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By Pertev I. Bediz

Pertev I. Bediz

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DEPTH DETERMINATION OF SEMI-INFINITE HORIZONTAL CONDUCTIVE LAYER BY ELECTROMAGNETIC-GALVANIC METHODS

by

Pertev I. Bediz

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INTRODUCTION

Purpose of this Investigation

The purpose of this investigation is to find a method by which it will be possible to determine the depth of horizontally stratified media by electromagnetic galvanic means of prospecting.

Electromagnetic Prospecting

The introduction of alternating current in the audible range into the ground for the purpose of locating conductive ore zones has been in use for some time. This method has also found limited application in petroleum and engineering geology. The technique has been to apply a primary field to the area under investigation through a large insulated loop or through direct contact with stakes driven into the ground.

In either case, a primary field is set up in the earth which induces a secondary current to flow in any subsurface conductor. This secondary current, in turn, sets up a field which opposes the primary field. The resultant field measured at the surface varies with amplitude, depending upon the depth and relative conductivity of the subsurface conductor. There is also a shift in the phase of the resultant field which is dependent upon relative conductivity contrast.

The resultant field may be resolved into its components X, Y, and Z; the Z components being vertical, the Y component being perpendicular to the strike of the conductor, and the X component along the strike. It is generally sufficient to explore either the Z or Y component to analyze the subsurface conditions. For this purpose, detection coils of suitable dimensions are oriented in either a horizontal plane or in a vertical plane parallel to the strike of the conductor, depending upon the component desired.

Previous Investigations

Most of the earlier investigators into electromagnetic methods have either been satisfied with broad approximations or have arrived at purely theoretical and highly complex results which are not applicable to geophysical prospecting. This wide divergence of treatment is due to the fact that only the electromagnetic field vectors at the surface are known and from them the unknown geometrical configuration as well as unknown physical constants, such as dielectric constant and magnetic permeability, must be deduced. In most problems of electrodynamics we know the strength of the exciting field, the electrical conductivity, the geometric disposition of the body under investigation, and we solve for the field vectors.

When the only knowns are the source field and the boundary values of the resultant field over one surface of the volume of investigation, we cannot uniquely determine the desired unknowns. Even when deficiencies are replaced by reasonable assumptions, the mathematical difficulties are enormous, and, as Slichter says, "As yet theory provides the geophysicist no tools of sufficient power for a direct analysis of the problem."

For that reason, the interpretation of electromagnetic results has necessarily been indirect and has relied upon the empirical matching of unknown field conditions with known laboratory conditions.

An approximation method in depth determination involves the relative value of anomaly. The deeper the conducting layer beneath the surface, the smaller the values of the horizontal component of field strength. When the phase relation between the secondary and primary fields due to the conducting layer and the loop, respectively, are measured, it is found that the rate of change of phase may also give an independent indication of depth. This method might be of use in local investigations where ore types and occurrences are alike and previous results of known similar deposits are available.

Haalck and Ebert(1) studied the difference in conductivity in the ground by working with more or less horizontal layers of different conductivity. They shifted the two power electrodes, by which the energy is conducted into the ground, successively and uniformly in opposite directions. By means of an induction coil, the inclination of the magnetic vector was measured. From the form of the curve obtained graphically by plotting the inclination of the coil as a function of the distance between the electrodes, a conclusion was drawn whether and at what approximate depth there is a layer having a higher or a lower conductivity.

PROCEDURE

Equipment and Apparatus

During the course of this investigation, the primary field was energized galvanically; therefore, only that set-up will be considered in this discussion. Figures 1 and 2 show schematically the arrangement and connections of the instrument as well as the relative position of the tank, orebody, and power supply.

The experiments were carried out in a concrete tank designed especially for electromagnetic work (Fig. 20). It has a length of six meters, a width of three meters, and a depth of two and a half meters. A striding platform capable of carrying instruments and observer is free to traverse the length of the tank. This platform also carries a sealed wooden beam which is free to rotate through 360 degrees about a vertical axis to which the search coils are attached.

The tank was filled with city water to which six pounds of table salt had been added to increase its conductivity.

The alternating frequency power was supplied by a General Radio, type 608-A, beat frequency oscillator, operating at 500 cycles. The power was supplied galvanically by submerging two pieces of copper screen, two inches square, into the water. These screens were connected to the oscillator by shielded microphone cables whose shields were grounded.

The conductive layer was a tabular box, measuring nine feet by six feet by four inches, made of 16 gauge, galvanized iron. The model was suspended at any desired depth with ropes from each side (Fig. 1).

The coils were free to rotate about a vertical axis through 360 degrees and about a horizontal axis from 0 degrees to 90 degrees, thus making it possible to pick up any component of the total field.

