

T-899

MEASUREMENT OF INDUCED POLARIZATION
WITH VARIATION OF WATER SATURATION
IN CORE SAMPLES

By
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ABSTRACT

A study of induced polarization exhibited by core samples containing disseminated metallic sulphides was made with respect to variation of water saturation in these cores. The cores tested exhibited three ways in which polarizability vary with decrease of water saturation, designated type I, type II, and type III. This variation may be due to the differences in the properties of the cores, such as metallic sulphide content, porosity, and the way the metallic sulphide particles are disseminated. If the core is represented by a simple resistor-capacitor circuit, the polarizability appears to be proportional to the product of resistance and capacitance, and on this basis a discussion of the variation of polarizability with water saturation is presented.

In addition, the relation between induced polarization and charging current and excitation time was studied. The results of these studies show that there is a uniform

increase of induced polarization with increase of current and excitation time, which are in accordance with the results obtained by previous workers.

INTRODUCTION

The object of this thesis is to investigate the effect of water saturation on induced polarization potential observed in core samples. Induced polarization is a phenomenon whereby a transient voltage is observed when an applied current is interrupted. The magnitude of induced polarization can be expressed by the area under the transient-voltage curve in terms of millivolt-seconds. Induced polarization is exhibited by many materials, among which are, metallic ores and graphite grains embedded in some kind of rock such as granite, sandstone, or limestone, sandstones in which the sand grains are coated with a thin film of clay particles, and some limestones (Henkel and Van Nostrand, 1957, p. 359). Pure quartz sandstones will give rise to only slight induced polarization. There seem to be numerous factors that effect induced polarization not all of which are known.

Conrad Schlumberger (1930), was the first worker to

observe induced polarization in the field. Bleil (1953, p. 641) stated that induced polarization is generated instantaneously at the interface between different conducting media where there is a change in mode of conduction from ionic to electronic or vice versa. This statement was also supported by Henkel and Van Nostrand (1957, p. 359), who also stated that induced polarization is a surface phenomenon, the polarization of the metal depending largely on the nature of its surface. A clean surface does not polarize nearly as much as the one that is covered with corrosion. The induced polarization also depends on composition. Vacquier et al (1957, p. 661) and Henkel and Van Nostrand showed by laboratory experiments that I.P. is proportional to the magnitude and duration of the charging current.

A typical record of induced polarization and potential drop across a core sample observed in the laboratory is shown in Figure 1. The ratio of the magnitude of induced polarization in millivolt-seconds to the potential drop across the core sample is defined as polarizability by Vacquier et al (1957, p. 665). The polarizability will be the quantity used to express the relationship between induced polarization and water saturation in this thesis.

SANBORN Recording Paper

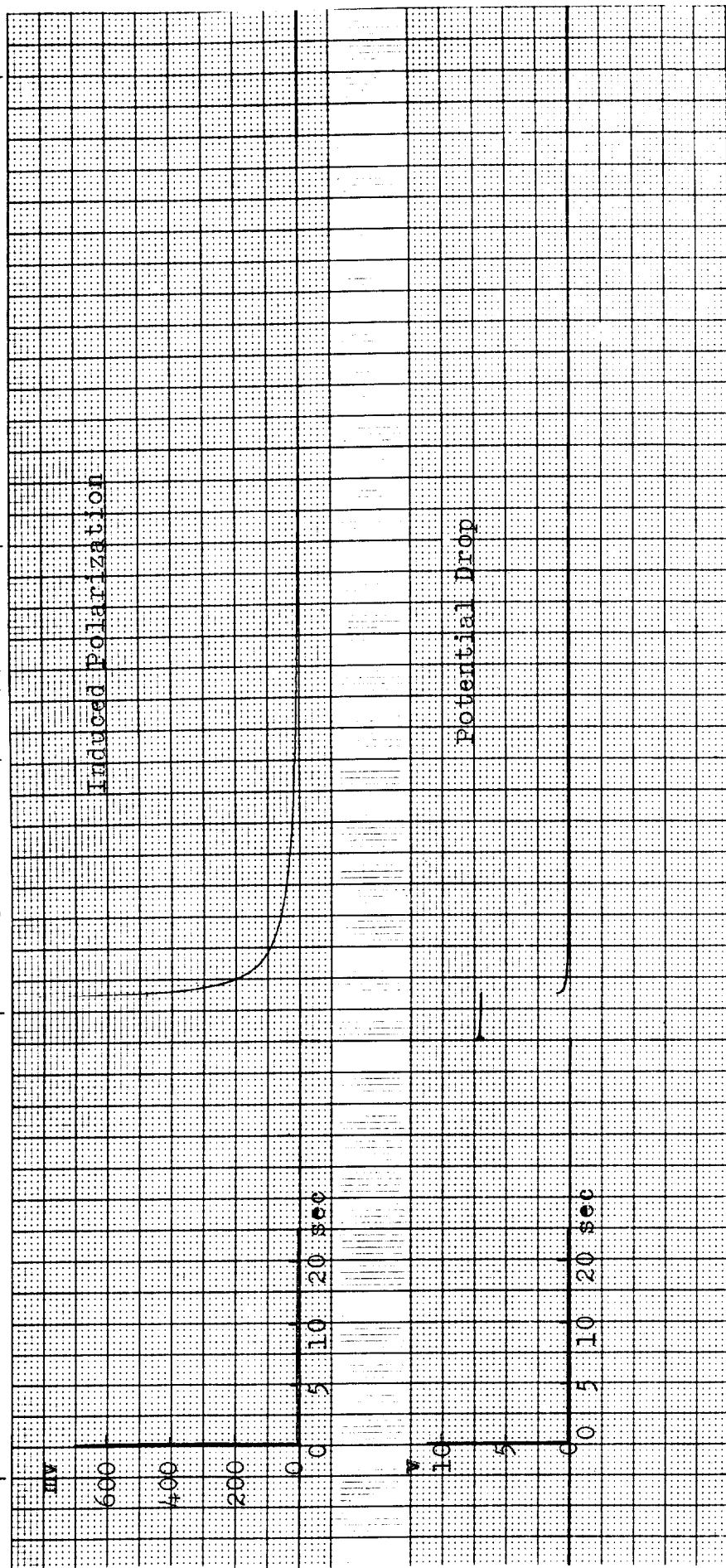


Fig. 1 (a).

A typical record of induced polarization and potential drop across a core.

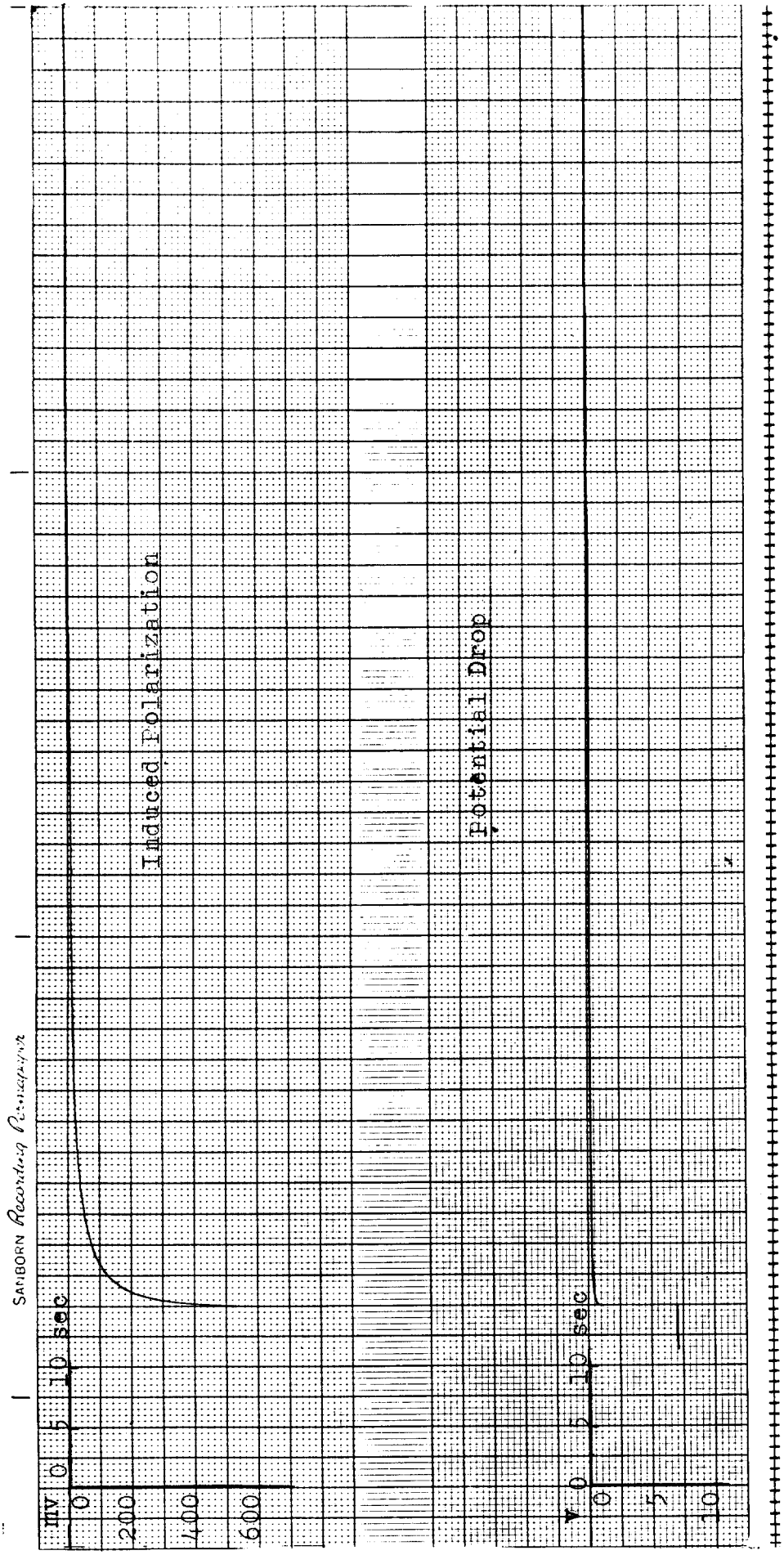


Fig. 1 (b).

Record of induced polarization and potential drop when the signal is reversed.

EXPERIMENTAL WORK

Experimental work was conducted on ten core samples, four of which contained iron pyrite with small amounts of chalcopyrite embedded in either quartz monzonite porphyry or granodiorite porphyry; the rest contained iron pyrite in limestone. The core samples were first saturated with water, and then desaturated stage by stage. At each stage of desaturation, the induced polarization was measured for a series of excitation times. For each core, the induced polarization was also measured with variation of charging current.

Saturation of Cores

The core samples to be investigated were dried in an oven at about 250 C for about 9 to 10 hours to drive out any water originally contained in the cores. They were then weighed on a chemical balance. After weighing, they were saturated by placing in a beaker of water under a bell

jar which was connected to a vacuum pump and evacuating the air from the cores. After saturation, the core samples were weighed again to give the amount of water contained in these cores.

To preserve the core samples at a constant water saturation, they were placed on a porcelain platform in a dessicator-type jar filled with water to a level a little below the platform, and the lid was sealed with grease. This way the humidity of the core would not vary more than two percent.

To vary the water saturation, the core samples were left at room temperature and room humidity from several minutes to several hours. The cores could lose up to 40% of the water content depending on the time exposed to the air. After each limited drying period, the cores were reweighed to determine the water content remaining. The induced polarization was measured at each stage of desaturation. The desaturation was very fast for the first 30 minutes, after which it proceeded more slowly. Many hours are required to reduce the water content by 10% when the core is below 40% water saturation.

The remaining 40% of the moisture was removed by heating the core slowly in an oven from several minutes to several hours. To keep the water content constant

after each desaturation, the core samples were placed in the controlled-humidity jar. Only when it was necessary to determine the amount of water in the core and to measure the induced polarization was the core removed from the jar.

Description of Sample Holder and Electrodes

The sample holder is shown in Figure 3. The electrodes consist of two nearly semicircular copper plates and a thin copper strip 1/10 inch wide mounted on a circular wooden plate as shown in Figure 2. The copper strip was separated from the two semicircular copper plates by a 1/10-inch gap of insulating material. The two nearly semicircular plates serve as current electrodes and the strip serves as a potential electrode.

Two electrode assemblies of the type shown in Figure 2 were used; one was fixed whereas the other was mounted with a screw arrangement so that it could be moved forward and backward to fit the length of the core, as shown in Figure 3. When the induced polarization was measured, the core sample was placed tightly in contact with these electrodes with blotting paper moistened with distilled water placed between the core and the electrode surfaces.

