the value of Q within the range illustrated, curves obtained by field measurements and plotted for different frequencies will cross each other at the value of the ratio a/h shown by the illustrative curves.

The above considerations suggest a method for utilizing the frequency dependence of the resistivity to determine the depth to the bottom layer of a two-layered earth. The method would consist essentially in plotting, as ordinate, the percentage variation in apparent resistivity corresponding to a number of frequencies of energizing current against the electrode spacing (a), as abscissa, and locating the point of con-



occurrence. The abscissa of that point is then substituted in the empirical relation $a/h = 0.9$ to obtain the value of h .

The frequency dependence of resistivity thus provides an indication of the occurrence of an underlying polarizable layer, an indication to the depth to such a layer, and a basis for discrimination against the background noise produced from polarizable metallic materials.

The graphical method of interpretation presented promises efficiency in determining the depth from the surface to the horizontal discontinuity in a two-layered earth provided the lower infinite layer is the polarizable one, i. e., wet with fresh water and has clay contamination. This subsurface situation is just what a ground-water prospector desires to locate for subsequent exploitation.

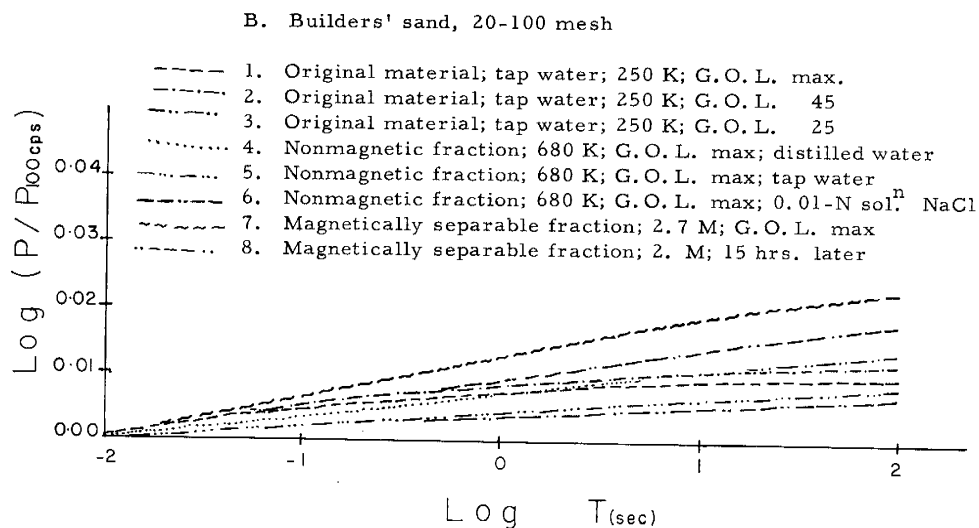
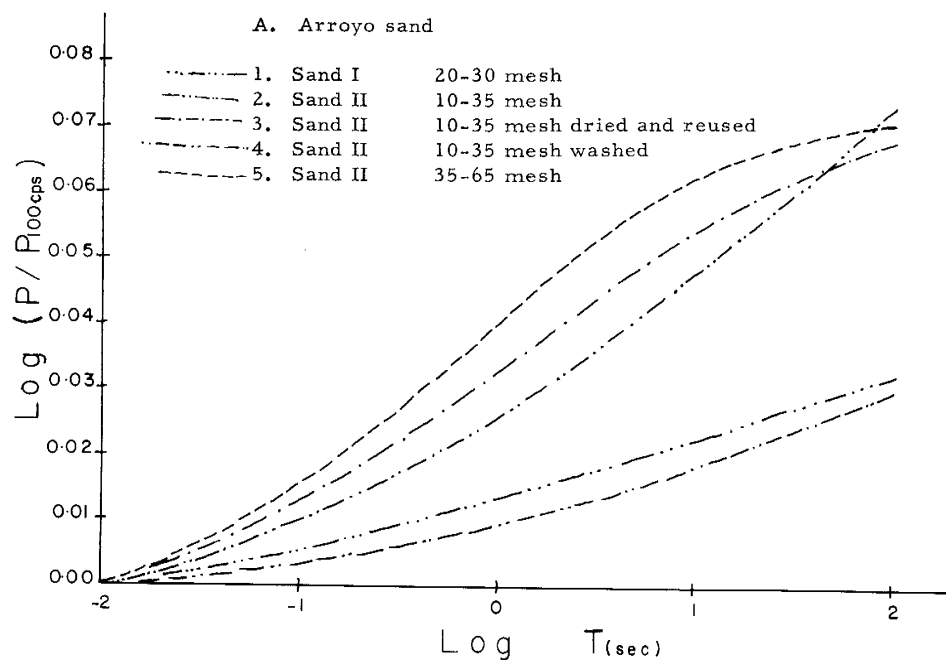


Fig. 11 Frequency response of polarization signals
Plot of selected data, Tables in appendix IV

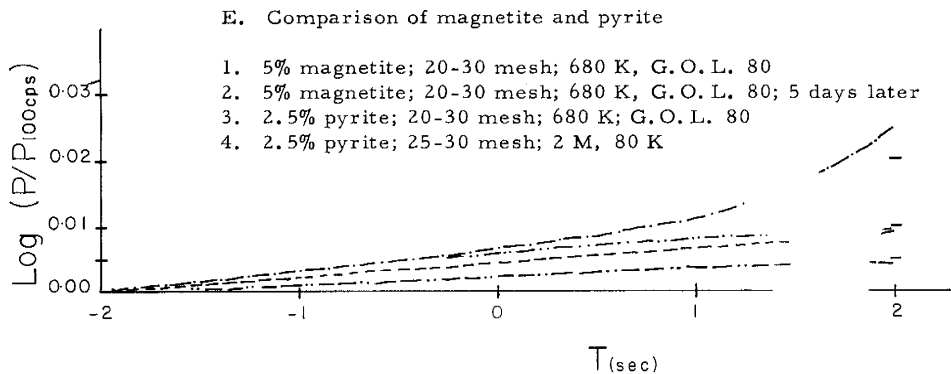
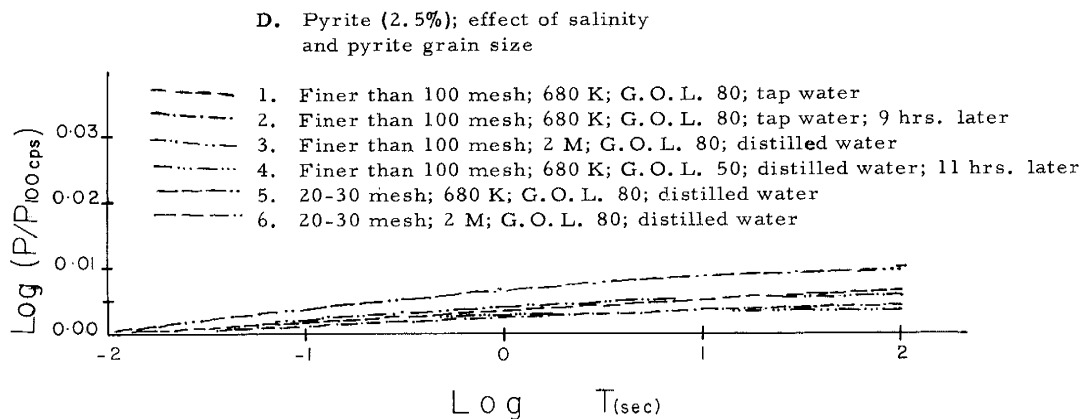
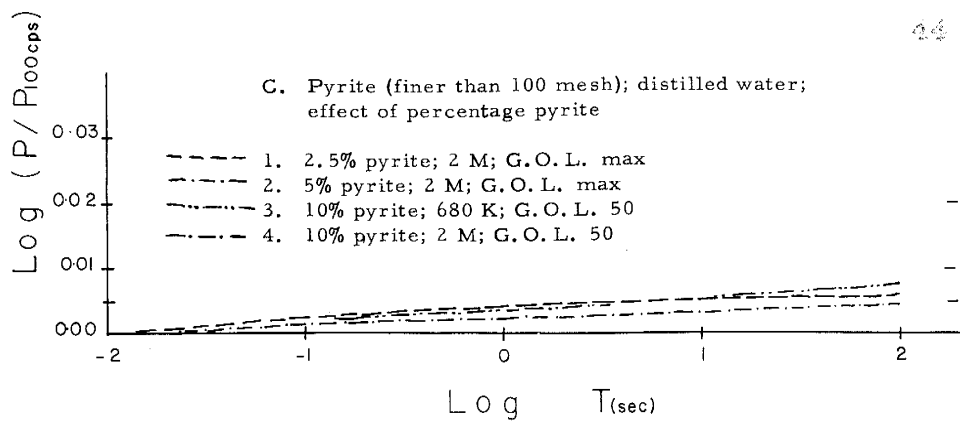