The pick-up coils were designed especially for model work. They were identical and had a mean diameter of 7.5 inches with 340 turns of single, silk-covered #26 enameled copper wire. They were tested for electromagnetic identity according to the method suggested by the Imperial Geophysical Survey[2] and were found to match perfectly.

The intensity ratiometer used was built by Dr. J. E. Hawkins for his doctorate thesis at the Colorado School of Mines in 1940. For details of this instrument one should refer to Dr. Hawkins' thesis.[3] Figure 4 illustrates the generalized circuit.

It was necessary to amplify the micro-current from the pick-up coils in order to detect the null condition of the bridge. For this purpose a General Radio amplifier, type 814-A, equipped with a 500 cycle resonant filter, was employed. The impedance of the input circuit was

5 megohms in parallel with 36 microfarads. The output impedance was 70,000 ohms. The auxiliary filter circuit was found very necessary if a sharp null was to be detected.

Model Relations

There has been an attempt to preserve the same relative dimensions in the tank work as prevails under normal field conditions. However, it should be appreciated that the electrical properties have not been adjusted. The value of an exhaustive determination of the model relations involving the conductivity of the media and the frequency of the primary field was doubtful at the outset of the investigation. Hence, these relationships were left for empirical determination by comparing model experiments with field results after the preliminary work had been done.

Selection of Nature of Current and Frequency

An alternating current is preferred in electromagnetic prospecting as it has many advantages. In this method of prospecting we deal with induced fields of small magnitude. Such fields, if produced by an alternating current excitation, will, themselves, be of alternating nature, and it would be possible to amplify them easily until detection is possible. A second and most important advantage is the fact that an alternating electromagnetic field induces eddy currents along the edge of any conducting body exposed to the field. These eddy currents generally will increase the strength of the secondary fields and thus give a more pronounced indication of the conductor.

A low frequency, 500 cycles per second, is rather generally used for electromagnetic prospecting; high frequencies offer many difficulties and disadvantages. The ground acts as a filter to high frequencies thus diminishing the current penetration. Very good insulation of field equipment is necessary, especially when working in moist climate zones. Such insulations are difficult and expensive to obtain. Secondary conductors with comparatively low conductivity, especially if near or above the ground surface, are excited, and the magnetic fields associated with them are of magnitude comparable with the fields that are associated with good conductors of greater depth.

Method of Operation

The procedure used in the model experiments simulated the procedure used in the field. It was experimentally determined that the minimum distance between pickup coils should be 0.4 meters to avoid mutual inductance and interference between them. A series of traverses was run across the conductor with the coils at a 0.4 meter spacing and the rear coil occupying, in each case, the previous position of the forward coil. All measurements were made of the Z component. The voltage ratio and phase difference detected by the two coils were then plotted as ordinates against distance as abscissa (Figs. 8-14). For convenience, the conditions at the leading coil were always referred to the rear coil for comparison.

In order to obtain more values and of closer interval along the traverse, the rear coil was left fixed and the leading coil advanced in 10 cm. intervals (Fig. 3). The conditions at the movable coil were then referred to the voltage and phase at the fixed coil.

In the above described procedures, the power electrode separation was kept constant at about 5 to 6 meters. Additional traverses were run using the expanding interval between coils just mentioned and varying the distance between power electrodes for the purpose of changing the depth to which the primary current penetrated. The electrodes were first placed 10 cm. apart and then increased in 10 cm. steps until a distinct phase shift was detected. It was necessary to keep the coils removed from the electrodes at all times to prevent the effect of the primary field from obscuring the anomaly.

Difficulties Encountered

Difficulties encountered in carrying out the electromagnetic tank experiment as well as their solution will be mentioned here for the sake of future investigators. No such a tank experiment, at least to the knowledge of the writer, has ever been carried out; therefore, it is the writer's belief that such details concerning the experimental work should be enumerated.

The effect of body capacitance introduced a serious problem because the effect varied with the change in relative position of the observer to the instruments. This change in the balance of the ratiometer was minimized by standing away from the tank and always assuming the same position when taking a reading.

It was found necessary to use rubber insulated and shielded microphone cable for all instrumental connections, especially between the search coils and the ratiometer, to minimize the effect of the stray fields in the area.

It was also necessary to check the calibration of the ratiometer when small pickup coils were used instead of the regular field coils for which the ratiometer was designed and calibrated. The water which filled the tank was a very poor conductor, and its conductivity was increased by adding a few pounds of table salt.

The pickup coils should not be a great distance, vertically, from the surface of the water. This is to eliminate another homogeneous layer, the air. The bare part of the power electrodes should be completely submerged into the water, thus preventing any strong primary current from flowing through the air, thereby inducing a strong field in the coils which will tend to mask any variation due to the secondary field.