Measurement of Induced Polarization

For the measurement of induced polarization, the

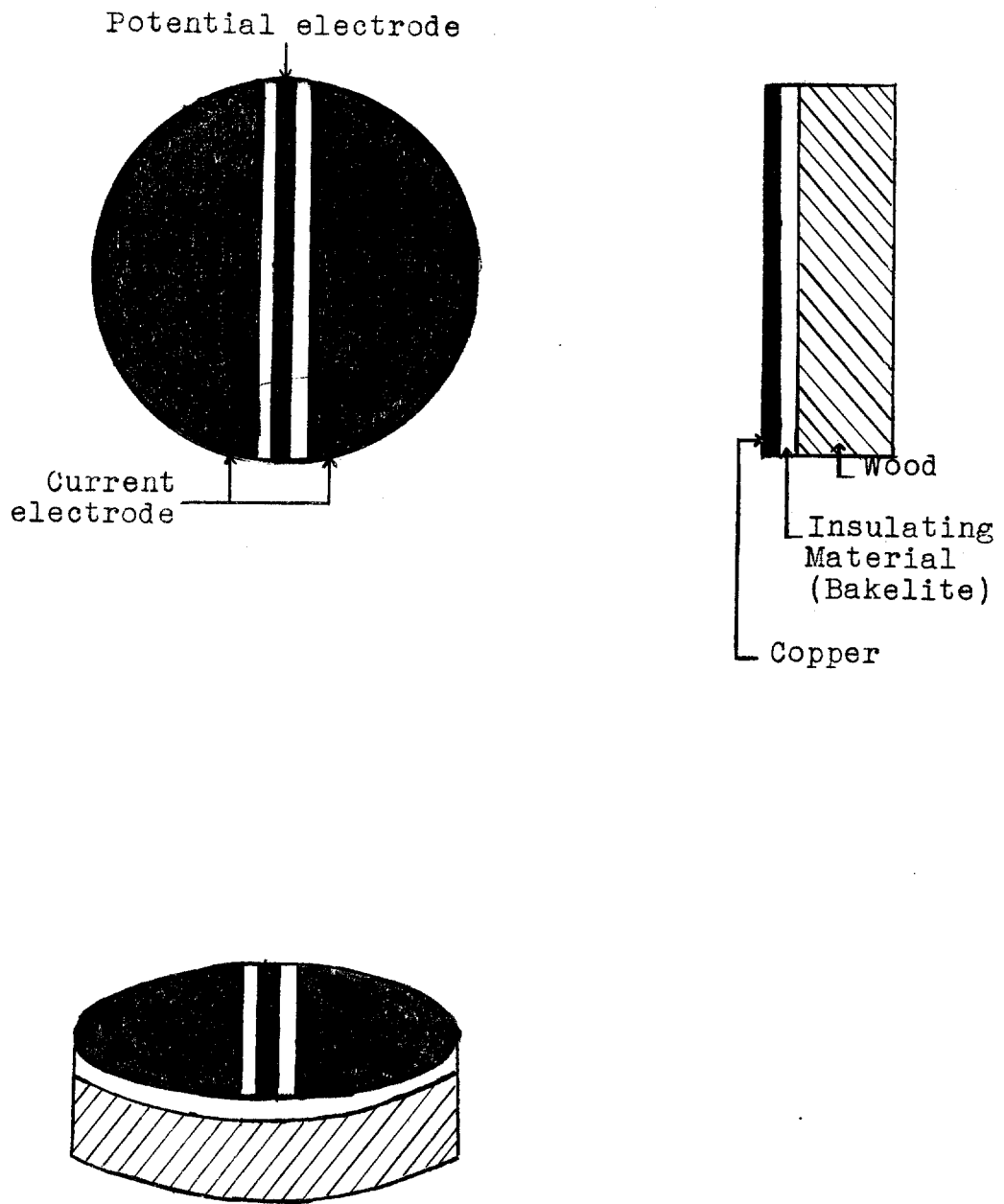


Fig. 2.
Diagram of electrode used for the measurement of
induced polarization.

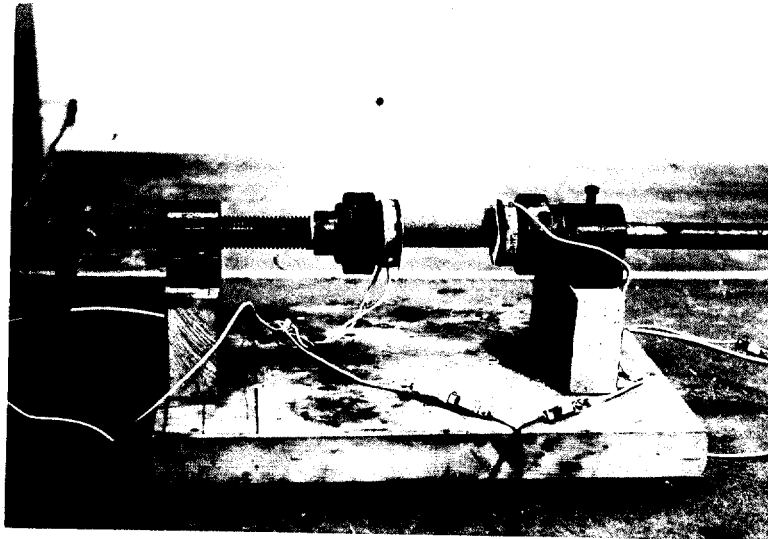


Fig. 3.

Sample holder for the measurement of
induced polarization.

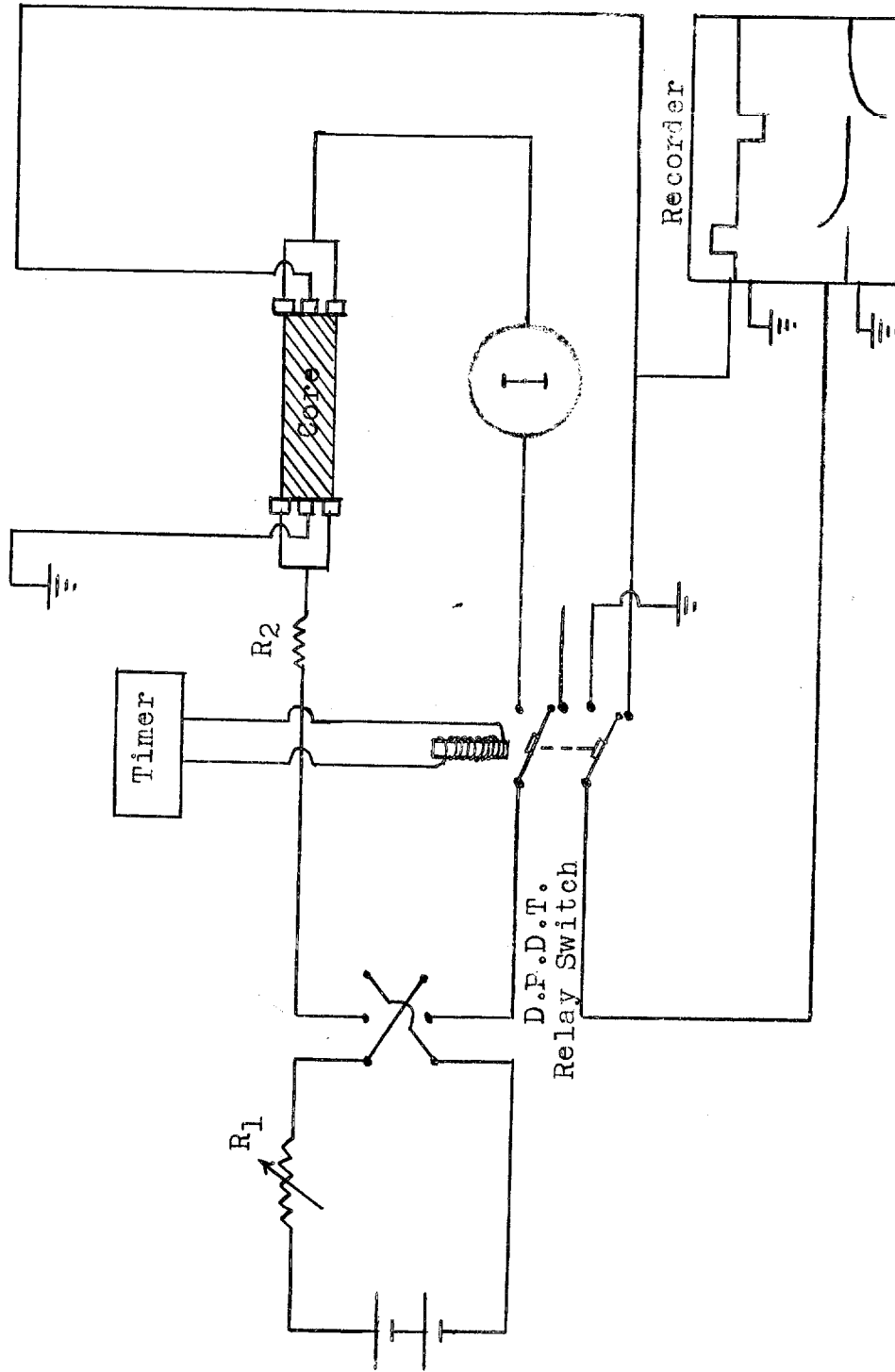


Fig. 4.

Circuit diagram for the measurement of induced polarization

apparatus as shown in the circuit diagram was set up. Direct current, in the form of pulses, was applied to the core. The polarity of each alternate pulse was reversed by the use of a double-pole double-throw switch. The voltage source was a set of dry-cell batteries. The voltage applied to the system was 10 volts except when the induced polarization was measured as a function of current. For these measurements the voltage was varied between 1 and 60 volts by use of a variable resistor R_1 . Alternating current-pulses were used so that a cumulative polarization at the electrodes would not be produced. By working with the average of the positive and negative signals, it was possible to eliminate any natural potential difference between the electrodes (Henkel and Van Nostrand, 1957, p. 357). Three andesite core samples saturated with water were tested for I.P.. Even though the andesite core samples will not exhibit I.P., if electrode polarization is pronounced, a transient voltage should appear. But no transient voltage was observed. Therefore electrode polarization must be very small and negligible for the electrodes used in this experiment. Henkel and Van Nostrand (1957, p. 357) in their laboratory experiments had tried nonpolarizing

electrodes but stated that they gave the same results as the copper electrodes which were more convenient to use. The separation between potential and current electrodes used in their experiment, however, is much larger than the separation used in this experiment.

The resistance R_2 has a value of 1500 ohms. The timer (Heathkit Enlarger Timer Model ET-1) operated an AC 115-volt, double-pole double-throw relay so that the excitation time could be varied from 1 second to 60 seconds. The transient voltage-decay curve was separated from the steady-state voltage record by use of one of the poles of the double-pole double-throw relay. The potential electrodes were connected to the relay so that, when the current was flowing through the core, the I.P. channel of the recorder was short circuited; and when the current was not flowing through the circuit, this channel was connected to the potential electrodes. In this way, the recorder registered only the voltage-decay curve and not the potential drop across the core. The potential drop across the core was recorded on a separate channel, as shown in Figure 1.

The recorder used was a dual-channel Sanborn recorder; the recorder was calibrated by using a known voltage input or by the internal calibration system standard to Sanborn recorders. Shielding of the core sample holder and the

relay was essential to eliminate 60-cycle pickup. Shielding was achieved by placing the sample holder and the relay in a wooden box lined with aluminum foil, and then grounding the aluminum linings.

A set of measurements was made by setting the timer, switching the double-pole double-throw switch, to one side and switching the timer on. The recorder was operated at a paper speed of 2.0 mm per second during this procedure. After the induced polarization was recorded, the polarity of the current and pickup electrode was reversed with the D.P.D.T. switch, and the measurement was repeated. This procedure gave an induced polarization record opposite in direction to the preceding one. The average of the magnitudes of the two was used in the interpretation. It was found that there was a difference of about 15% in the observed values of induced polarization.

As the magnitude of the induced polarization was expressed by the area under the voltage-decay curve, the area was determined by counting the millimeter squares under this curve. To save time and labor, an electrical analog integrator can be used to determine the area under the voltage-decay curve.

The resistance of the core was calculated from the value of the steady-state potential drop across the core

and the current. The resistivity was calculated by using the resistance and the geometry of the core. It is customary to express the relation between water saturation and resistivity in terms of resistivity index, which is the ratio of the resistivity of the core partially saturated to resistivity of that same core at 100% saturation. Resistivity indices for the cores were determined.

Result

Data for each core sample are presented at the end of the thesis. For each core sample, five graphs are plotted as follows:

1. Induced polarization in millivolt-seconds as a function of current in milliamperes.
2. Polarizability in millivolt-seconds per volt as a function of current in milliamperes.
3. Polarizability in millivolt-seconds per volt as a function of excitation time in seconds, for various stages of water saturations.
4. Resistivity index as a function of water saturation.
5. Polarizability in millivolt-seconds per volt as a function of water saturation, for a series of excitation times.