Fig. 11 Frequency polarization signals
 Plot of s in appendix IV

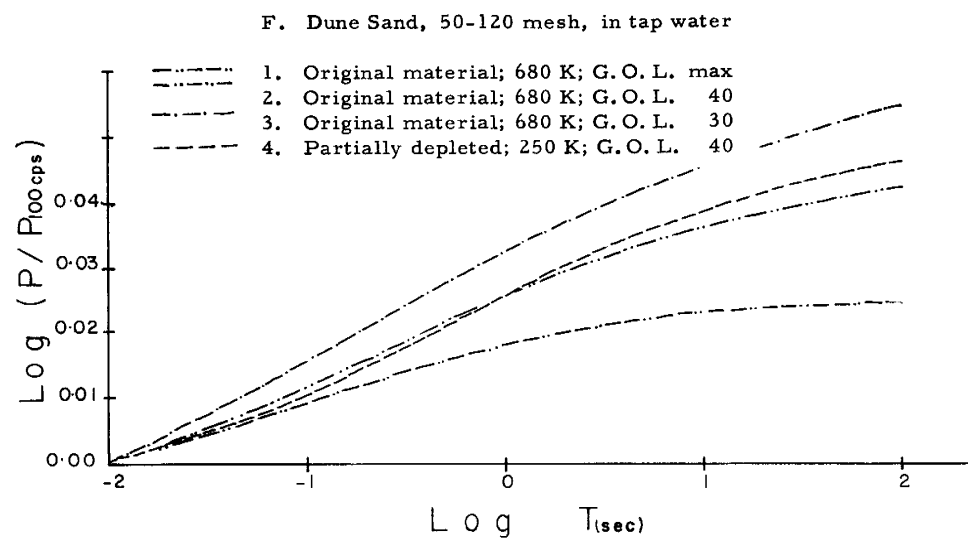


Fig. 11 Frequency response of polarization signals
Plot of selected data, Tables in appendix IV

Summary and Conclusions

Thirty samples were tested in the laboratory under different conditions. The parameters varied were the conductivity of the electrolyte, the grain size, nature, and percentage by weight of the impurity, and the grain size of the impurity. The matrix in most of the samples tested was obtained by magnetically purifying a quantity of sand of the type used in a concrete mix. The rest of the samples were natural arroyo sand. Magnetite and pyrite were the minerals used for comparison with clay. The signal studied was the variation in the potential difference measured across the potential electrodes as a function of frequency.

On the basis of frequency response in sample resistivity, an analysis of the data shows that the polarization signal induced by the flow of electrical current through a saturated sand-clay earth material can be differentiated from the signal produced in a metallic mineralized sample, both by the magnitude of the signal produced in the two sample types and by the time constant of the sample polarization. The difference in time required for the polarization of the respective materials to reach saturation values provides for discrimination between these types of material and serves as the basis for a simple field technique of detection of ground water.

The following observations can be made about the frequency dependence of the properties of mixtures of sand with the various material studied.

1. Clay will decrease the resistivity and increase the polarizability of a sand sample considerably. The curvature of the logarithm of the potential signal with respect to logarithm of time is positive.

2. Pyrite decreases both the resistivity and polarisability for the concentrations used, the decrease in both being greater for greater percentage by weight if the size of the pyrite grains is kept constant. For larger grains of pyrite, the decrease is less than for finer pyrite grains. The curvature of the logarithm plot of the potential signal is negative.
3. Magnetite increases both the resistivity and polarisability. The curvature of the logarithm plot of the potential signal is positive.
4. More conductive electrolytes will cause a decrease in the detectable polarization signal.

A fundamental conclusion has been established in this work; namely, that there cannot be a general rule for expressing the relation between polarisability and resistivity. The two properties are quite independent of each other.

The problem of a two-layered semi-infinite earth in which the bottom layer is polarisable and less resistive than the overlying one is analysed. A simple empirical method of determining the thickness of the top layer is presented. The method promises success in the case of negative values of

$$Q \left(= \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1} \right) \text{ (i. e., where the lower layer is less resistive),}$$

but not for the reverse condition. Usually, the former case has significant importance to a ground-water prospector in areas of water-table problems, since the presence of water in the lower section of the rock tends to decrease the resistivity of that section.

APPENDIX

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Appendix I

Previous Investigations in Induced Polarisation (I. P.)

Phenomena related to I. P. were studied extensively prior to investigations of a geophysical nature. Hartshorn (1926) gave an exhaustive summary of earlier work in the study of dielectrics. Late in the 19th and early in the 20th centuries, the Curies, Pellat, Maxwell and Wagner carried out a great deal of research on induced polarisation of dielectrics. Their analytical approach is helpful in understanding the phenomenon of I. P. They differentiated the current flowing in a material into three parts and accounted for them as ohmic conduction, capacitive charging, and an anomalous charging current. Von Schweidler (in Hartshorn, 1926) offered another reasonable explanation of the time dependence of I. P. He represented the decay curve, after a step-form current is cut off, as the sum of exponential decay functions; i. e., he assumed the presence of a number of relaxation times. Later, however, he modified this explanation and replaced the constant coefficients of the decay functions by a statistical-distribution function defining the density of relaxation-time constants.

Heiland (1940) reviewed the transient or "Eltron" methods. In these methods a current impulse is impressed on the ground, and the time decay of the corresponding potential impulse is determined. Polarisation potentials are produced by applying an electric current through an electrolyte. Such induced polarisation cannot exceed definite values for given conditions and solutions, no matter how much the field is increased.

In most Eltron arrangements used at that time, the transients were measured in a separate potential circuit and not in the customary

Wenner-Gish-Rooney configuration. One method, used by White, consisted in charging a bank of condensers with high voltage and then discharging them through the ground and recording the time gradient of the surge, or measuring the maximum height of the transient. Another Eltran method is based on the assumption that the ground-circuit impedance is capacitive as well as resistive. Present-day transient studies of electrical polarization ordinarily minimize the induction effect of the earth by employing exciting currents of frequencies much lower than those used in the Eltran methods.

In the early 1950's three mechanisms were suggested concerning the time dependence of I. P. Brant and Gilbert (1952) gave an explanation in terms of electrode polarization at the metal electrolyte interface. Dakinov and his coworkers (1952) explained the phenomena as electro-osmosis in porous rocks. Keller and Licastro (1955) suggested ionic polarization in a permselective membrane such as a clay-bearing rock.

When a current is passed through some materials, a growing potential appears between any two points in the material superimposed on the IR drop across the same two points. Similarly, if the current is cut off, a decaying potential difference persists for as much as several minutes. This phenomenon has been called by Schlumberger (1930) provoked potential. Vacquier and his group (1957) call it induced polarization. Madden et al. (1957) recommend, however, the use of the term interfacial polarization. In the latest publication on the subject, Brant and his coworkers (in Walt, 1959) describe the phenomenon as over-voltage. These last three are the main terms in the U. S. A. devoted to such studies. Their work will be presented in more detail later.

With the exception of the investigations patented by Schlumberger for well logging, the research undertaken prior to 1945 was directed toward an academic or classical study of the observable characteristics of the phenomenon of I. P. In the past two decades interest has revived in I. P. as a possible method of geophysical prospecting. Research has

been done both by individuals and groups.

The earliest of these investigations was published by Bleil (1953), whose discussion related chiefly to prospecting for sulfide mineral ores. More recently, Henkel (1958) presented a simple mathematical theory treating both the transient square wave and the sinusoidal wave. In the same paper, he analyzed the polarization induced in a two-layer earth and presented theoretical calculations.

Investigations have also been conducted outside the U. S. A., particularly in Russia and Japan. Sulashevich (1957), in his discussion of the physical basis of the phenomenon of I. P. as applied to prospecting for sulfide ore bodies, stressed the fact that two factors enter the process of I. P., the polarization of the ore body and the polarization of the surrounding formations. Both of these effects are parallel. The polarization of adjoining zones may reach great intensity and seems to be independent of the ore body itself.

Kudymov and Kotov (1958) carried out laboratory experiments on I. P. in platinum, copper, lead, and clay, as well as in sandstone, limestone, and clayey sands. They concluded that the principal cause of I. P. appears to be the attenuation of movement of the solutions in the capillaries of the rock after cutting off the current--essentially an electro-osmotic aftereffect.

Yanagihara (1959) explained the phenomenon of I. P. in terms of concentration cells at the effective membrane formed by the capillaries of clay particles rather than in terms of capillary constrictions between the sand grains. The latter explanation was proposed by Vaccarier et al. (1957). As yet, it appears that no experiments have been carried out to test the relative validity of the two types of concentration cells.

In recent years there have been principally three teams in the U. S. A. whose investigations have the main purpose of utilizing the phenomenon of I. P. for geophysical exploration. The earliest of these

group is supervised by Dr. Arthur A. Brant and sponsored by the Newmont Mining Corporation and its subsidiary, Newmont Exploration Ltd. The second group is supervised by Dr. T. Madden, at the Massachusetts Institute of Technology. Professor Victor Vacquier formerly directed the work of the third group at the New Mexico Institute of Mining and Technology. The interest of the first two groups lies chiefly in the application of I. P. for mining sulfide ore deposits. Of these two only the first has included an investigation into the behavior of clay minerals, primarily to evaluate the background or "normal" effect (Wait, 1959, ch. 10 A and 10 B). The work done by the New Mexico group is most nearly related to the present study, which was suggested by Dr. Paul R. Kintzinger, a member of that group. More details will now be given about each group separately.