When one of the detector coils was less than 0.15 meters from the wall of the tank, the readings obtained were most likely erroneous. This was due to the wall effect (Fig. 16). Therefore, no reading should be taken when coils are too close to the wall of the tank.

One should be careful that no large masses of metallic bodies be within a distance of five meters of the tank. It is also important that an alternating current field of a frequency the same as the one utilized in the tank experiment, 500 cycles in this particular case, does not exist in the immediate vicinity.

DISCUSSION OF RESULTS

Let us consider the conductive layer in Fig. 19 between the electrodes and let us first assume that direct current is used and that current flows in the direction shown in the figure. The galvanically impressed current flow is concentrated mostly along the edges of the ore-body (Vector I). This current will produce a magnetic field of which the line of force will be circles along the edges of the conductor. If, now, alternating current were used, after one-half cycle or 1/1000 second, with 500 cycle primary current, the direction of both current and magnetic field will be reversed. The current I is given by:

$$I = I_o \sin 2\pi f t$$

where f is frequency and I_o maximum amplitude of current.

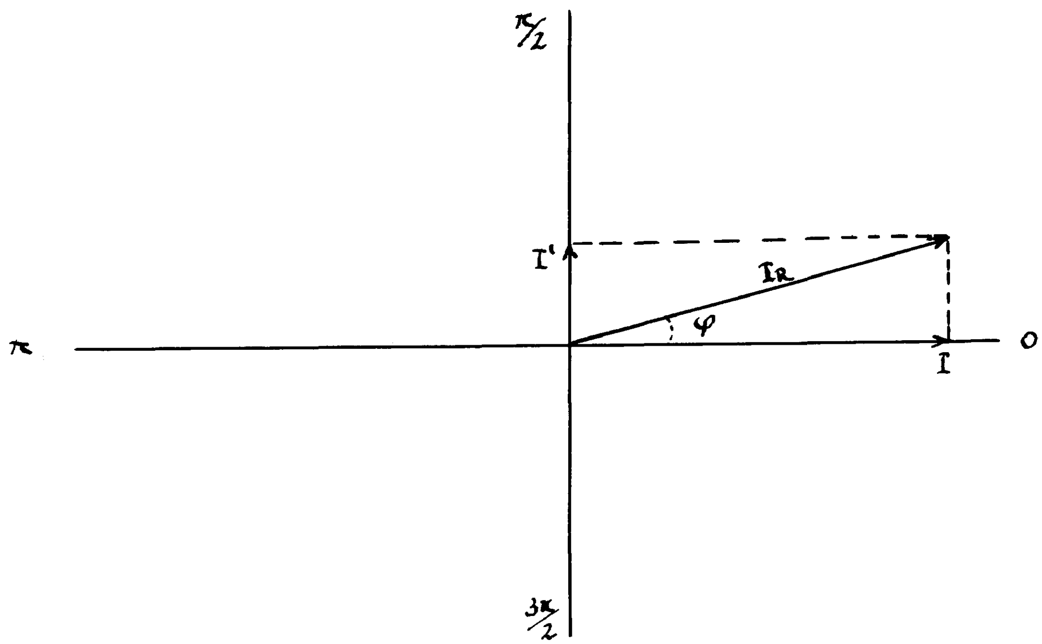
Since there is no difference in time between the creation of a current and its magnetic field, there will be no time or phase difference between the current I and its magnetic field H, which is:

$$H = H_o \sin 2\pi f t$$

where H_o is the maximum field strength. This alternating magnetic field will produce an induced current I', opposite in direction to the primary current I, along the edge of the conductive layer. The amplitude of the induced current at a certain moment is proportional to the rate of change of the magnetic field or to $\frac{dH}{dt}$. The amplitude of I' thus can be represented by:

$$I' = I'_o \cos 2 \pi f t = I'_o \sin (2 \pi f t + \frac{\pi}{2})$$

This indicates that there is a phase difference between I' and I, or the primary and the induced current. This may be represented by:



$$\varphi = Tan^{-1} \frac{I'}{I} \quad \text{and} \quad I_R = \sqrt{I^2 + I'^2}$$

The experimental work indicates that there is a close relationship between the theoretical consideration of the secondary field set up by the conductive zone and the secondary field measured in the tank.

The current flowing between the two power electrodes tends to concentrate along the more conductive zones, and the magnetic field set up around the edge of the conductor may be represented at any instant by the right hand rule. The induced current I' also creates a magnetic field, which is superimposed upon the field caused by the primary current. The windings of the search coils are cut by the resultant flux from the primary and induced fields.