Only examples of graphs plotted are presented. On the graphs presented here, circles, crosses, triangles, and squares are used to represent data observed for separate cores.

The first curve for each core as shown in Figures 5(a), 5(b), and 5(c), shows that induced polarization varies linearly with the current. The second curve for each core as shown in Figures 6(a), 6(b), and 6(c) shows that polarizability increases very slightly with the increase of current. Polarizability, instead of I.P., was plotted as a function of excitation time and water saturation.

The third curve for each core shows the relationship between polarizability and excitation time for various degrees of water saturation, as shown in Figure 7. The relationship between resistivity index and water saturation for each core plotted on a logarithmic coordinate does not have the linear form which is generally accepted. The curve plotted here agrees with the results obtained by Licastro and Keller (1952, p. 19). According to Archie (1958, p. 51) and many other investigators, the resistivity index should increase as the water saturation decreases in the following manner:

$$I = S_w^{-n}$$

Where I is the resistivity index,

S_w is the water saturation, and

n is the saturation index.

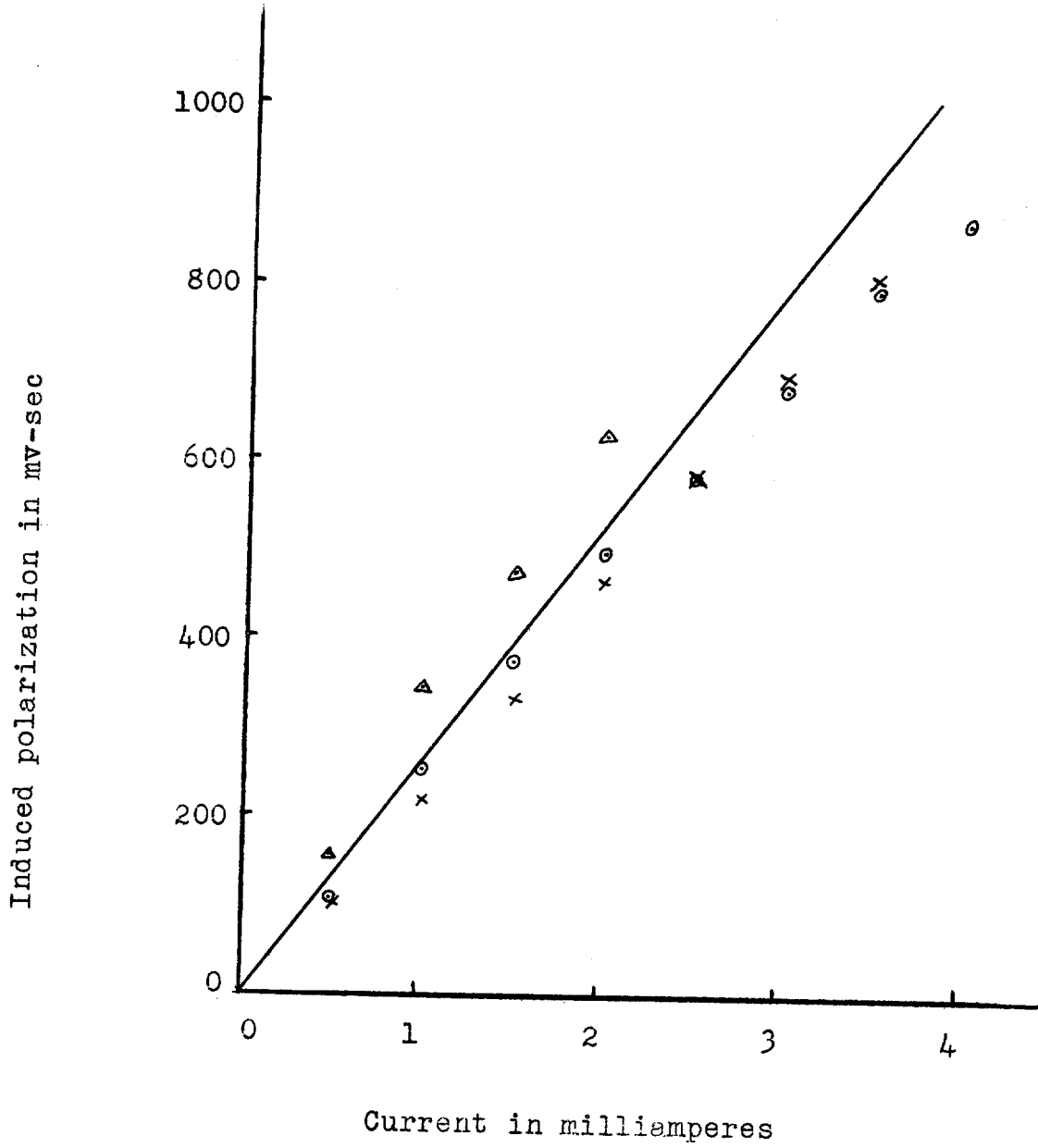


Fig. 5(a).

Induced polarization as a function of current exhibited by cores exhibiting type 1 curves

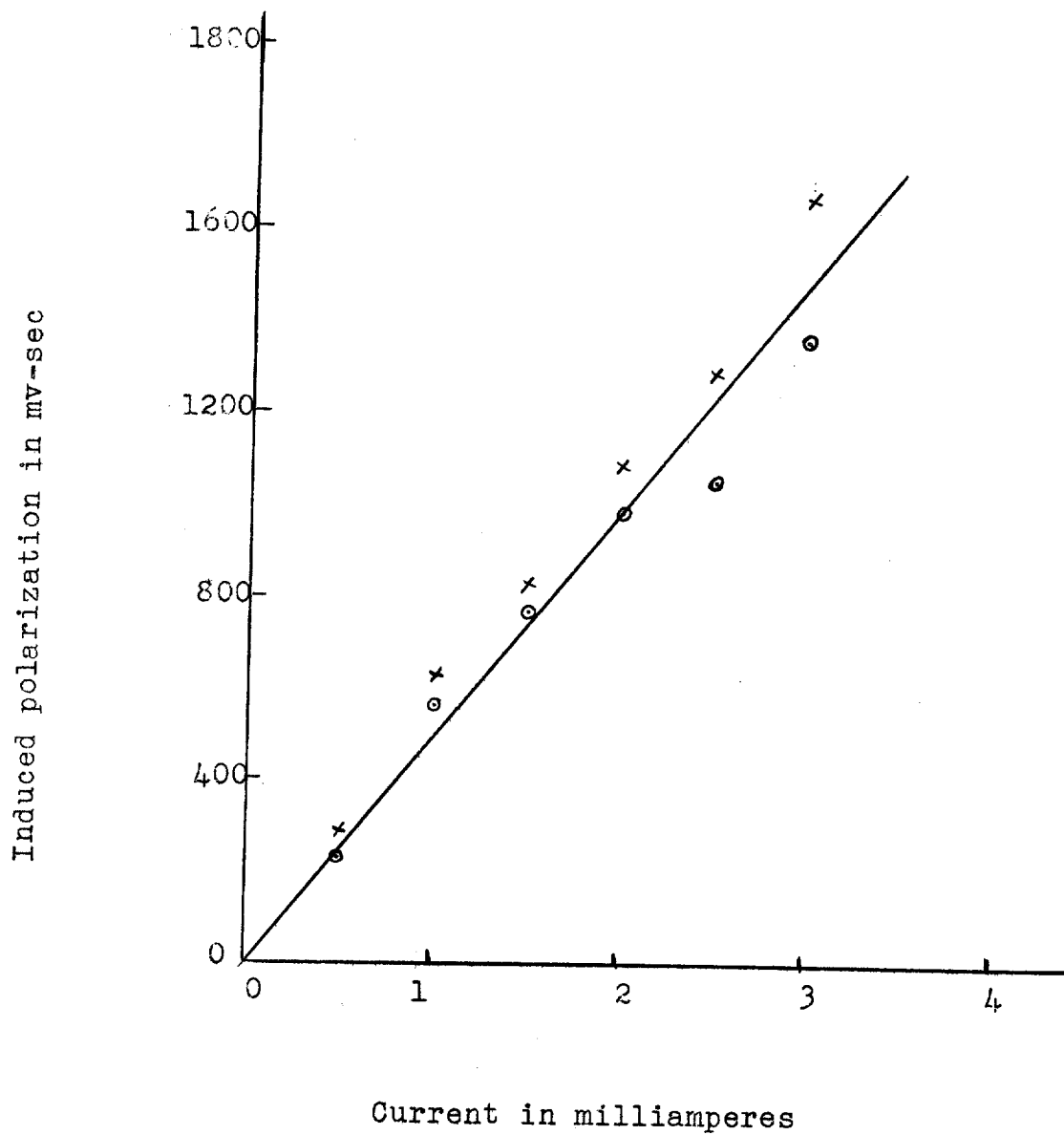


Fig. 5(b).

Induced polarization as a function of current exhibited by cores exhibiting type 11 curves.

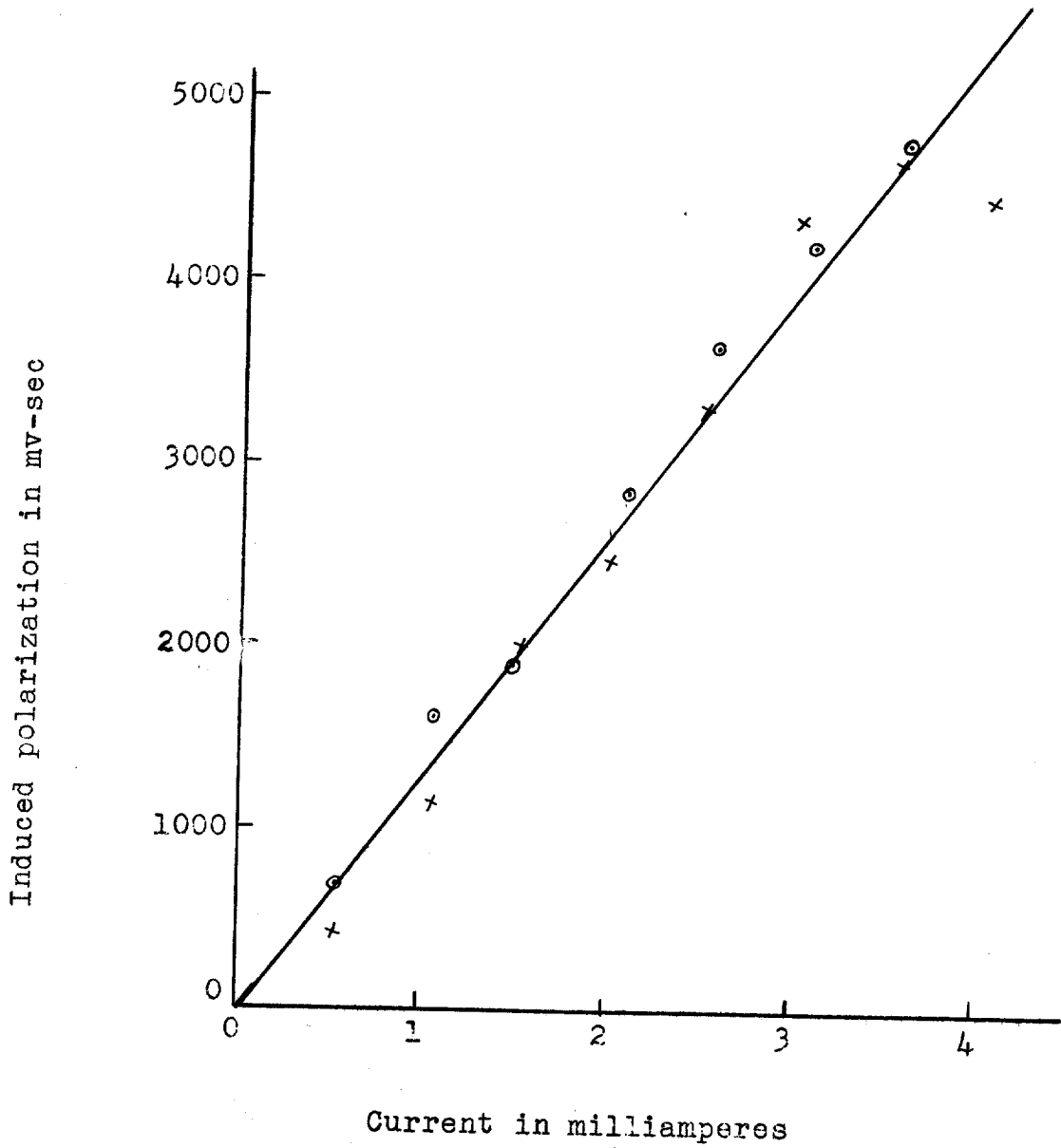


Fig. 5(c).