Research by Newmont Group*

The first investigations made by the Newmont group were the result of a suggestion made by Radio Frequency Laboratories of Boonton, New Jersey. By 1948, the joint effort of the latter and the two Newmont organizations produced a truckmounted field equipment that could energize the ground for 30 seconds and then record for 3 seconds (starting a few milli-seconds after the charging is cut off). K. A. Raddock designed most of the field devices. The equipment was essentially a transient step-function generator with times of excitation ranging from 3 to 12.5 seconds. The direction of the dc pulses was applied in alternate fashion, and the pulses were separated from one another by a no-flow or recording time (see appendix, fig. 1). A combination of a vacuum-tube voltmeter and a fluxmeter-type galvanometer measured and recorded the integrated signal.

In 1950 L. S. Collett and H. O. Siegel (in Wait, 1959), found

*Wait (1959)

that for higher frequencies there was marked decrease in resistivity of rock samples containing scattered sulfides. The recording time was 1 second. By 1952, Siegel (1959) had developed the first mathematical expression for I. P. anomalies across mineralized bodies of geometric form when charged by a square-wave dc pulse such as was used by Newmont.

A second type of pulse generation, used by Wait (in Wait, 1959), was the variable-frequency ac. Instead of the pulsed dc with a charging-and-listening procedure, he had a sinusoidal energizing current on all the time. The frequency range used was continuous variation between 0.1 and 10^5 cps. Both methods (the Siegel transient and the Wait variable-frequency ac) have been tested by Collett and others.

Collett in his discussion stressed the idea that the most fundamental test in electrical phenomena of this kind is for "linearity." A linear medium is usually defined as one in which the response of the system is proportional to the applied force. Collett presented evidence for a slight nonlinearity in the decay curves (plotted on a logarithmic time scale) and suggested that one exercise caution in extrapolating the laboratory results to much lower values of primary current density. For field applications, the current densities used are of the order of 10^{-5} times the values employed in the laboratory.

Wait (in Wait, 1959) analysed results of tests using a step pulse of current to energize the ground and suggested 3 criteria for analysis: the first, second, and third derivatives of the decay curve. The data analyzed were from samples composed of a matrix of crushed andesite, with pyrite as the only "impurity." Different electrolytes were used in different concentrations.

G. V. Keller (in Wait, 1959) made analyses of a number of transient measurements on igneous, sedimentary, and metamorphic rocks. He concluded that the most active rocks are those containing

electronic conductors, such as base metal sulfides or hematite. The clay-bearing sediments showed less activity; least active were the limestones and the silicic igneous rocks. He presented data of very low resistivity and polarization from a few odd samples that contained metallic minerals, and remarked that these rocks must contain massive or continuous, rather than disseminated, electronic conductors.

Response data obtained from the variable-frequency technique were analyzed by N. F. Ness (in Wait, 1959). Ness observed that large values may be associated with nonmineralized materials, and correspondingly small values with mineralized samples. He selected as the optimum frequency band for I.P. the values between 10 cps and 0.01 cps. Outside that range, either the time would be too long and the record would be affected by stray earth potentials, or the frequency would be so high that inductive effects would have to be considered in the interpretation of field results. In brief, Ness tried to fit an assumed exponential time-decaying series, of the form suggested by Von Schweidler (see above, p. 49) to the actual observed data and then determined the coefficients by least squares analysis. Qualitatively, high-frequency response is associated with time response at small moments from the onset of the excitation, whereas low-frequency response is analogously associated with time response at large moments. This concept has been clearly demonstrated in the present work by Figure 3.

Ness presented two main conclusions: first, that the phenomena present a spectrum spread out over a range well over the one used (0.01-10 cps); second, that there appear to be no well-defined characteristic differences of spectrum behavior that can be utilized to predict the actual presence of metallic conducting particles. The results obtained in the present study, however, indicate that clay-sand-water material can be detected in the presence of metallic material and differentiated by the technique presented.

Baldwin (1959) noticed that barren rock can display a considerable range of response, and that anomalies not caused by sulfides have been due to magnetite and probably graphite.

As far as the present work is concerned, the work of Mayper (in Wait, 1959) seems to be the most interesting. Mayper shows that clay minerals with high ion-exchange capacity can give a considerable overvoltage response. The main interest of his group (the Newmont), however, was in the detection of sulfide minerals, and they have termed the response due to clay content as a "normal" effect. According to Mayper, the normal chargeability is usually equivalent to that which would result from the presence of about 1 or 2 percent of conducting mineral in the rock matrix. He critically analyzes a number of hypotheses that have been suggested to account for the normal effect, and presents results of experimental investigations to check the rest. He has eloquently disproved the hypothesis of electrokinetic response of air bubbles in rock pores and of irregularities in the rock pore capillaries, as well as the surface-conduction hypothesis, which had been assumed as explanations for the normal effect. Of the remaining possibilities, the ion-exchange hypothesis is considered slightly more probable than the poor-conductor hypothesis. Mayper concludes that the normal effect is caused by electrochemical phenomena within and on the surface of particles of clay and claylike deteriorated mica in a rock. In addition, the presence of unrecognized conducting minerals has often caused effects undistinguishable from the normal effect. Some anomalously high normals are ascribed to pore-structure effects in tight rocks or to the presence of large amounts of unrecognized active material. These conclusions of Mayper have been arrived at principally on the basis of assays, petrographic analyses, porosity measurements, resistivity measurements, and critical experiments on a number of samples. The latter consisted largely of measurements

of I. P. response before and after the attempted elimination of clay by heating, by electro-dialysis, and by crushing and removing the less than 2 micron fraction.

Research by M. I. T. Group

The experimental work carried out at the Massachusetts Institute of Technology under the direction of Dr. Theodore R. Madden (1959) had as its primary aim the obtaining of a backlog of empirical results of interest to persons involved in the making of field measurements. The measurements were made on samples of igneous and metamorphic rocks that came almost exclusively from mining districts. Such measurements were made by observing on an oscilloscope the voltage decay across the sample after the interruption of current flow through the sample. The frequency information was derived from these curves by means of Fourier analysis carried out numerically. A summary of the empirical results is presented in the form of histograms. Model studies also were carried out in layered media for cases of horizontal and vertical discontinuities. The instrumentation was essentially a sending and receiving system in the frequency range of 100 to 600 kcps.

Research by N. M. I. M. T. Group

By far the most extensive research on clayey materials was done through laboratory investigations and field tests at the New Mexico Institute of Mining and Technology. The transient electrical prospecting developed at N. M. I. M. T. was the first attempt to use induced electrical polarization as a method for finding ground water. Such experiments were started at N. M. I. M. T. in the fall of 1953 (Vacquier, 1957) under the direction of Prof. Victor Vacquier. As mentioned earlier, Schlumberger observed that the effect from wet soil completely masked the effect that he expected to get from the metallic sulfide ore

body for which he was prospecting. In fact, the Schlumbergers were the first to attempt the use of I. P. for geophysical exploration.

It has been observed at N. M. I. M. T. that neither sand alone nor clay alone when mixed with water shows any appreciable amount of polarizability. However, a mixture of sand and clay that is dried and then resaturated is polarizable and stays so indefinitely, i. e., as long as the clay coating on the sand particles is not washed off. Various sand-clay mixtures saturated with many different electrolytes were studied. After excitation times ranging from 1 to 120 seconds, the current was interrupted and a decay curve recorded a few milliseconds later. In the analysis of most of the earlier data, the areas under the voltage decay curves, evaluated by integration, were studied. Later, comparison was on the basis of the values of the ordinate 5 sec and 20 sec after the current was cut off. The ratio of these two ordinates gives additional information; i. e., some measure of the rapidity of the voltage decay. Generally, the polarizability decreases with decrease in resistivity, so that clay banks and saline waters should give small effects. The chemistry of solution, particularly the positive ions, as well as the type of clay and its state of dispersion and flocculation, has a great effect on the magnitude of the polarizability. The polarizability of a certain montmorillonite used in some of the experiments increased by a factor of seven after slow percolation of a 100-ohm-meter solution of calcium chloride. It was further found that the rate of polarization decay is independent of the concentration of the electrolyte and does not seem to be affected greatly by the kind of clay and the chemistry of the water. It is, however, principally influenced by the grain size of the sand. Slower decay is correlated with coarser alluvium. Some of the data presented indicate that the valence of the cation has little to do with the polarization phenomenon.

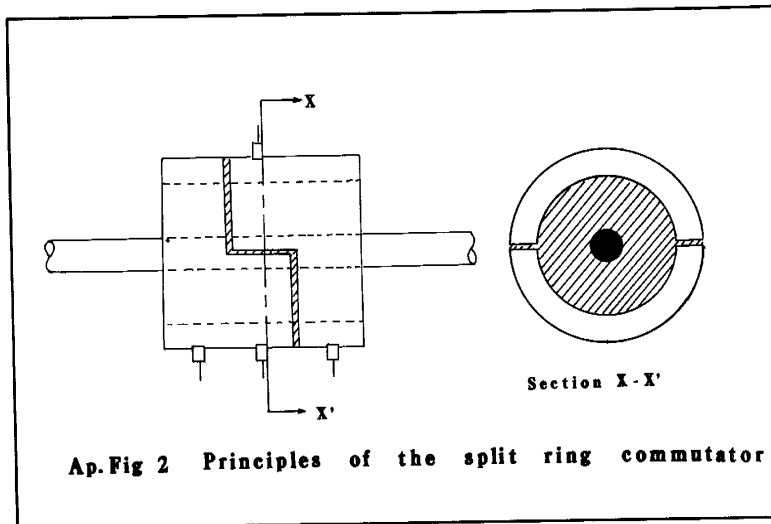
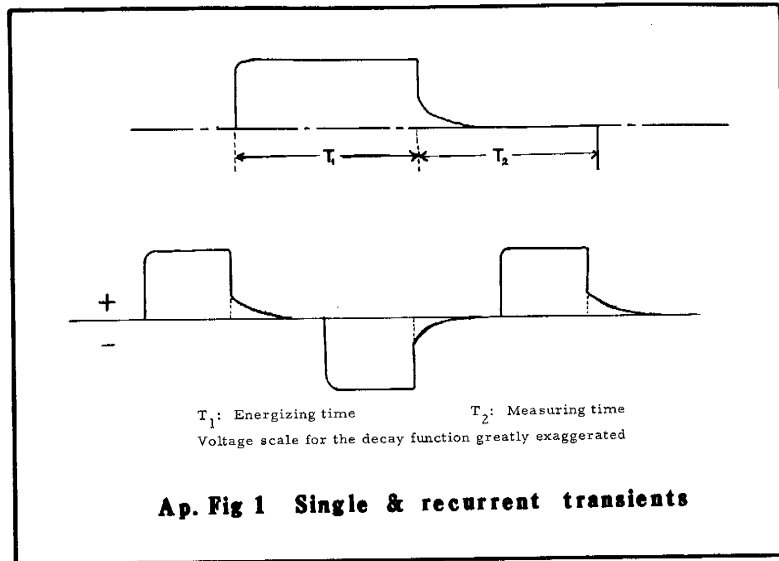
The studies at N. M. I. M. T. led to the conclusion that polarization is the result of local electrodiffusion of clay across semiperme-

able partitions formed by adjacent sand grains. The conduction over the clay in the constricted regions affects the concentration of the exchangeable cation of the double layer. It is necessary to pass the current for several minutes before equilibrium is reached. When the current is cut off, the exchangeable ions redistribute themselves along the clay. It was proposed tentatively that the function of the clay during such a relaxation phenomenon is to provide a source and a sink of ions. Hence, if the clay subjected to electro dialysis (Classtone, 1953) in situ cannot move by electrophoresis, it sets up concentration cells in the liquid-filled pore spaces of the matrix when the current is cut off. The rate of decay of these cells must be determined by the mobility of the exchangeable ions on the clay itself. Larger grain size gives longer paths over which the ions have to travel. This is reflected by the lengthening of the relaxation time with larger grain size.

Streaming potentials and electroosmosis were proposed by Dakbav et al. (1952) to account for I. P. as applied to well logging. The experiments carried out at N. M. L. M. T., however, show that these two effects are much too small to account for the magnitude of the I. P. observed. The streaming potentials for clean sand and sand with 1 percent bentonite are very nearly the same, whereas the I. P. effects differed by a factor of 20.

The hypothesis proposed by Vacquier for I. P. has been tested (Schuffe, 1959) by measuring I. P. in the presence of different cations. The results show a decrease in I. P. with increase in valence of the cation for the highest concentration used (0.005 N). This would be expected on the basis of the cation-exchange mechanism. As concentration decreased, the I. P. values for sodium, calcium and lanthanum nitrates appear to increase and approach a common value. For thorium nitrate, however, the value remains low even at the lowest concentrations. The experiments give support to the explanation of I. P. in

terms of the cation-exchange mechanism, but owing to the apparent inconsistency just noted do not exclude the possibility that other factors may be involved.



Appendix II

Developments in the Energizing and Recording Technique

The earliest attempts in the present work to achieve the square form desired for the excitation current were purely mechanical in nature, the principle of the rotating split ring being employed. Later, two pairs of relays, operated by an electronic timer, replaced the split rings. A number of difficulties forced a change of both the relays and the timing system. A mercury-wetted relay was introduced. Because of contact bounce, the relays had to be discarded as a means of direct commutation of the energizing current. Moreover, they could not be used to rectify the potential signal for dc measurements. The timing system was then slightly modified to operate a combination of thyatrons for reversing the energizing current. The final, workable combination was a combination of low-frequency function generator for current source, and a differential-input oscilloscope for recording the potential signal induced in the sample. Each step of this development will now be described in more detail.

Split-ring rotating commutator

The split-ring commutator consisted of two pairs of split rings mounted on the same shaft. One pair commutated the energizing current from a dry cell to give the current through the sample a square form with alternately positive and negative half cycles. The function of the second pair of split rings was to invert every other half cycle of the potential signal to give a dc effect that could be measured by dc instruments. A dc milliammeter in series with the battery measured

the current; and a Kay-Lab microvoltmeter of high input impedance, connected across the output of the potential inverter, operated an Esterline-Angus recorder.

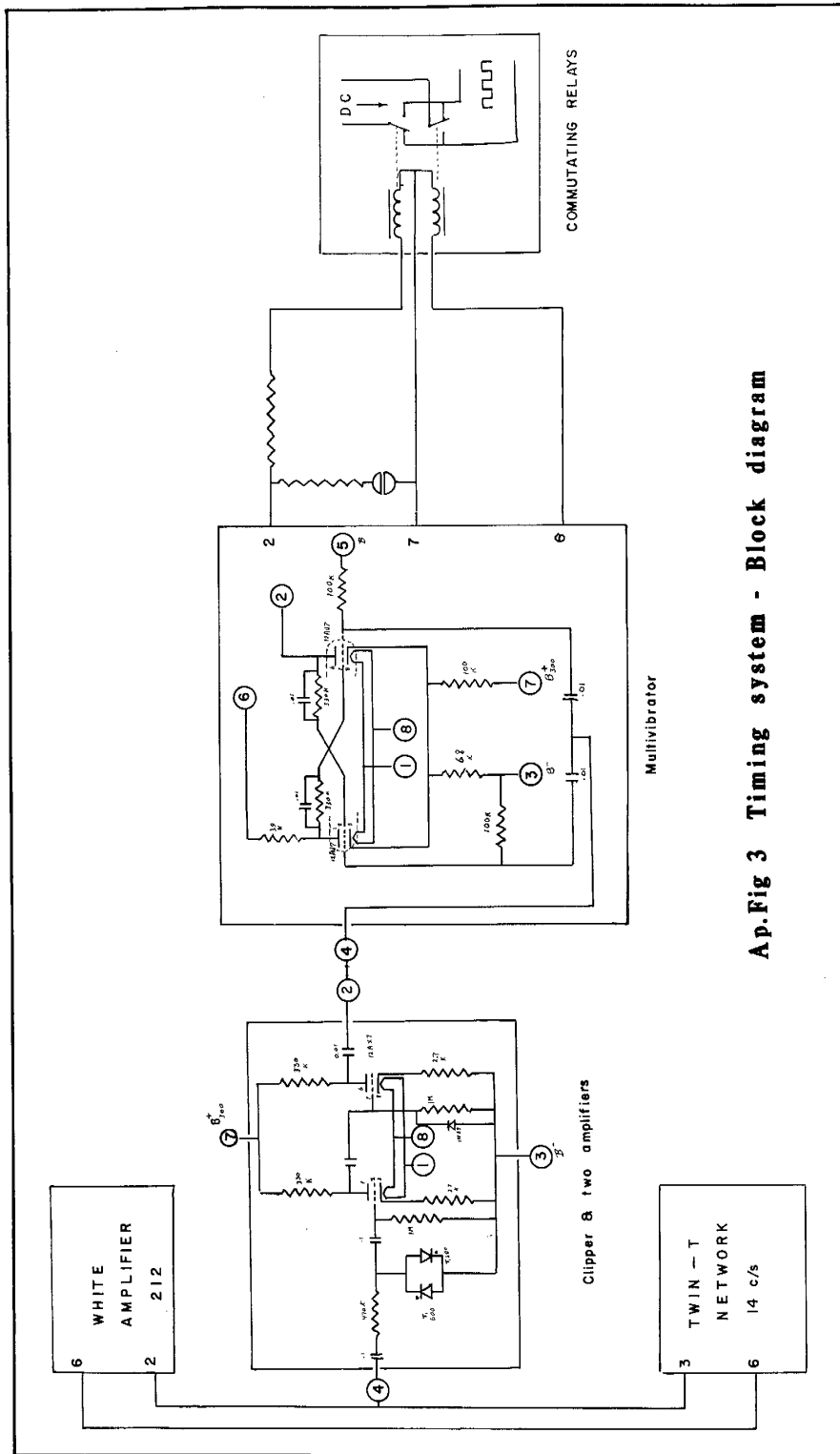
A driving motor with a speed-varying device was used to change the rpm of the commutator from 1 to about 30 rpm. The higher frequencies were determined by an electronic stroboscope. A resistance calibration net of comparable resistors simulated the sample. Since the potential-difference (PD) signal was commutated every half cycle, any stray potential (SP) that was originally unidirectional appeared as a square ripple superimposed on the rectified signal that was due to the energizing current.* This necessitated the addition of a spontaneous-potential dc balancing circuit. In effect, the SP balance raised or lowered the potential of the electrode to which it was connected, as need might be, with respect to the other potential electrode.