Induced polarization as a function of current exhibited by cores exhibiting type 111 curves.

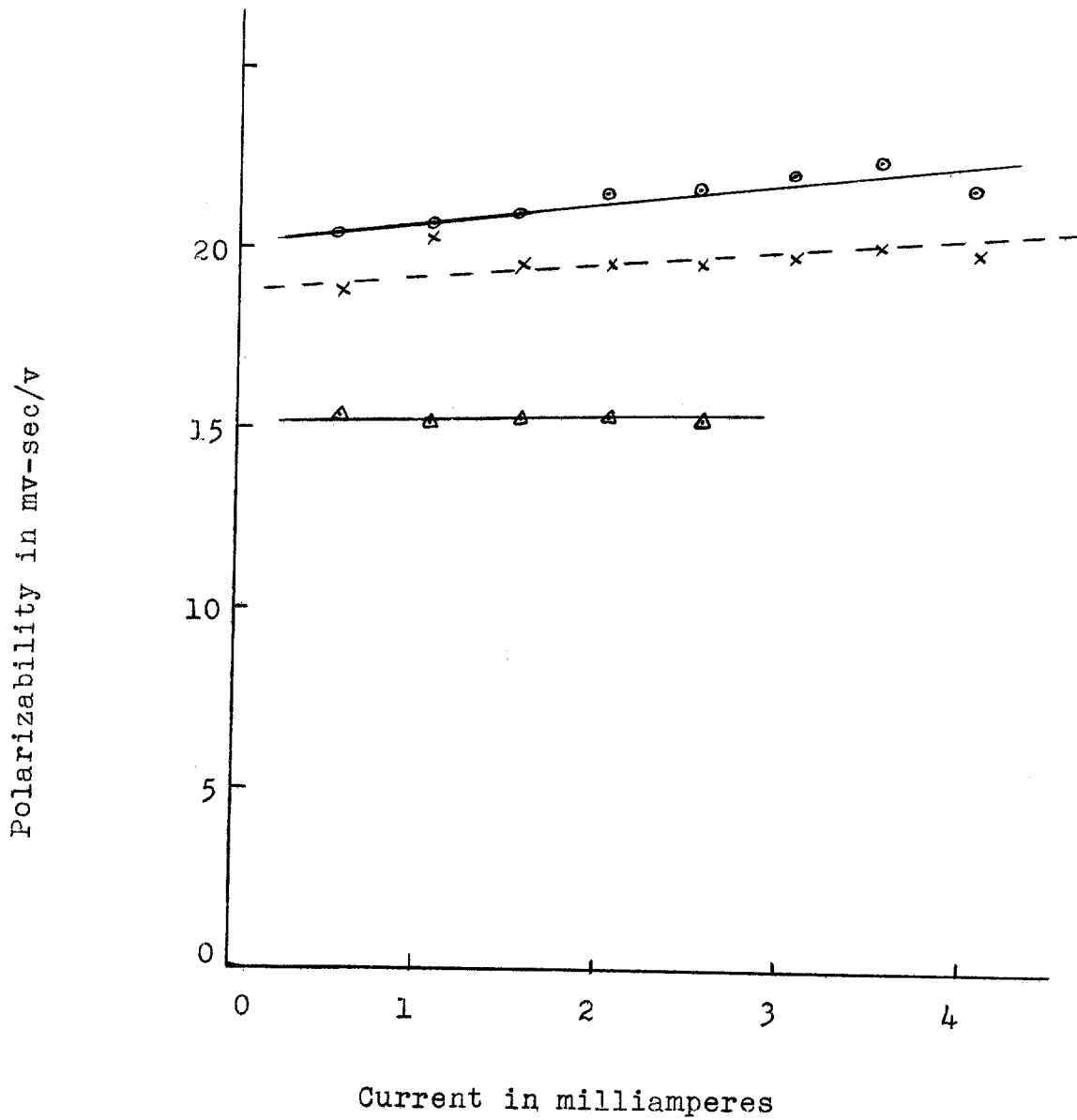


Fig. 6(a).

Polarizability as a function of current exhibited by cores exhibiting type 1 curves.

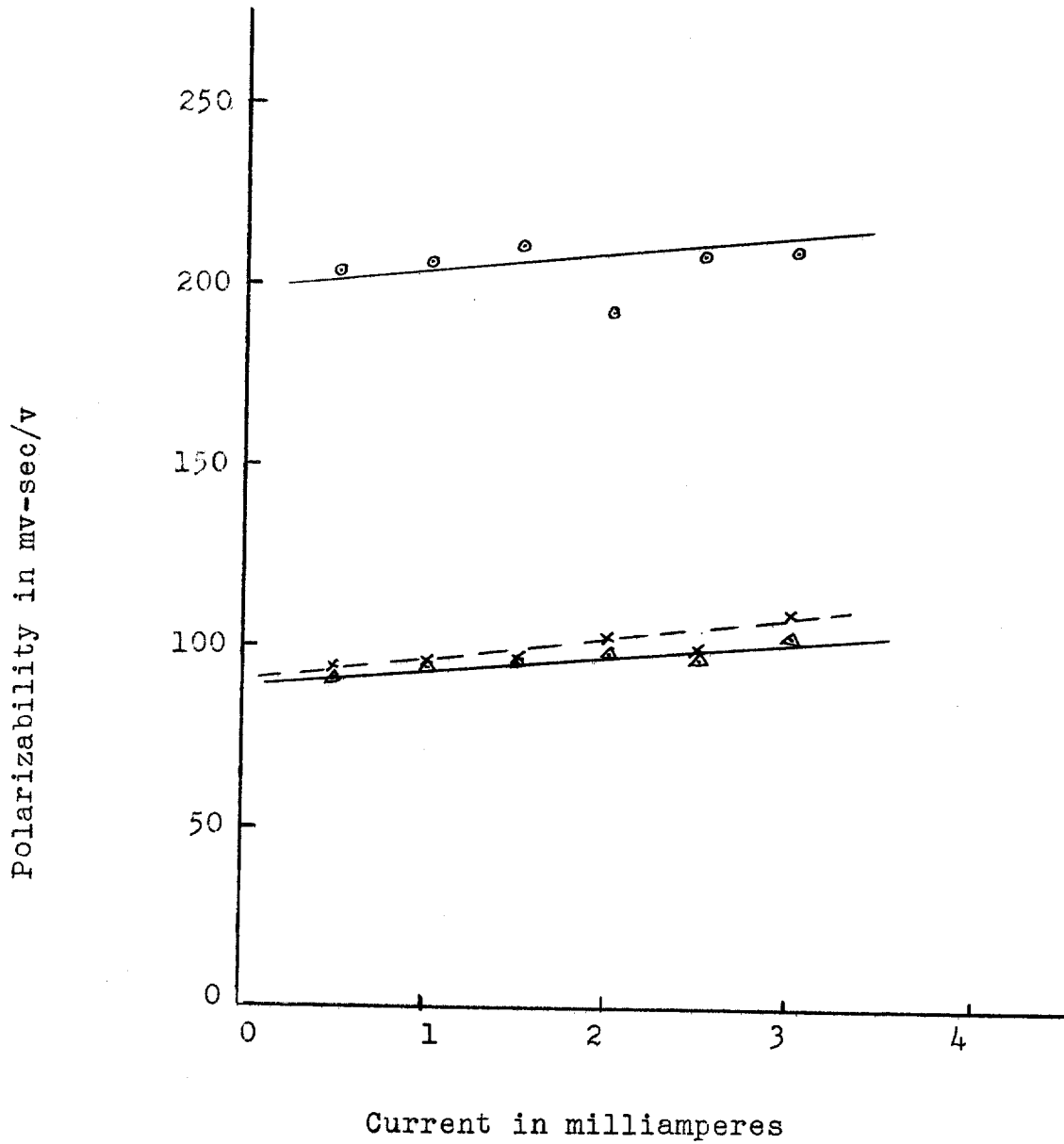


Fig. 6(b).

Polarizability as a function of current exhibited by cores exhibiting type 11 curves.

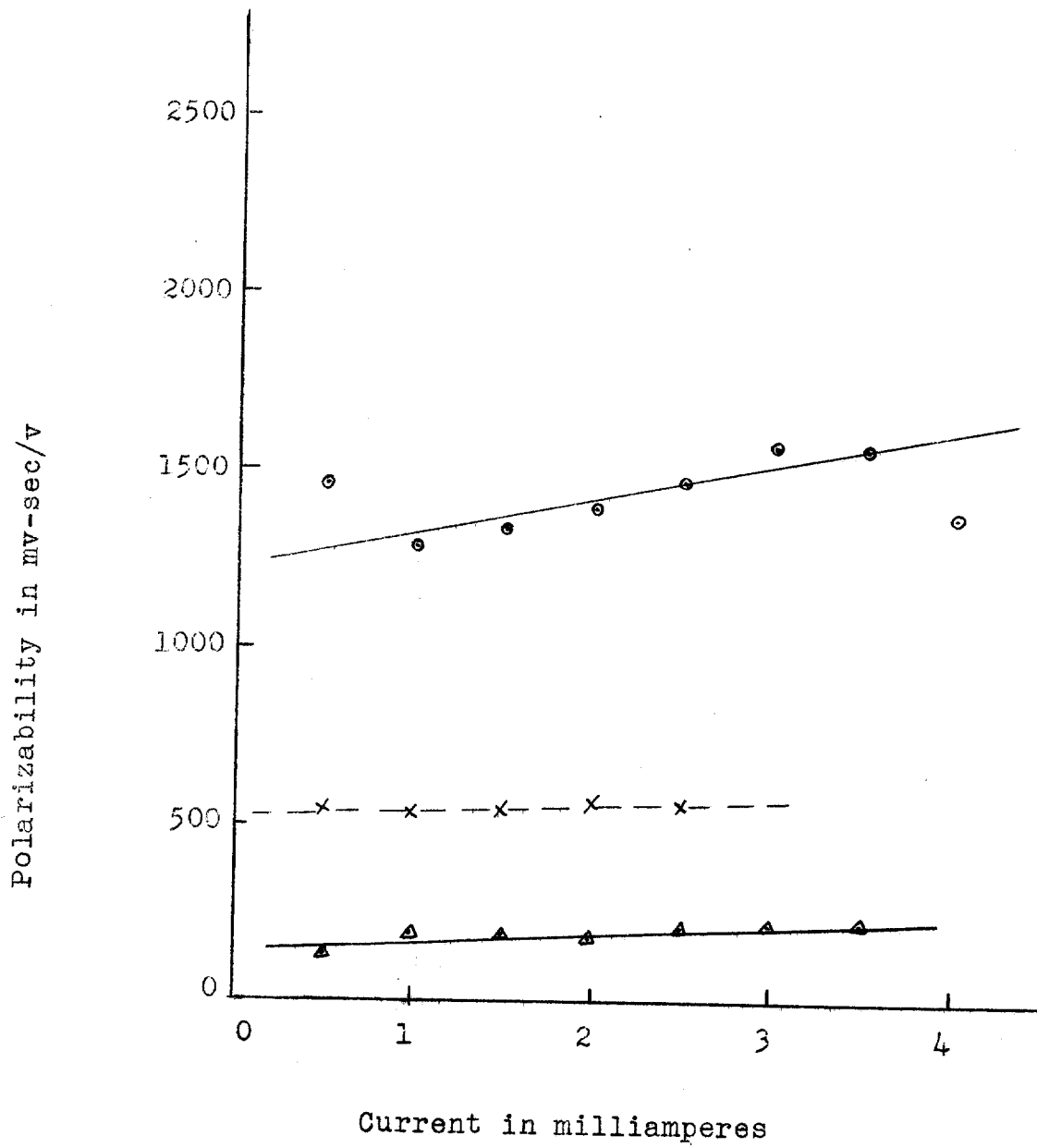


Fig. 6(c).

Polarizability as a function of current exhibited by cores exhibiting type 111 curves.