The trouble with such a system of commutation was the potential noise caused by friction between the sliding contact points, as well as at the time interval during which the contacts were transferring from 1 ring to the other. In addition, the same set of frequencies could not always be reproduced, because the variation of motor speed was continuous and could not be preset to definite values.

Electronically Operated Relays

Two pairs of Potter Brumfield single-pole, double-throw

*Effect of SP on rectified signal: Let the signal caused by the energizing current be $+V$ and $-V$, and the SP be $+v$. When the current passes in one direction, the PD will be $V+v$; when the current passes in the reverse direction, the PD will be $-V+v$ (by superposition), and upon inversion it will be $+V-v$. Thus, at alternate half cycles, the signal will be $V+v$ and $V-v$; that is, with a ripple of magnitude $2v$, peak to peak, superimposed on the direct signal.



Ap. Fig 3 Timing system - Block diagram

(SPDT) hermetically sealed electromagnetic relays served exactly the same purpose as the previous two pairs of split rings, one pair commutating the current, the other rectifying the signal. An electronic timing system was adapted to operate the relays at the desired frequencies. The function of such a system was to turn a current on and off through the coils of the relays at a regular frequency at definite preset values (app. fig. 3).

The system consisted of an oscillator and a clipper amplifier. The output of the oscillator passed through a narrow-band-pass filter*. The clipping was achieved through a pair of semiconducting diodes. The output of the clipper-amplifier was a series of negative and positive pulses that were applied to the grid of a triode, so that it was conducting every other half cycle. The output of the last unit supplied the power to operate the coils of the Potter Brumfield relays.

This system switched the commutator relays in one direction or the other electronically. It had nothing to do with energizing the sample. The coils of the potential relays were connected in the same circuit to operate on and off simultaneously with the current relays.

There were a number of troubles with this system. For one thing, the stability of the multivibrator was too critical, which made it difficult to maintain the steady wave form necessary for operation of the relays. In addition, there was too much trouble of mechanical origin within the individual relays, causing mechanical bounce of the traveling reed every time it hit the fixed contact points. The relatively long time of flight of the moving contact also introduced a step into the square wave at the zero level, during which no current was flowing and the established induced potential was decaying. The

*The band-pass filter is changeable and can be replaced by another filter of any desired frequency.

bounce of the reed greatly distorted the shape of the signal and completely masked any induced-polarization (IP) effects that would otherwise have been detectable. Moreover, the electromechanical characteristics of the four relays, no matter how carefully chosen, could never be identical. Consequently, the traveling reeds would not leave one set of contacts or arrive at the other set of contacts all at the same time. Such nonsimultaneous action would result in any or all of the following undesirable effects: shorting the battery, shorting the potential electrodes, and reversing the signal too early or too late.

Mercury-wetted Relay

In an attempt to eliminate these three sources of trouble, a single four-pole, double-throw, mercury-wetted relay* was chosen to replace the four SPDT relays. This type of relay reduced contact bounce and flight time to zero. One coil operated all four reeds simultaneously and practically eliminated nonsynchronous switching. One pair of contacts was used to alternate the direction of the energizing current, the other pair to rectify the potential signal.

Both ac and dc types of voltmeter were used for measuring and recording the potential signal. An ac peak voltmeter** was used to measure the square signal from the potential electrodes after balancing any S. P. For the purpose of calibrating the voltmeter, a square-wave low-frequency function generator supplied an output of constant level at each desired frequency. The frequencies of the relays had been arbitrarily preset at 1, 2-1/2, 7, 15, and 37 cps by

*Manufactured by C. P. Clare & Co.

**Peak voltmeter, model 67, Measurements Corporation, Bonton, New Jersey.

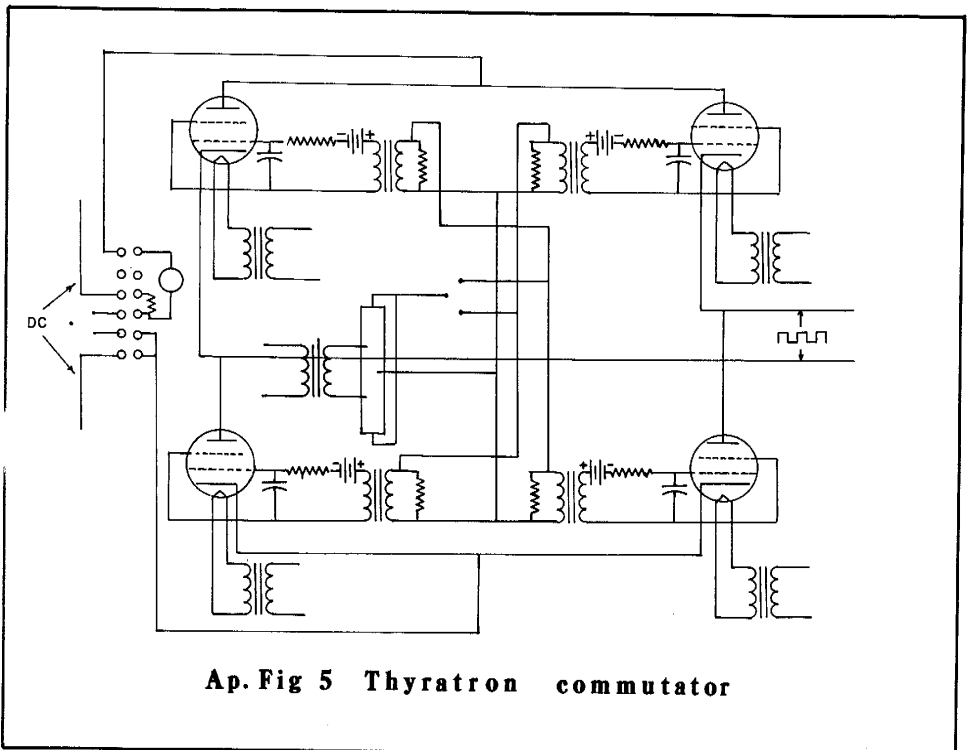
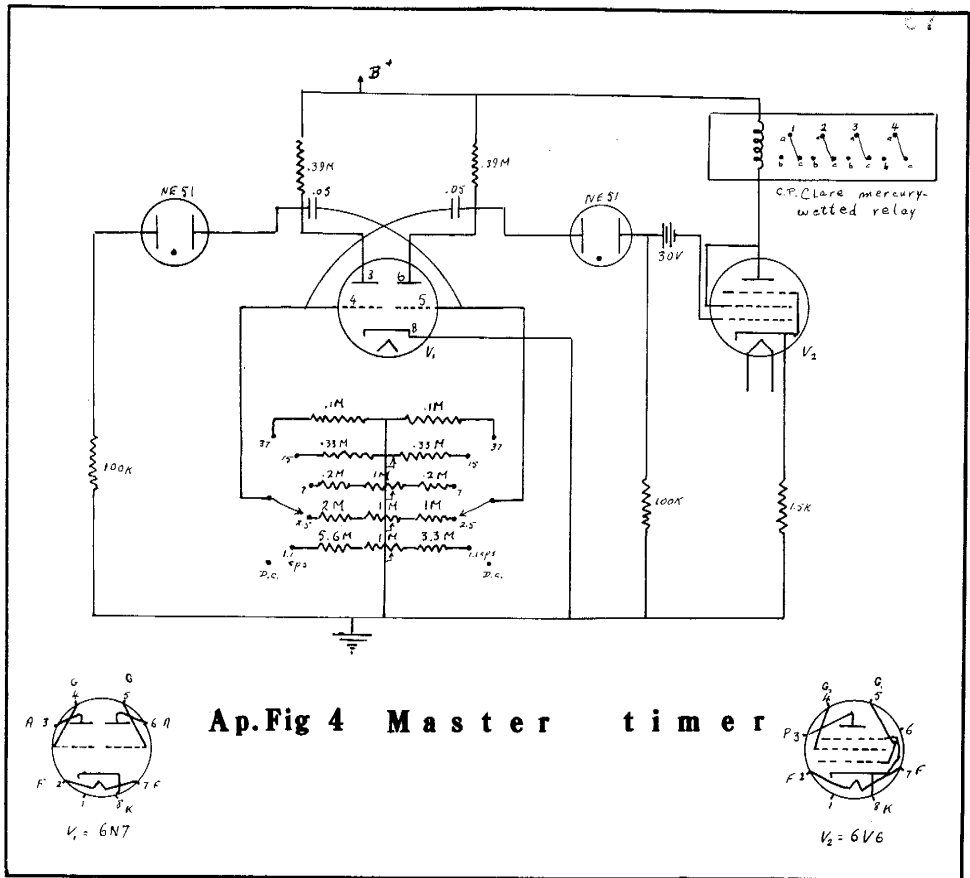
the timer described below (also in app. fig. 4). The output of the voltmeter was recorded by an Esterline-Angus milliammeter recorder. Although this measuring recording combination gave a fairly constant frequency response for frequencies higher than 7 cps, the system response dropped steeply below 7 cps, thus eliminating the possibility of using an ac voltmeter.

In this system the timing unit that controlled the current on and off through the coil of the single relay, consisted essentially of a bistable multivibrator. A pair of capacitors, of fixed values, and a set of interchangeable pairs of resistors operated the multivibrator at frequencies of 1, 2-1/2, 7, 15, and 37 cps. The output of one side of the multivibrator (12 AU7) was tapped off the plate and turned a 6V6 vacuum tube on and off. The plate current of the latter tube, in series with the relay coil, drove the relay.

For a time this system seemed to be ideal. The relays, however, turned out to be of the make-before-break type, so the energizing battery, the current electrodes, and, more important than anything else, the potential electrodes were shorted for a time fraction of each cycle, which was progressively longer with increase in frequency. For that reason relays of any kind could not be used for direct control of the current through the sample, nor could the synchronized relays be used to rectify the signal. A completely different technique had to be designed.

Thyatron-Diode Combination

This energizing system consisted of a combination of four 2051 thyratrons (connected as shown in the diagram) arranged as two banks in parallel, each bank consisting of two thyratrons in series. The voltage required was double that normally used with any one of the thyratrons. The minimum operating voltage required



for each was about 30 volts. The sample was connected across the midpoints (i. e., between the thyratrons) of each bank.

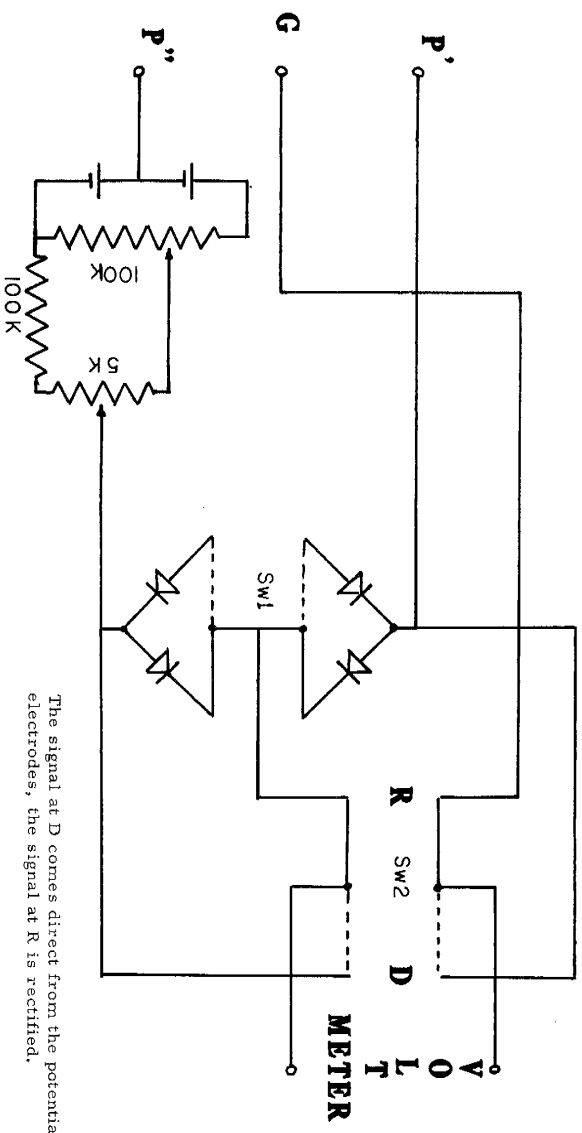
The operation of this system may be described as follows: If one pair of diagonally opposite thyratrons is made to conduct while the other is nonconducting, a current will pass through the sample in one direction; then, when the conducting pair stops, the other pair turns on, and the current passes through the sample in the reverse direction. A 2051 thyatron will "fire," or conduct, if its grid is at a potential slightly higher than its cathode. The grid potential then has no subsequent control on the thyatron. The only way to stop conduction is by cutting the voltage off the plate, or by shorting the plate to the cathode. This mode of operation suggested the use of the make-before-break property of the mercury-wetted relay. One SPDT element of the relay would create inductively the necessary signals on the grids of the two pairs of thyratrons alternately, the bias batteries being connected in such a direction as to supply the desired effect at the instant of break. The two fixed contact points of the second SPDT element of the relay, if connected to the common positive and negative points of the thyatron banks, provide the necessary shorting. Thus, during the make-before-break period, the plate voltage is cut off, and the four thyratrons are nonconducting; at the instant of break, the plate voltage is turned on, the grids of one pair are energized, and that pair conducts. During the next make-before-break period, the plate voltage is again cut off, and conduction is stopped in all four tubes. At this break instant, the reed of the first SPDT disconnects the other pair of thyratrons while the power is being turned on by the action of the second SPDT, and that pair conducts. Thus the square-wave form is achieved through the sample, with a period of only several micro-seconds during which no current passes and the

sample is not shorted.

The leads of the two remaining SPDT elements being useless for signal rectification, a bridge of semiconductor diodes was substituted for this purpose. A rotary selector switch was included to reverse the direction of rectification at will and to provide a position for dc measurement. The silicon diodes were chosen for their especially high back resistance. The diode bridge, as shown in the figure, consists of two pairs of diodes, of which only one pair is included in the circuit at any one time, the other being in a standby position. One pair allows currents to pass away from the center of the bridge, whereas the other pair allows currents to pass toward the center of the bridge. Thus an alternating signal fed into the ends of the bridge will be fully rectified with either pair. The deflection observed on the Kay-Lab microvoltmeter is positive with one pair and negative with the other. This procedure takes care of any inaccuracy in the position of the zero of the microvoltmeter.

The use of a diode bridge for signal rectification requires that the sample be divided by a central electrode for potential measurement. The following short discussion indicates the importance of placing a central electrode (Lor partitioning configuration) exactly midway in the sample. A number of ways of balancing the transient potential difference between the potential electrodes not caused by the energizing current are also treated.

Let us make the following postulates: (1) The potential difference between P^+ and P^- due to the energizing current (I) is $2a$. (2) The deviation of potential of the G electrode from zero, because its position is slightly off center, is d . (3) G is nearer to P^+ , so it has the same sign as P^+ . (4) P^- has a slight transient or spontaneous potential $(+\epsilon)$ higher than P^+ . (5) The SP in postulate 4 is evenly distributed along the sample.



The signal at D comes direct from the potential electrodes, the signal at R is rectified.

Ap. Fig 6 Spontaneous potential balance & rectifying bridge

From the fifth assumption one obtains

$$P' @ = \frac{\epsilon}{2}, \quad P'' @ = \frac{\epsilon}{2}, \quad \text{and } G @ = \frac{d}{a} + \frac{\epsilon}{2},$$

and owing to the passage of current (I) in one direction,

$$P' @ = a, \quad P'' @ = a, \quad \text{and } G @ = d.$$

When current of the same intensity (I) passes in reverse direction, one obtains

$$P' @ = a, \quad P'' @ = a, \quad \text{and } G @ = d.$$

The quantity observed by the voltmeter will be unidirectional, and its magnitude can be shown to be

$$\left(a - \frac{\epsilon d}{2a}\right) + \left(d - \frac{\epsilon}{2}\right).$$

With the other pair of diodes, the deflection will be reversed and of the magnitude

$$\left(a + \frac{\epsilon d}{2a}\right) + \left(d + \frac{\epsilon}{2}\right).$$

Thus a ripple of amplitude $\left(d + \frac{\epsilon}{2}\right)$ or $\left(d - \frac{\epsilon}{2}\right)$ as the case may be, is superimposed on the signal. The signal itself will be increased on one side by an amount $\frac{\epsilon d}{2a}$ and decreased on the other side by the same amount, which is the departure of the SP of G from zero. Hence this shift will not produce error as long as both pairs of diodes are used every time; i. e., as long as deflection of the meter is observed in both directions.