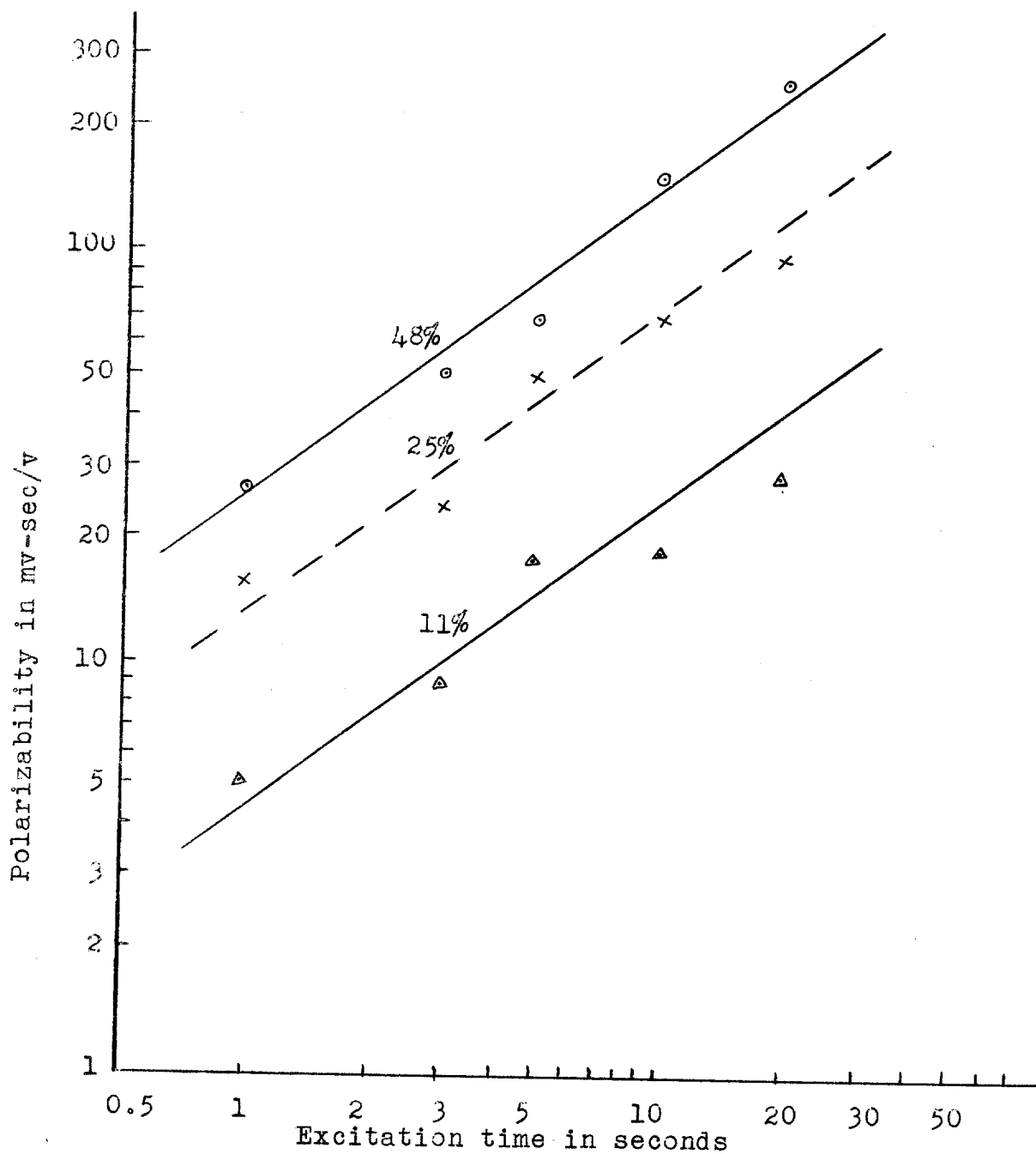


Fig. 7.

An example of polarizability as a function of excitation time for 3 stages of water saturations.

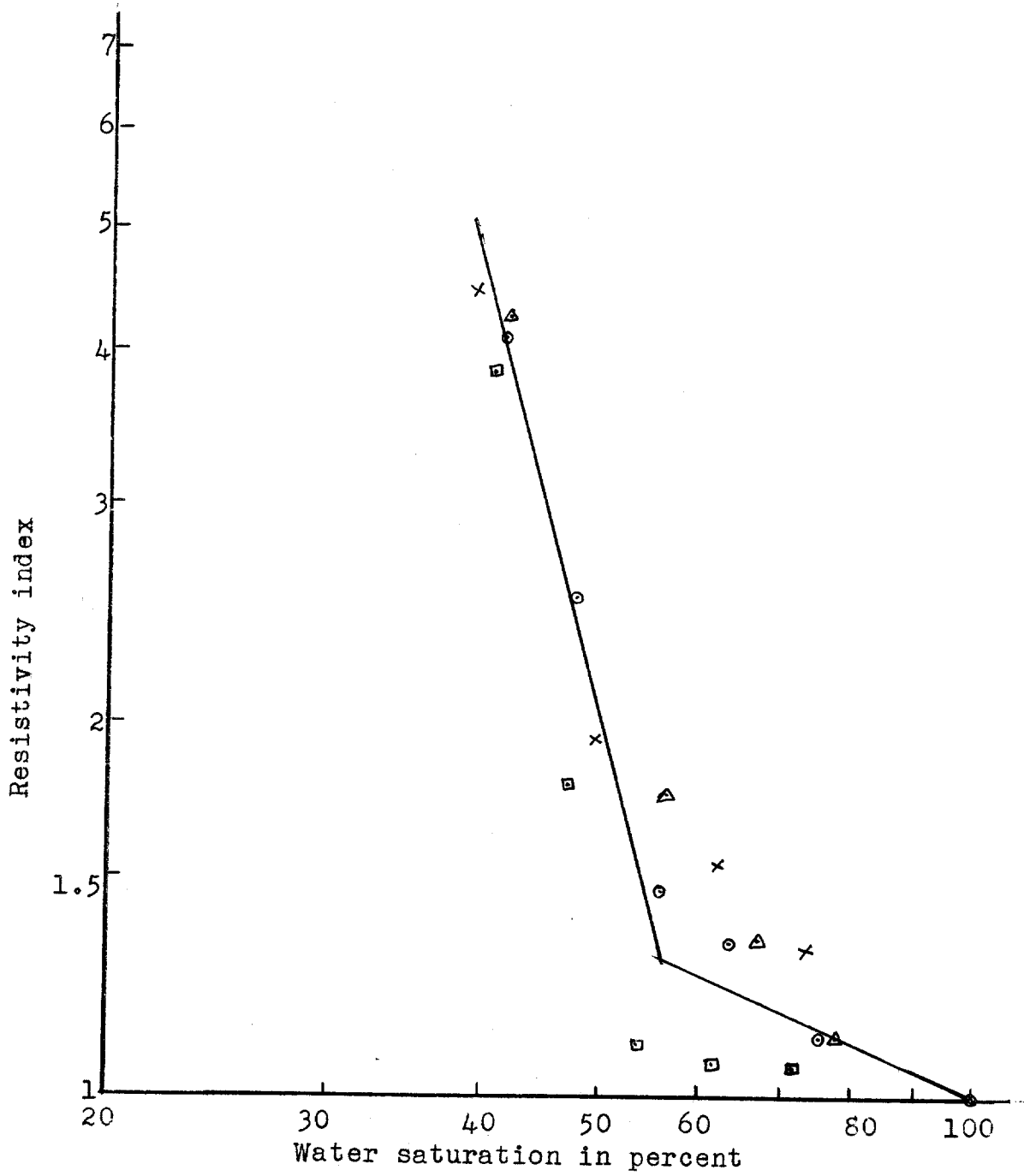


Fig. 8(a).

Resistivity index as a function of water saturation exhibited by cores exhibiting type 1 curves.

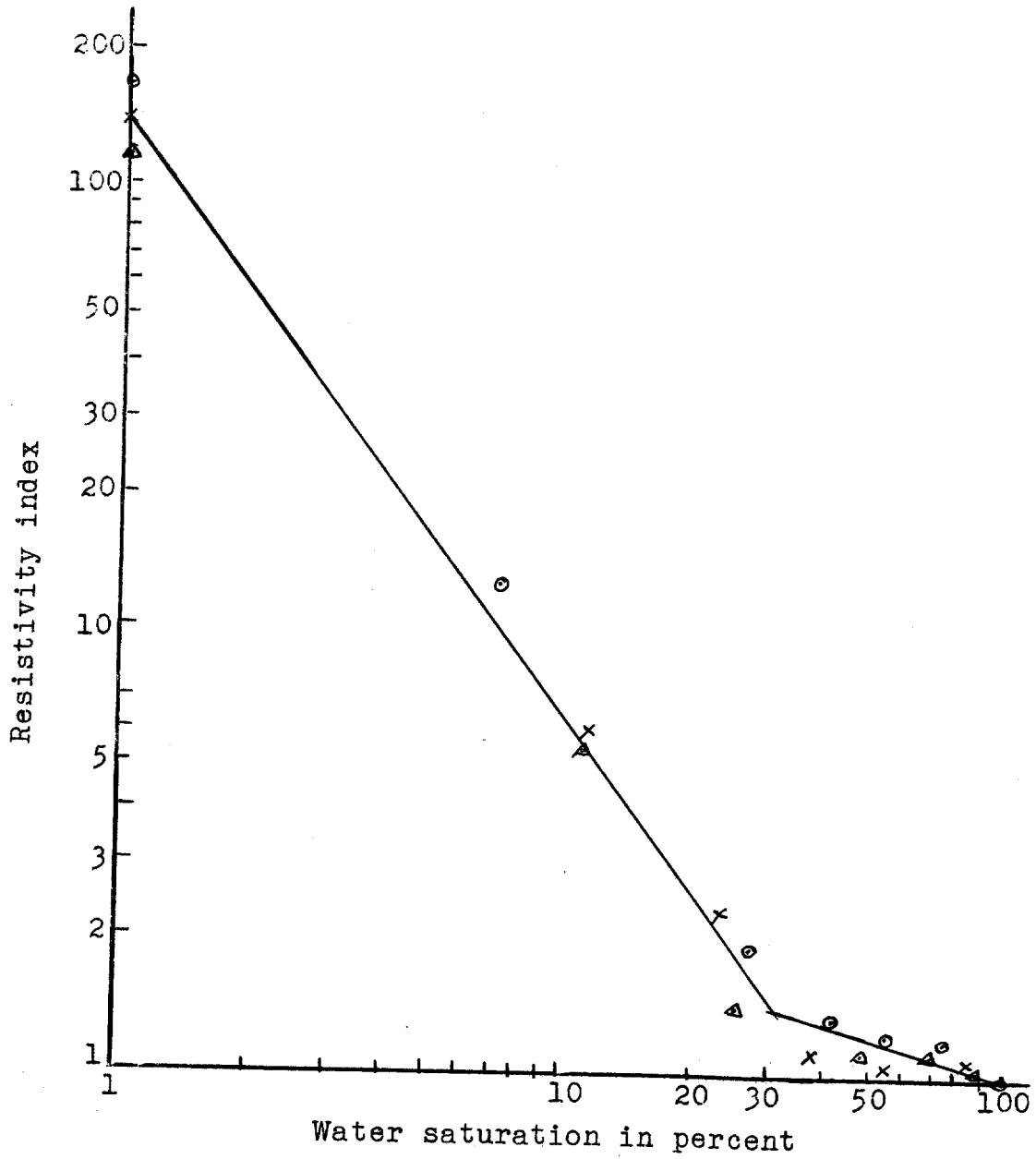


Fig. 8(b).

Resistivity index as a function of water saturation exhibited by cores exhibiting type 11 curves.

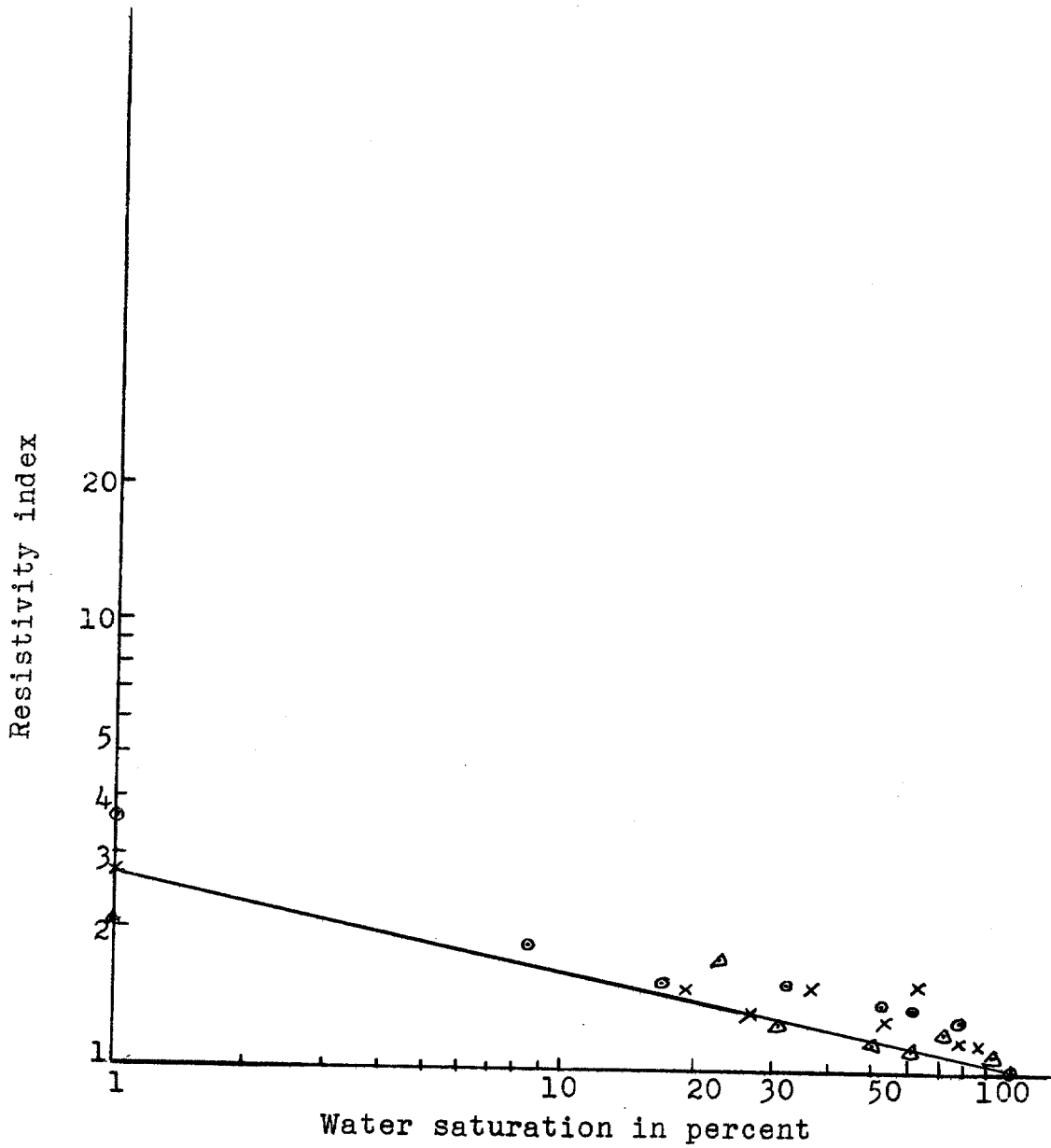


Fig. 8(c).