Next, let the bucking potential be used to eliminate the ripple. If V' and V'' represent the potential differences between G and P' and between G and P'' respectively, it is easy to show that $V'' - V'$ equals $2\left(d - \frac{\epsilon}{2}\right)$. If that amount is tapped off the bucking circuit and subtracted from P'' , the separation between the two signals (left and

right) will be $2a - (d - \frac{\epsilon}{2}) \pm \epsilon$. That is, the signal is decreased, and the SP difference between the potential electrodes shows up as a ripple. On the other hand, if one attempts to eliminate the original ripple by connecting the voltmeter to P' and P'' (the same as for dc reading) and to balance the difference to zero (i. e., raise the potential of P' by ϵ), the resulting signal will be

$$2a \pm 2d.$$

Thus, the voltmeter would be measuring the actual signal ($2a$), as well as a ripple of amplitude (d) superimposed on it on each side. That ripple can be nullified by fixing the position of G so that it is electrically midway between P' and P'' .

It is thus shown arithmetically that the even distribution of the S. P. initially assumed to be present there, cannot affect the readings in the long run, if both pairs of diodes are used. If either pair is used by itself, the signal will suffer a dc increase, or decrease amounting to $\frac{\epsilon d}{2a}$.

Thus all the faults observed in the previous techniques have been eliminated. The thyratrons-diodes system supplies a square wave, except for a very short zero step, which is free from bounce. There is no need to synchronize the rectifying system with the energizing system. However, the following difficulties in the new system remained unsolved: (1) The resistances in the thyratrons circuit must be kept below a certain limit to provide the plate voltage required by the series-connected thyratrons. (2) When the thyratrons fire and become conducting, a large percentage of the plate voltage is applied to the sample, and consequently a very large current passes. Attempts to decrease the current by adding wing resistors to the sides of the sample does not solve the problem. The thyratrons stop firing when the resistance exceeds a certain limit. That limit is still too small to cut the energizing current to the range re-

quired (of the order of microamperes). The small current requirement could possibly be met, however, with a sample shunt. (3) No point in the sample can be grounded, because the whole system already has one ground (the common cathode); if the sample is also grounded, both of the lower thyratrons will be shorted. (4) The principal difficulty with this system is in recording the signal. The noise-to-signal ratio cannot be made small enough to measure reliably the signal caused by induced polarization. In addition, the silicon diodes are at the same time rectifying 60-cycle pickup as well as the signal under investigation. In view of these difficulties, rectification was abandoned in favor of measuring the ac polarization signal just as it comes off the potential electrodes, the conventional voltmeter being replaced by a cathode-ray oscilloscope.

The final system used is believed to be the most reliable of the several techniques; namely, the function generator and the oscilloscope combination. This system is discussed in the text.

APPENDIX III

Analytical Considerations of the Observed Signal

The phenomena studied and presented in this thesis are different from those studied by earlier investigators. The present study is concerned with what is essentially a charging effect, whereas the work of previous investigators centered around what is essentially a discharging or relaxation effect. The following considerations will emphasize this difference.

Let the time of half a cycle be T , and let time, (t) , be counted from the instant the current is turned on. Three factors are to be considered when making a calculation of the signal, (P) ; namely, the IR drop, (V) , the polarization potential difference, (v) , and the "relaxation" change of the polarization potential difference, (p) . If the simplest form of relaxation be assumed, the factor would be $e^{-\alpha t}$.

$$\text{At time } t = 0, \quad P = V,$$

$$\text{and at time } t = T, \quad P = V + v.$$

During the interval $T < t < 2T$, the previously induced potential is decaying, while in superposition another potential is being induced in the reverse direction, $-v$. So that at time

$$t = 2T, \quad P = -V - v + v e^{-\alpha T}, \text{ or}$$

$$P_{2T} = -V - v(1 - e^{-\alpha T}).$$

In a similar way,

$$P_{3T} = +V + v - v(1 - e^{-\alpha T})e^{-\alpha T} = +V + v(1 - e^{-\alpha T} + e^{-1\alpha T}).$$

Generally, then,

$$P_{(nT)} = (-1)^{n-1} \left[V + v \sum_{k=0}^{n-1} (-1)^k e^{-k\alpha T} \right].$$

where $P_{(nT)}$ is the peak value of the signal at the instant of reversing the energizing current.

The separation between peak to peak for any value of n , (i. e., after n reversals) would be

$$P_n = 2V + 2v \left[\sum_{k=0}^{n-1} (-1)^k e^{-k\alpha T} + \frac{1}{2} e^{-(n-1)\alpha T} \right].$$

$$P_{n+1} - P_n = 2v \left(\frac{1}{2} e^{-(n-1)\alpha T} - e^{-n\alpha T} \right),$$

$$\lim_{n \rightarrow \infty} (P_{n+1} - P_n) = 0.$$

Hence the series is convergent. This is actually a geometrical series whose common ratio is $r = -e^{-\alpha T}$, with an additional term $\frac{1}{2} r^{(n-1)}$. The summation of such a series is

$$S_n = a \frac{1 - r^n}{1 - r}.$$

$$S = \lim_{n \rightarrow \infty} S_n = \frac{a}{1 - r}, \text{ provided } |r| < 1,$$

and the additional term vanishes:

$$\lim_{n \rightarrow \infty} P_n = 2V + 2v/(1 + e^{-\alpha T}).$$

The summation factor $1/(1 + e^{-\alpha T})$ is the contribution due to the relaxation characteristic, whereas the term $2v$ is the induced polarization due to charging. The last relation shows that if enough time is allowed, eventually it is possible, for all practical purposes, to read the actual polarization signal ($2v$).

If the frequency is varied, other values of $2v$ are obtained (on the assumption that the miniature batteries generated in the sample continue to charge). Hence, by varying the frequency, the charging curve is determined as a function of time from a plot of the values of $2v$ against time.

APPENDIX IV

Detailed Tables of Selected Data*

The data presented in Table F were taken before introducing the cancelling modification into the measuring technique, i.e., without cancelling the relatively undesirable 90 percent of the signal. The table shows a comparison between the response of dune sand (naturally occurring composition) and that of the same sand depleted of some of its magnetic components. In the first case, different current densities were applied, ranging from 3 to 14 microamp. The resistance does not show dependence on current density. The larger polarizability indicated for smaller currents probably reflects current-electrode polarization.

The data in these tables are plotted in Figure 11.

Table A. Arroyo Sand with Distilled Water, 680 K (W. R.)

| A _i | A ₁ | | A ₂ | | A ₃ | | A ₄ | | A ₅ | |
|----------------|----------------|---------|----------------|---------|------------------|---------|----------------|---------|----------------|---------|
| Material | 20-30 mesh | | 10-35 mesh | | Dried and reused | | Washed | | 35-65 mesh | |
| COL* | 50, 2 Meg. | | 50 | | 50 | | 80 | | 80 | |
| | P | D log P | P | D log P | P | D log P | P | D log P | P | D log P |
| 100 cps | 25.1 | 0.00516 | 56.3 | 0.01172 | 82. | 0.01305 | 189. | 0.00343 | 47.6 | 0.01436 |
| 10 | 25.4 | 0.00847 | 57.84 | 0.00936 | 84.5 | 0.02008 | 190.5 | 0.00567 | 49.2 | 0.02403 |
| 1 | 25.9 | 0.00995 | 59.1 | 0.02706 | 88.5 | 0.02154 | 193.0 | 0.00946 | 52. | 0.02594 |
| 0.1 | 26.5 | 0.00811 | 62.9 | 0.02678 | 93. | 0.01379 | 197.25 | 0.01189 | 55.2 | 0.00625 |
| 0.01 | 27. | | 66.9 | | 96. | | 202.25 | | 56.0 | |
| I μa | 2.4 | | 11.8 | | 12 | | 11.6 | | 11.8 | |
| R KΩ | 11.22 | | 6 | | 8 | | 17.5 | | 4.8 | |
| % change | 7.53 | | 18.8 | | 17.1 | | 7.3 | | 17.6 | |