Resistivity index as a function of water saturation exhibited by cores exhibiting type III curves.

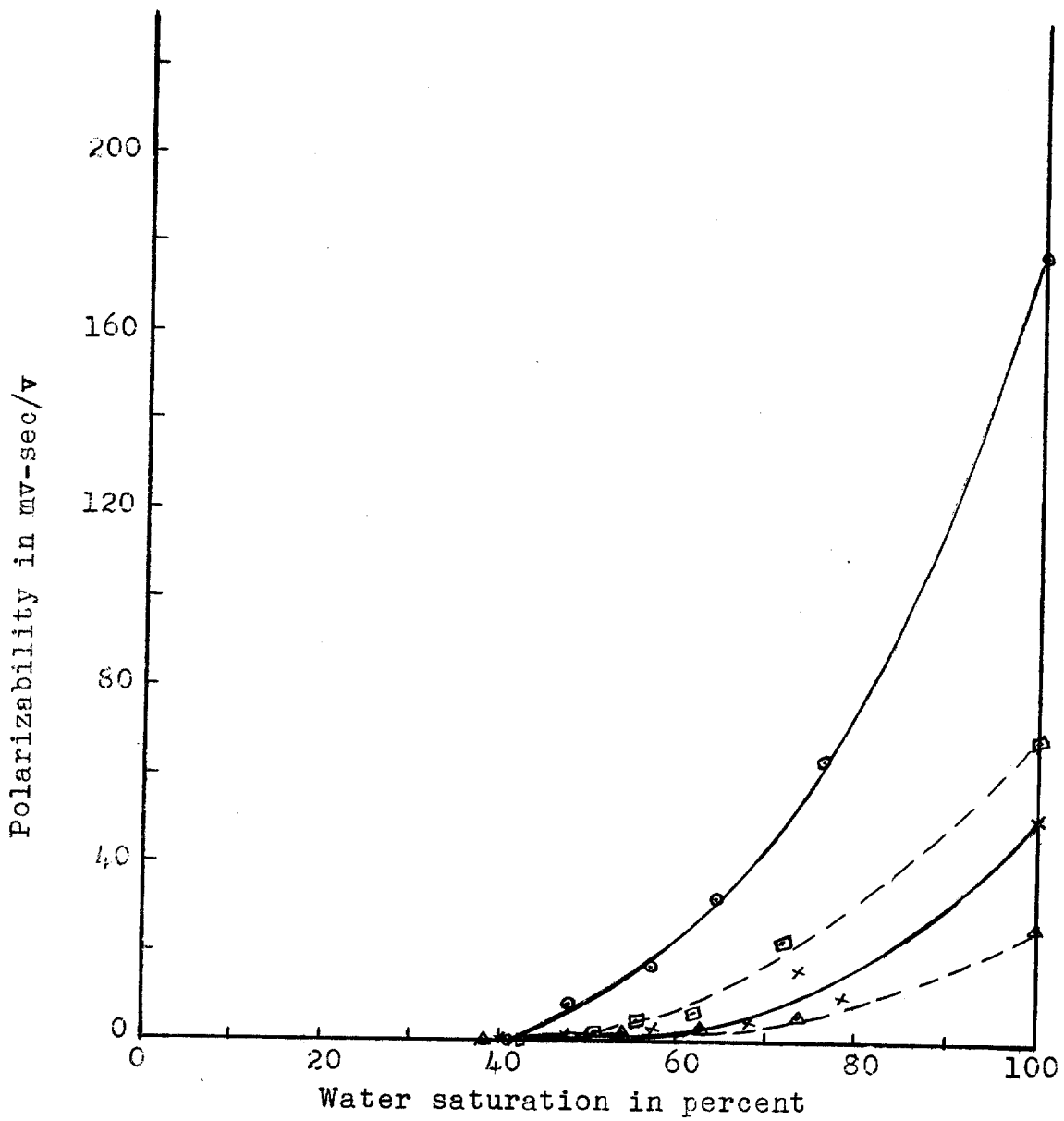


Fig. 9(a).

Type 1 curve.
Polarizability as a function of water saturation
for an excitation time of 20 seconds for 4 cores.

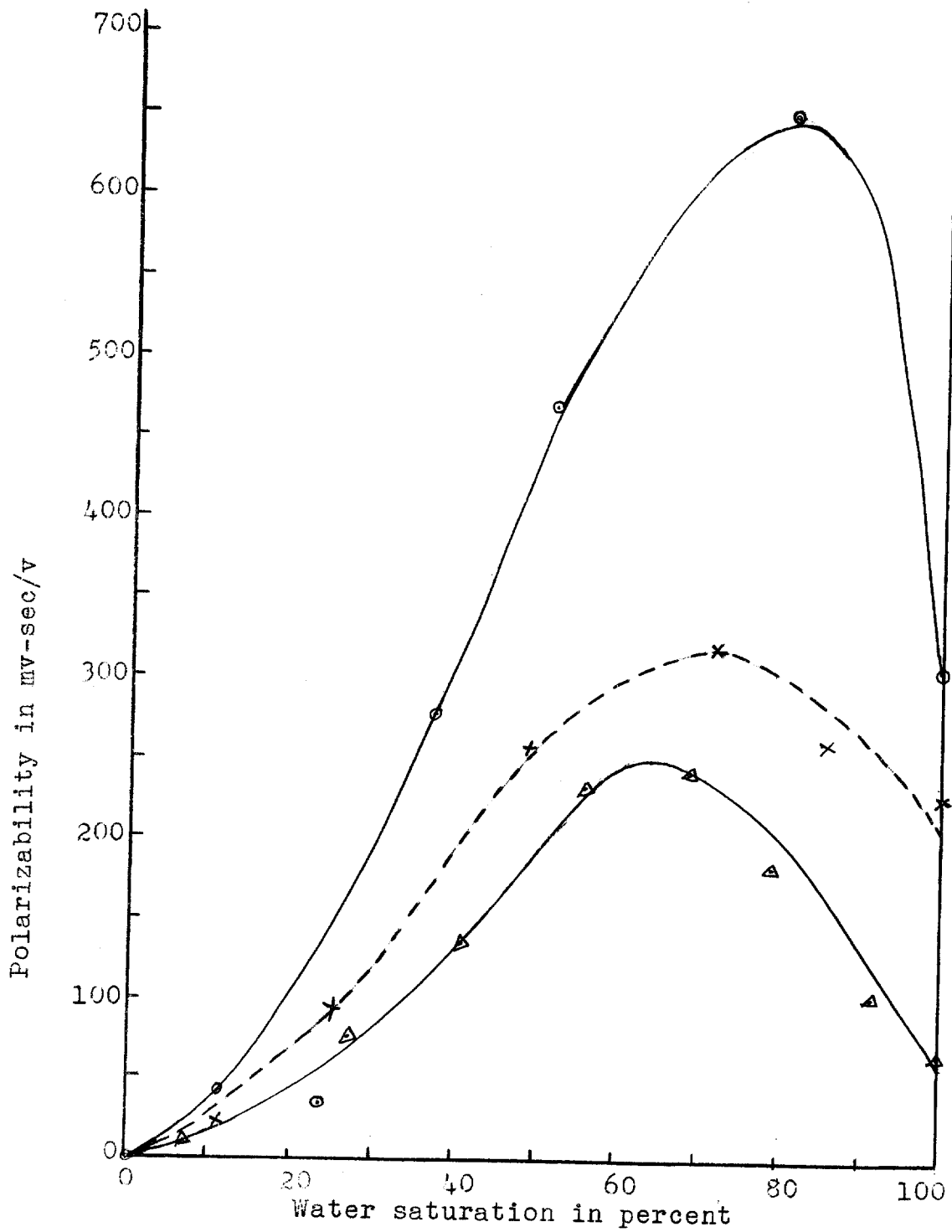


Fig. 9(b).

Type 11 curve.
Polarizability as a function of water saturation
for an excitation time of 20 seconds for 3 cores.

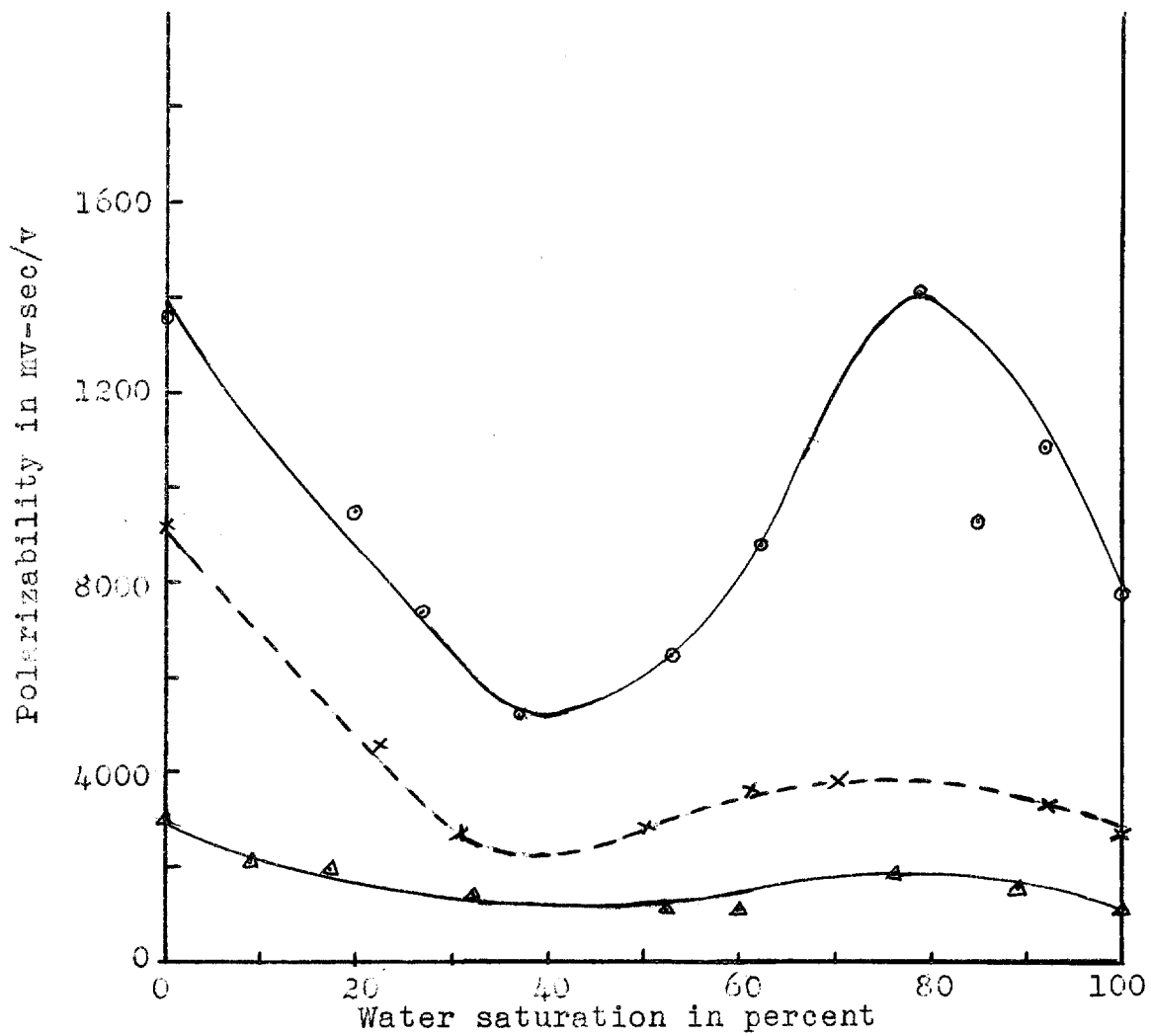


Fig. 9(c).

Type III curve.
Polarizability as a function of water saturation
for an excitation time of 20 seconds.

The above equation does not describe the data obtained in this work. An equation which better describes the data obtained in this work was given by Licastro and Keller (1952, p. 19):

$$I = S_w^{-n_1}$$

$$S_w > S_{wc}$$

$$I = bS_w^{-n_2}$$

$$S_w < S_{wc}$$

Where n_1 is the water saturation exponent for water saturation above S_{wc}

n_2 is the saturation exponent for water saturation below S_{wc}

S_{wc} is the saturation where the rate of increase of resistivity changes

b is a multiplying factor which enters the equation below S_{wc}

The limits within which these four parameters vary are given below:

$$n_1 \quad 1.5 \text{ to } 2.3$$

$$n_2 \quad 4.4 \text{ to } 5.3$$

$$b \quad .025 \text{ to } .042$$

$$S_{wc} \quad .47 \text{ to } .54$$

for quartz monzonite porphyry
or granodiorite porphyry

$$S_{wc} \quad .25 \text{ to } .36$$

for limestones.

The value of S_{wc} obtained for limestone is very close to

the value given by Licastro and Keller (1952, p. 19) for Bradford Sand.

The relationship between polarizability and water saturation is shown by the fifth set of curves for each core. A series of polarizability values for various excitation times were plotted as a function of water saturation. Three types of relationship between polarizability and water saturation are evident from these curves. The three types are designated as type I, type II, and type III, as shown in Figures 9(a), 9(b), and 9(c). For type I, there is a maximum value of polarizability within the range of 25 to 200 millivolt-seconds/volt for an excitation time of 20 seconds. They were obtained on Bear Creek samples which contain iron pyrite with small amounts of chalcopyrite disseminated in either quartz monzonite porphyry or granodiorite porphyry. Type II curve shows a maximum value of polarizability of 300 to 700 millivolt-seconds/volt for the same excitation time, and were obtained on Climax samples 0.14, 0.15, and 0.16, which contain iron pyrite disseminated in limestone. Type III curve shows a maximum value of polarizability within 2500 to 14,000 millivolt-seconds/volt for the same excitation time and were obtained on Climax samples 0.13, 0.18, and 0.20, which contain veinlets of iron pyrite embedded in limestone.

RELATIONSHIP BETWEEN
POLARIZABILITY AND
WATER SATURATION

The three types of curves relating polarizability to water content are exhibited by core samples with different physical and chemical properties. It is likely that the shape of the polarizability versus water-content curve is related to differences in physical and chemical properties of the core samples. A description and a comparison of the properties of the core samples are given below.

Properties of Core Samples

Since the explanation of the different types of relationship between polarizability and water saturation probably lies in the differences in the properties of the core samples, it is appropriate at this point to describe the properties of the different cores.

Bear Creek samples, which exhibited type 1 curves, contain iron pyrite, with small amounts of chalcopyrite disseminated in either quartz monzonite porphyry or grano-

diorite porphyry. The total metallic sulphide content is estimated to be about 3 to 5%. The grain size of the metallic sulphide is estimated to be about $\frac{1}{2}$ - 1 mm in diameter. The water content in samples with a volume of 75 to 100 cc is only 0.7 to 1.25 grams. Therefore the porosity of these cores is about 0.9 to 1.5%.

Type 11 curves are exhibited by Climax samples 0.14, 0.15, and 0.16, which contain pyrite in a limestone matrix. The pyrites are uniformly distributed and the core seem to have fairly high content of iron pyrite, probably as much as 10%. The pyrite grain size is larger also, probably as large as 2 mm in diameter. The porosity is also much higher than the Bear Creek samples since the core with a volume of 25 to 40 cc contain between 2.5 to 4.3 grams of water. Therefore the porosity is about 8 to 14%. High porosity and high metallic sulphide content in these cores may cause these samples to exhibit type 11 curves.

The Climax samples that exhibit the type 111 curves contain veinlets of pyrite 1 to 2 mm thick which extend parallel to the length of the core. The pyrite content is estimated to be about 15 to 20%. The water content is approximately the same as the preceding samples. In these cores the veinlets of metallic sulphides seem to play an important role in causing the samples to exhibit type 111

curves.

Before proceeding further with the discussion of each type of curve, a review of the causes of induced polarization will be presented.

Causes of Induced Polarization

The passage of an electrical current through a rock is accompanied by electrochemical processes, the character and intensity of which are determined fundamentally by the physical and chemical properties of the minerals and the electrolyte in the rock. Induced polarization observed in rocks after the interruption of current flow are the results of these processes. Marshal and Madden (1959, p. 797) say that

The polarizable materials are capable of maintaining for a certain time, an electric current flow after an applied field is turned off. Actually what is observed is a voltage gradient.....energy is stored in the medium when the current is passed through, and usually at least some of this energy is released by maintaining electric current flow after the driving force is turned off. The five ordinary forms of energy storage are, electric, magnetic, mechanical, thermal, and chemical.

The physical-chemical processes which take place in a rock consisting of a complex aggregation of particles, differing both in mineralogic composition and physical properties in producing induced polarization, may be divided into:

1. metal-electrolyte interface polarization

2. membrane polarization
3. electro-osmotic polarization

The metal-electrolyte interface polarization occurs at the boundary when there is a change in the mode of conduction from ionic to electronic or vice versa, when electric current passes through a rock containing metallic particles and electrolyte. This phenomenon is the same phenomenon that occurs at a polarized electrode (Brant, 1952; Bleil, 1953, p. 664; Marshal and Madden, 1959, p. 790; Dakhnov, 1952, p. 46). At the metal-electrolyte interface according to Marshal and Madden (1959, p. 790):

Chemical or electrochemical barriers exist which the current carriers must overcome in order to allow current flow to pass across the electrode-liquid interface. Forcing a net current flow to take place across this interface entails an added voltage drop above and beyond that needed to overcome the ohmic losses in the solution and in the electrode. This additional voltage is called the overvoltage.

The picture that is used to explain the induced polarization effects in mineralized rocks involves the ionic current flow in the rock polarizing the metal particles within the rock. Qualitatively...., these effects behave somewhat as the ordinary dielectric property of the materials.

The energy stored at the metal-electrolyte interface is analogous to that stored when a capacitor is charged.

Membrane polarization occurs due to selective ions diffusion through a membrane such as clay-bearing rocks when the current passes through such rock. (Vacquier et al, 1957, p. 674-676; Marshal and Madden, 1959, p. 894-807).

According to Vacquier et al. (.957, p. 674-675),

The conduction over the clay affects the concentration of the exchangeable cation of the double layer. When the current is shut off, the exchangeable ions slowly redistribute themselves along the clay.

This redistribution of the ions give rise to induced polarization. The membrane polarization is usually smaller in magnitude than the metal-electrolyte interface polarization, but may still be significant in many cases. In the prospecting for metallic ores by the induced polarization method, the membrane polarization may mask the metal-electrolyte interface polarization, so that the method is not practicable in some places where the metallic ores occur in sedimentary rocks which exhibit membrane polarization.

When a voltage is applied to a rock containing an electrolyte, the liquid phase moves with the electric field. This motion is called electro-osmosis, and according to Dakhnov (1952, p. 46),

When the current is interrupted, equilibrium will be re-established through the formation of a streaming potential. This streaming potential will be the induced polarization which is measured for a particular rock.

According to Marshal and Madden (1959, p. 803) and Vacquier et al. (1957, p. 676), the electro-osmotic effects are relatively unimportant in causing induced polarization.

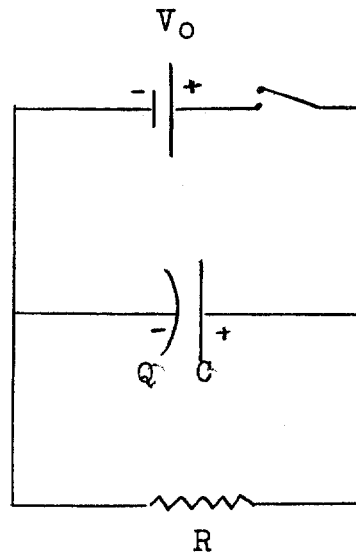


Fig. 10.

Equivalent resistor-capacitor circuit for a core.

Induced polarization in the core samples I have investigated is probably of the metal-electrolyte interface type. A sample exhibiting this type of induced polarization may be considered as containing in effect a large number of condensers. Such a core could be represented by a circuit consisting of a resistor and a capacitor as shown in Figure 10. When the current is passing through the core, the capacitor will be charged. When the current is interrupted, the capacitor will discharge through the resistor. The induced polarization potential is analogous to the potential of a discharging capacitor. For a simple resistor-capacitor circuit, the discharging voltage will be given by the equation

$$V = V_0 e^{-t/RC}$$

where V is the instantaneous voltage,

V_0 is the voltage across the capacitor when the capacitor starts to discharge at $t = 0$,

t is the time,

R is the resistance, and

C is the capacitance.

The discharge voltage is controlled by the parameters R and C . The magnitude of the induced polarization is given by the area under the voltage-decay curve and

$$\int V dt = V_0 \int e^{-t/RC} dt$$

The discharge current $i = \frac{V_0}{R} e^{-t/RC}$, and hence

$$\int V dt = R \int i dt.$$

But $\int i dt = Q$

where Q is the total charge on the capacitor, so that

$$\int V dt = RQ$$

The magnitude of induced polarization will therefore be proportional to RQ . If the magnitude of induced polarization is divided by the potential drop across the core, the resulting ratio is polarizability, which will be proportional to RC , since Q/V_0 is the capacitance C .

For a core sample, the resistance will be that of the core, the capacitance will be the interfacial capacitance at the metal-electrolyte boundaries, and V_0 will be the potential difference across the core. We can extend our proportional relation to resistivity and dielectric constant. Bulshevich (1956, p. 504) had shown in his paper, that the polarizability is proportional to the product of resistivity and dielectric constant. With this hypothesis

of induced polarization, let us proceed to discuss the different types of polarizability curves that are exhibited by the cores when the water saturation is varied.

Types of Curves

There are three types of relationship between polarizability and water saturation obtained on the core samples. The observation of the different types of curves may be related to the differences in the properties of the core samples. In the following sections discussions for each type of curve are presented.

Type 1 Curves: All Bear Creek samples exhibited this type of polarizability curve with variation of water saturation. If polarizability is proportional to RC , as assumed in the preceding sections, the polarizability should increase due to increase of resistance of the core when the water saturation is decreased. But a decrease of polarizability was observed. Therefore the decrease of C must be larger than the considerable increase of R . Since the metallic sulphide content is low and sparsely disseminated and since the porosity is low in these cores, removal of any amount of water will reduce the surface areas of the metal-electrolyte interfaces, and thus in turn reduce the capacitance noticeably.

At 38 to 42% water saturation, the polarizability is

zero. At this saturation all the water that was in contact with the sparsely disseminated metallic sulphides must have been removed. Since there is no available metal-electrolyte interface, the capacitance will be zero. It was also noticed that the resistivity index increased with a greater rate after about 47 to 54% water saturation, indicating that the water remaining in the core must be in discontinuous globules (Licastro and Keller, 1952, p. 20).

The low value of polarizability exhibited by these cores can be explained by the fact that these cores had low porosity and low metallic sulphide content.

Type 11 Curves: The major difference between the type 1 and type 11 curves is that instead of the polarizability decreasing with decrease of water saturation, the polarizability increases to a maximum point at about 70 to 80% water saturation, and then from that point it decreases with decrease of water saturation. The increase of magnitude of induced polarization appears to be due to the longer time the voltage-decay curve takes to drop to zero level, i.e. the time constant of the voltage-decay curve increases with decrease of water saturation down to 70 to 80% water saturation.