Table B. Builders Sand 20-100 mesh. Effect of Current density and of Salinity

| B _i | B ₁ | | B ₂ | | B ₃ | | B ₄ | | B ₅ | | B ₆ | |
|----------------|--------------------------------|---------|----------------|---------|----------------|---------|----------------------------------|---------|----------------|---------|----------------|---------|
| Material | Original material, W. R. 250 K | | | | | | Nonmagnetic fraction W. R. 680 K | | | | | |
| Water | Tap Water | | | | | | Distilled water | | Tap water | | 0.01-N NaCl | |
| GOL | maximum | | 45 | | 25 | | maximum | | maximum | | maximum | |
| | P | D log P | P | D log P | P | D log P | P | D log P | P | D log P | P | D log P |
| 100 cps | 340 | | 158.8 | | 31.5 | | 216.1 | | 126.8 | | 64.0 | |
| 10 | 343.5 | 0.00445 | 160.6 | 0.00490 | 31.8 | 0.00412 | 217.7 | 0.00321 | 127.4 | 0.00205 | 64.32 | 0.00217 |
| 1 | 345.5 | 0.00253 | 161.8 | 0.00323 | 32.1 | 0.00408 | 219.55 | 0.00367 | 128. | 0.00204 | 64.6 | 0.00188 |
| 0.1 | 347.7 | 0.00180 | 162.6 | 0.00214 | 32.25 | 0.00202 | 221.35 | 0.00355 | 128.6 | 0.00203 | 64.8 | 0.00135 |
| 0.01 | 348 | 0.00072 | -- | 0.00163 | -- | 0.00300 | 223.1 | 0.00342 | 129.2 | 0.00202 | 64.99 | 0.00127 |
| I μa | 33.5 | | 17 | | 3.1 | | 11.35 | | 11.8 | | 12 | |
| R KΩ | 10.4 | | 9.6 | | 10.4 | | 19.5 | | 11 | | 5.4 | |
| % change | 2.34 | | 2.78 | | 3.33 | | 3.25 | | 1.9 | | 1.53 | |

| B _i | B ₇ | | B ₈ | |
|----------------|---------------------------------|---------|--------------------------|---------|
| Material | Magnetically separable fraction | | | |
| Water | 0.01-N NaCl solution | | | |
| GOL | 80, 2.7 Meg | | 15 hr later 60, 2 Meg | |
| | P | D log P | P | D log P |
| 100 cps | 21.5 | | 21.65 | |
| 10 | 21.8 | 0.00602 | 21.9 | 0.00498 |
| 1 | 22.12 | 0.00633 | 22.1 | 0.00395 |
| 0.1 | 22.4 | 0.00546 | 22.3 | 0.00391 |
| 0.01 | -- | 0.00465 | -- | 0.00428 |
| I μa | 2.9 | | 3.3 | |
| R KΩ | 7.8 | | 6.5 | |
| % change | 5.31 | | 4.02 | |

* Function-generator output level.

Table C. Demineralized Sand Plus Pyrite (finer than 100 mesh)

Effect of Pyrite Content, Using Distilled Water.

| C _i | C ₁ | | C ₂ | | C ₃ | | C ₄ | | C ₅ | |
|-----------------|----------------|---------|----------------|---------|----------------|---------|----------------|---------|--------------------------|---------|
| Material | 2.5% pyrite | | 5% pyrite | | | | 10% pyrite | | | |
| GOL | 80, 2 Meg | | 80, 2 Meg | | 80, 2.7 Meg | | 50, 680 K | | 50, 2 Meg | |
| | P | D log P | P | D log P | P | D log P | P | D log P | P | D log P |
| 100 cps | 40.9 | 0.00265 | 32.7 | 0.00132 | 19.55 | 0.00221 | 31.25 | 0.00139 | Too small to be reliable | |
| 10 | 41.15 | 0.00158 | 32.8 | 0.00106 | 19.65 | 0.00111 | 31.35 | 0.00069 | | |
| 1 | 41.3 | 0.00105 | 32.88 | 0.00158 | 19.7 | 0.00220 | 31.4 | 0.00138 | | |
| 0.1 | 41.4 | 0.00048 | 33.0 | 0.00066 | 19.8 | 0.00196 | 31.5 | 0.00069 | | |
| 0.01 | 41.48 | | 33.05 | | 19.89 | | 31.55 | | | |
| I _{μa} | 3.6 | | 3.6 | | 2.5 | | 7.6 | | | |
| R KΩ | 11.5 | | 9.2 | | 7.9 | | 4.2 | | | |
| % change | 1.42 | | 1.07 | | 1.71 | | .96 | | | |

Table D. Demineralized Sand Plus Pyrite (2.5% Pyritic Sand)

Effect of Salinity and Size of Pyrite Grains

| D _i | D ₁ | | D ₂ | | D ₃ | | D ₄ | | D ₅ | | D ₆ | |
|-----------------|---------------------|---------|----------------|---------|-----------------|---------|----------------|---------|-----------------|---------|-----------------|---------|
| Material | Finer than 100 mesh | | | | | | 20-30 mesh | | | | | |
| Water | Tap water | | 9 hours later | | Distilled water | | 11 hours later | | Distilled water | | Distilled water | |
| GOL | 80, W.R. 680 K | | 80, W.R. 680 K | | 80, W.R. 2 meg | | 50, W.R. 680 K | | 80, W.R. 680 K | | 80, W.R. 2 meg | |
| | P | D log P | P | D log P | P | D log P | P | D log P | P | D log P | P | D log P |
| 100 cps | 89.1 | 0.00185 | 84.7 | 0.00154 | 40.9 | 0.00265 | 62.0 | 0.00175 | 137.2 | 0.00347 | 43.65 | 0.00347 |
| 10 | 89.48 | 0.00155 | 85.0 | 0.00102 | 41.15 | 0.00158 | 62.25 | 0.00104 | 138.3 | 0.00219 | 44.0 | 0.00295 |
| 1 | 89.8 | 0.00144 | 85.2 | 0.00087 | 41.3 | 0.00105 | 62.4 | 0.00035 | 139.2 | 0.00281 | 44.3 | 0.00245 |
| 0.1 | 90.1 | 0.00145 | 85.37 | 0.00066 | 41.4 | 0.00048 | 62.45 | 0.00021 | 139.92 | 0.00093 | 44.55 | 0.00048 |
| 0.01 | 90.4 | | 85.5 | | 41.48 | | 62.48 | | 140.2 | | 44.6 | |
| I _{μa} | 12 | | 12 | | 3.6 | | 6.7 | | 12 | | 3.9 | |
| R KΩ | 7.5 | | 7.13 | | 11.5 | | 9.3 | | 11.7 | | 11.5 | |
| % change | 1.35 | | 0.95 | | 1.42 | | 0.78 | | 2.19 | | 2.18 | |

Table E. Comparison of Magnetite and Pyrite

| E_i | E_1 | | E_2 | | E_3 | | E_4 | |
|-------------|----------------------------|---------|--------------|---------|--------------------------------|---------|---------------------|---------|
| Material | 5% magnetite 20-30 mesh | | | | 2.5% - 5% Pyrite 20-30 mesh | | Finer than 100 mesh | |
| GOL | 80,680 K | | 5 days later | | 80,680 K | | 80, 2 Meg. | |
| | P | D log P | P | D log P | P | D log P | P | D log P |
| 100 cps | 226.2 | | 152.8 | | 137.2 | | 32.7 | |
| | | 0.00306 | | 0.00227 | | 0.00347 | | 0.00132 |
| 10 | 227.8 | | 153.6 | | 138.3 | | 32.8 | |
| | | 0.00361 | | 0.00226 | | 0.00219 | | 0.00106 |
| 1 | 229.7 | | 154.4 | | 139.2 | | 32.88 | |
| | | 0.00433 | | 0.00224 | | 0.00281 | | 0.00158 |
| 0.1 | 232 | | 155.2 | | 139.92 | | 33 | |
| | | | | | | | | |
| 0.01 | 239.3 | | 155.95 | | 140 | | 33.05 | |
| | | | | | | | | |
| $I \mu a$ | 11.4 | | 11.6 | | 12 | | 3.6 | |
| R $K\Omega$ | 21. | | 13.2 | | 11.7 | | 9.2 | |
| % change | 5.8 | | 2.72 | | 2.19 | | 1.07 | |

Table F. Dune sand (50-120 mesh in tap water)

| F_i | F_1 | | F_2 | | F_3 | | F_4 | |
|-------------|----------------------|---------|-------|---------|-------|---------|--------------------|---------|
| Material | Original composition | | | | | | Partially depleted | |
| W. R. | 680 K | | 680 K | | 680 K | | 250 K | |
| GOL | maximum | | 40 | | 30 | | 40 | |
| | P | D log P | P | D log P | P | D log P | P | D log P |
| 100 cps | 110 | | 46.05 | | 23.4 | | 119.4 | |
| | | 0.00899 | | 0.01163 | | 0.01569 | | 0.01007 |
| 10 | 112.3 | | 47.3 | | 24.3 | | 122.2 | |
| | | 0.00897 | | 0.01357 | | 0.01685 | | 0.01502 |
| 1 | 114.65 | | 48.8 | | 25.25 | | 126.5 | |
| | | 0.00473 | | 0.00881 | | 0.00767 | | 0.00684 |
| 0.1 | 115.9 | | 49.8 | | 25.7 | | 128.4 | |
| | | 0.00150 | | 0.00863 | | 0.01820 | | 0.01072 |
| 0.01 | 116.3 | | 50.8 | | 26.6 | | -- | |
| | | | | | | | | |
| $I \mu a$ | 13.8 | | 5.4 | | 3.1 | | 13.3 | |
| R $K\Omega$ | 8.4 | | 9.4 | | 8.6 | | 9.6 | |
| % change | 5.83 | | 10.3 | | 14.34 | | 10.23 | |

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