It is interesting to note that a result similar to type 11 curves was obtained by a Russian investigator,

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Rokityanskiy (1957, p. 222), in his laboratory investigation of induced polarization on sandstones containing small amounts of clay. He found that the induced polarization increases with decrease in saturation to a certain point, and then beyond that point the induced polarization decreases. Saturation is defined by Rokityanskiy as the ratio of the weight of water contained in a partially or fully saturated core to the weight of the same core when it is dried. The behavior of induced polarization with saturation was explained in a later paper by Rokityanskiy (1959, p. 1055). The induced polarization observed by Rokityanskiy is caused by membrane polarization phenomenon.

The increase of polarizability with decreasing water saturation, shows that C must remain fairly constant or decrease very slowly at high water saturations. This is conceivable since the metallic sulphide content and porosity of these core samples are much higher than that of the preceding core samples, removal of some amount of water will not noticeably decrease the surface areas of the metal-electrolyte interfaces. The increase of polarizability must be due to the increase of resistance with decrease of water saturation, if the polarizability is proportional to RC .

After the maximum point a decrease of polarizability

is observed with decrease of water saturation. Below the maximum point, removal of water from the core will effect the available metal-electrolyte interfaces, and thus C must be decreasing rapidly, as indicated by the decrease of polarizability.

In this case since the cores contain more metallic sulphide and have higher porosity than the preceding cores, the surface areas of the available metal-electrolyte interfaces are not reduced appreciably until nearly all the water in the core is removed as shown by the observation of polarizability even at very low water saturations and only when the core is dry does the polarizability become zero. The higher intensity of the polarizability exhibited by these cores is due to the fact that they contain more metallic sulphide particles and have higher porosity.

Dakhnov (1952, p. 46) had pointed out that when pyrite is dispersed in carbonate rock, there will be both metal-electrolyte interface polarization and membrane polarization. No distinction could be made between the two causes of polarization in the resulting induced polarization that is observed. Membrane polarization in these cores may influence the variation of polarizability with decrease of water saturation. There is no literature on induced polarization exhibited by limestones. Until more

work is done on induced polarization exhibited by different types of rocks, discussion of the effects of induced polarization generated by membrane polarization phenomenon and other causes in these cores is impossible.

Type 111 Curves: In this case instead of polarizability decreasing to zero when the cores are completely dry, it decreases to a minimum point at about 30 to 45% water saturation, and then it increases with further reduction of the water content. The Climax samples that exhibited this type of relationship contain veinlets of pyrite about 1 to 2 mm thick parallel to the length of the core.

Since the cores in this case exhibited variation of polarizability with water saturation down to 30 to 45% water saturation similar to those of type 11 curves, the R and C in these cores must vary similarly to those of the cores that exhibited type 11 curves above the minimum point. On the basis of the assumption that polarizability is proportional to RC, the relation between the observation of high intensity of polarizability when the cores are dry, and the parameters R and C, is not very clear. When the cores are dry, there is only electronic conduction present (i.e. due to the presence of veinlets of pyrite), and therefore these cores should not exhibit induced polari-

zation. A large number of this type of cores should be investigated before we could confirm the observation of this type of relation between the polarizability and water saturation.

In this case the very high intensity of the polarizability observed at high water saturations, may be due to the presence of veinlets in these cores and due to the higher metallic sulphide content. Membrane polarization may also influence the polarizability that was observed.

SUMMARY AND CONCLUSIONS

An investigation of the effect of varying the water saturation in core samples on the polarizability exhibited by these cores was made. Polarizability is the ratio of induced polarization observed to the potential drop across the core. The 10 cores that were studied show 3 types of relationships between polarizability and water saturation, designated as type I, type II, and type III curves. These 3 types of polarizability versus water-saturation curves were exhibited by 3 groups of cores with distinct differences in physical properties, and it is likely that the above 3 types of curves are related to the physical properties of the cores.

Type I curves, exhibited by cores containing iron pyrite with very small amounts of chalcopyrite sparsely disseminated in tight porphyry rock, show a decrease of polarizability with decrease of water saturation. At 38 to 42 % water saturation, the polarizability is zero.

Type 11 curves, exhibited by cores containing iron pyrite disseminated in porous limestone, show an increase of polarizability with decrease of water saturation down to 70 or 80% water saturation, at which point the polarizability is maximum. Below this water saturation, the polarizability decreases with decrease of water saturation and is zero only when the cores are dry.

Type 111 curves, exhibited by cores containing veinlets of iron pyrite parallel to the length of core embedded in porous limestone, show a similar increase of polarizability with decrease of water saturation, and a maximum value at 70 to 80% water saturation. Below this saturation, the polarizability decreases as in the type 11 curves, but reaches a minimum at 30 to 45% water saturation. Below this water saturation, the polarizability increases with further decrease of water saturation. When these cores are dry the polarizability is very high, in some cases exceeding the previous maximum.

An attempt is made to relate polarizability with the product of resistance and capacitance of the core, by representing the core with a simple resistor-capacitor circuit. The variation of polarizability with decrease of water saturation cannot be fully reconciled with this simple model.

Additional investigations were made on induced polarization exhibited by these 10 cores with the variation of charging current and excitation time. The induced polarization increases linearly with the increase of current. Polarizability, which is expected to be constant with the variation of current, shows a slight increase with the increase of current. Polarizability versus excitation time plotted on a logarithmic coordinate shows a linear relationship. This linearity is fairly consistent for a core, even when the water saturation of that core is changed.

It is recognized that too few cores were examined to draw more than tentative conclusions; however, such conclusions are of interest.

If type 1 curves are typically representative of samples in which metallic sulphide is disseminated in porphyry rock, then it is impossible to use I.P. method for detecting porphyry metallic sulphide deposits in dry regions, where the mineral deposits are likely to occur above the water table. If type 11 and type 111 curves are typically representative of porous limestones containing metallic sulphides disseminated or as veinlets, then the I.P. method will be applicable in arid and semiarid regions where these mineral deposits may be expected to

occur above the water table.

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APPENDIX
EXPERIMENTAL DATA

Bear Creek Sample E 1506

Data for polarizability as a function of excitation time for various degrees of water saturations, resistivity index as a function of water saturation, polarizability as a function of water saturation for a series of excitation times.

Water Saturation	100%	76.2%	64.1%	56.8%	47.6%	41.1%
Resistivity Index	1	1.12	1.34	1.47	2.54	4.10
Time in Seconds	Polarizability in millivolt-seconds/volt					
1.0	77.3	21.0	6.6	4.2	3.25	Nil
3.0	76.0	27.0	12.1	6.1	4.5	Nil
5.0	87.0	38.0	15.5	8.5	5.5	Nil
10.0	135.0	49.0	21.5	13.0	6.25	Nil
20.0	177.0	64.5	32.2	17.0	8.6	Nil
40.0	240.0	78.5	41.3	23.1	11.1	Nil
60.0	275.0	92.3	53.8	27.0	12.9	Nil

Bear Creek Sample T 1580

Data for polarizability as a function of excitation time for various degrees of water saturations, resistivity index as a function of water saturation, polarizability as a function of water saturation for a series of excitation times.

Water Saturation	100%	78.0%	68.3%	57.5%	42.5%
Resistivity Index	1	1.125	1.35	1.76	4.30
Time in Seconds	Polarizability in millivolt-seconds/volt				
1	9.71	3.46	2.04	0.4	Nil
3	20.3	4.5	2.62	0.8	Nil
5	29.3	5.1	2.62	1.6	Nil
10	50.9	7.0	3.84	2.1	Nil
20	85.6	8.4	4.16	3.3	Nil
40	120.0	9.8			
60	180.0	11.5			

Bear Creek Sample T 1696

Data for polarizability as a function of excitation time for various degrees of water saturations, resistivity index as a function of water saturation, polarizability as a function of water saturation for a series of excitation times.

Water Saturation	100%	73.0%	62.2%	49.4%	38.5%
Resistivity Index	1	1.32	1.54	1.94	4.44
Time in Seconds	Polarizability in millivolt-seconds/volt				
1	6.95	3.35	2.60	1.5	Nil
3	12.1	5.15	3.90	1.8	Nil
5	15.15	6.80	4.35	1.9	Nil
10	22.0	7.80	6.15	2.1	Nil
20	26.0	8.30	6.21	2.4	Nil
40	44.0				
60	51.5				

Bear Creek Sample T 1798

Data for polarizability as a function of excitation time for various degrees of water saturations, resistivity index as a function of water saturation, polarizability as a function of water saturation for a series of excitation times.

Water Saturation	100%	71.8%	62.1%	54.0%	47.5%	40.5%
Resistivity Index	1	1.05	1.06	1.09	1.77	3.87
Time in Seconds	Polarizability in millivolt-seconds/volt					
1	56.4	16.8	3.43	1.7	1.25	Nil
3	62.7	18.5	4.14	1.8	1.30	Nil
5	63.5	19.5	5.15	1.9	1.45	Nil
10	65.85	21.6	5.51	2.0	1.60	Nil
20	67.6	22.4	6.21	2.1	1.55	Nil
40	73.1	23.1				Nil
60	76.4	24.3				Nil

Climax Sample 0.14

Data for polarizability as a function of excitation time for various degrees of water saturations, resistivity index as a function of water saturation, polarizability as a function of water saturation for a series of excitation times.

Water Saturation	100%	85.5%	72.2%	55.0%	41.5%	27.2%	7.1%	Oven heated Dry
Resistivity Index	1	1.13	1.24	1.28	1.38	1.92	12.9	166.0
Excitation Time in Seconds	Polarizability in millivolt-seconds/volt							
1	53.5	60.0	83.6	62.2	32.1	23.6	1.38	Nil
3	65.4	106.2	113.8	87.8	49.7	31.2	1.65	Nil
5	94.3	161.5	160.0	112.0	72.3	42.3	2.01	Nil
10	156.2	226.4	232.0	167.0	98.0	50.0	1.66	Nil
20	231.8	258.4	318.0	245.0	135.0	75.0	1.62	Nil
40	260.2							
60	273.0							

Climax Sample 0.15

Data for polarizability as a function of excitation time for various degrees of water saturations, resistivity index as a function of water saturation, polarizability as a function of water saturation for a series of excitation times.

Water Saturation	100%	88.5%	68.5%	48.4%	25.0%	11.0%	Oven heated Dry
Resistivity Index	1	1.08	1.11	1.16	1.44	5.42	112.1
Excitation Time in Seconds	Polarizability in millivolt-seconds/volt						
1	16.35	26.56	25.5	26.7	15.4	5.1	Nil
3	25.6	43.6	49.3	50.0	23.6	8.7	Nil
5	37.3	49.7	68.5	67.5	48.3	17.5	Nil
10	50.5	75.5	130.0	150.0	67.35	18.2	Nil
20	67.3	97.4	220.0	253.0	90.4	22.1	Nil
40	98.6	143.8					
60	120.2	152.1					

Climax Sample 0.16

Data for polarizability as a function of excitation time for various degrees of water saturations, resistivity index as a function of water saturation, polarizability as a function of water saturation for a series of excitation times.

Water Saturation	100%	81.0%	52.5%	37.0%	23.5%	11.23%	Oven heated Dry
Resistivity Index	1	1.03	1.07	1.12	2.32	5.95	133.0
Excitation Time in Seconds	Polarizability in millivolt-seconds/volt						
1	113.0	138.0	71.4	53.0	11.0	7.9	Nil
3	142.0	181.0	112.5	97.0	13.0	12.1	Nil
5	206.5	294.5	232.5	122.0	15.2	18.7	Nil
10	239.0	420.0	259.0	151.0	19.6	36.4	Nil
20	305.0	655.0	468.0	277.0	34.4	41.6	Nil
40	378.0						
60	862.0						

Climax Sample 0.13

Data for polarizability as a function of excitation time for various degrees of water saturations, resistivity index as a function of water saturation, polarizability as a function of water saturation for a series of excitation times.

Water Saturation	100%	92%	85.5%	78.5%	62.5%	53.0%	36.1%	27.0%	19.8%	Dry
Resistivity Index	1	1.08	1.19	1.19	1.54	1.28	1.52	1.34	1.54	2.8
Excitation Time in Seconds	Polarizability in millivolt-seconds/volt									
5	2470	5250	4050	5600	3150	1955	2240	4210	3680	5820
10	5770	7180	6940	7950	6250	3950	3360	5750	6340	9110
20	7050	10800	9200	14100	8750	6470	5200	7400	9560	13300

Climax Sample 0.18

Data for polarizability as a function of excitation time for various degrees of water saturations, resistivity index as a function of water saturation, polarizability as a function of water saturation for a series of excitation times.

Water Saturation	100%	92%	70.5%	61.3%	49.9%	30.6%	22.5%	Dry
Resistivity Index	1	1.09	1.24	1.12	1.16	1.29	1.81	2.10
Excitation Time in Seconds	Polarizability in millivolt-seconds/volt							
5	687	810	890	932	615	830	1460	2280
10	1625	1680	1770	1940	1215	1690	2430	3860
20	2980	3150	3390	3600	2718	2760	4520	9100