At the center of the orebody, two secondary electromagnetic fields exist, equal in magnitude but opposite in direction (Fig. 19). These will cancel each other, and the detector coils, when placed at this point, will measure only the flux of the primary field.

Figures 8-14 show graphically the phase relations obtained under various conditions. It will be noticed in these graphs that the phase shift is zero at approximately the middle of the orebody, maximum and minimum on its edges. These results are in accordance with the theoretical treatment of the current flow and distribution given in the previous paragraphs. It will be seen from figures 8-14 that the zero phase is shifted to the left of the point corresponding to the center of the conductor. This is probably due to the wall effect, as one edge of the conductor was closer to one wall of the tank. Experiments performed without the conductor in the tank substantiate this belief. There was an average phase lag of 2 degrees when operating 40 centimeters from the wall (see Fig. 16).

The sum of the leading and lagging phase angles is referred to as the "Total Anomaly" or, in other words, the algebraic sum of the positive and negative phase shift of the resultant field from the primary when traversing across the conductor. The total anomaly plotted against the depth of the conductor as abscissa indicates that there is a linear relationship between these two factors. Figure 15 represents this relationship for two different lateral positions of the conductive body. The deviation of one of the values from the straight line is attributed to the influence of the bottom of the tank.

The relation between the power electrode separation and depth of investigation was determined experimentally by expanding the electrodes and leaving everything else constant. It was found that the field measured at the two coils showed no phase shift until the spacing between the electrodes was equal to or greater than the depth to the conductor, at which point there was a sharp indication of a phase shift. The magnitude of the shift was not altered by further increasing the electrode separation.

Figure 18 illustrates the conditions of current flow at various electrode spacings and explains why no secondary field is present if the electrode spacing is not as great as the depth to the conductor. When the electrode separation is less than the depth of the conductive layer, a larger percentage of the current completes its circuit through the upper homogeneous layer. Not enough current flows through the conductive body to produce a detectable secondary field. When the electrode separation has increased to a certain point, the current lines penetrate to the conductor and set up a secondary field out of phase with the primary.

CONCLUSION

It is the belief of the writer that the problem is not entirely solved. He feels, however, that a considerable amount of preliminary work is accomplished which may be of some value for further investigations. As far as the author knows, these are the first attempts in carrying out such experiments.

A definite preliminary point established is the linear relation of depth to the magnitude of phase shift. A second point, and perhaps the most important, is the relation of power electrode separation to the depth of the conductive layer. No phase shift may be detected on the surface when the power electrode separation is less than the depth of the tabular form conductive layer. As soon as the electrode separation becomes equal, or nearly so, to the depth of the conductive layer, a phase shift is observed on the surface. A further increase of electrode separation does not have any effect on the magnitude of the phase shift.

This property can very easily be adapted to field work. A suggested field procedure will be as follows: The position of the coils where a maximum phase shift occurs is determined with one power electrode placed at infinity, the other somewhere above the conductor body. The detector coils will be left stationary at this position throughout the survey. Then, the power electrodes will be placed about 10 feet apart, and the spacing will be gradually increased to 20, 30, 40, 50, etc., feet until the first definite and sharp phase shift is detected. The electrode separation corresponding to the first phase shift detection will be equal, or nearly so, to the depth of a horizontal tabular shaped orebody.

Application of this method to field conditions should give satisfactory results provided there exists a distinct contrast in the conductivity of the horizontal layers. However, it must be clear that in this investigation, the results were obtained from a semi-infinite conductive layer. Further studies must be carried out for the depth determination of infinite conductive layers.

BIBLIOGRAPHY

(1) Haalck, H. and Ebert, H., An electromagnetic method of measurement by shifting the electrodes for detecting differences in conductivity; Zeitschrift für Geophysik, Braunschweig, vol. 8, No. 8, pp. 409-419, 1932 (in German).

(2) The Principles and Practice of Geophysical Prospecting, Imperial Geophys. Exp. Survey, p. 55.

(3) Hawkins, J. E., The design of a dual coil ratiometer suitable for geophysical investigations; doctorate thesis, Colorado School of Mines, 1940.

Gilchrist, L., Electrical and electromagnetic surveys of Abana property; Studies of Geophysical Methods, 1928 and 1929, Chap. VI, Canada Dept. of Mines Memoir 165, p. 50.

Hedstrom, H., Phase measurements in electrical prospecting; Am. Inst. Min. Met. Eng., Tech. Publ. No. 327.

Heiland, C. A., Geophysical Exploration, Electrical Methods pp. 619-824, New York, 1940.

Studies of Geophysical Methods, Canada Dept. of Mines, Memoir 165, Electrical and electromagnetic methods of prospecting p. 23, 1928-1929.

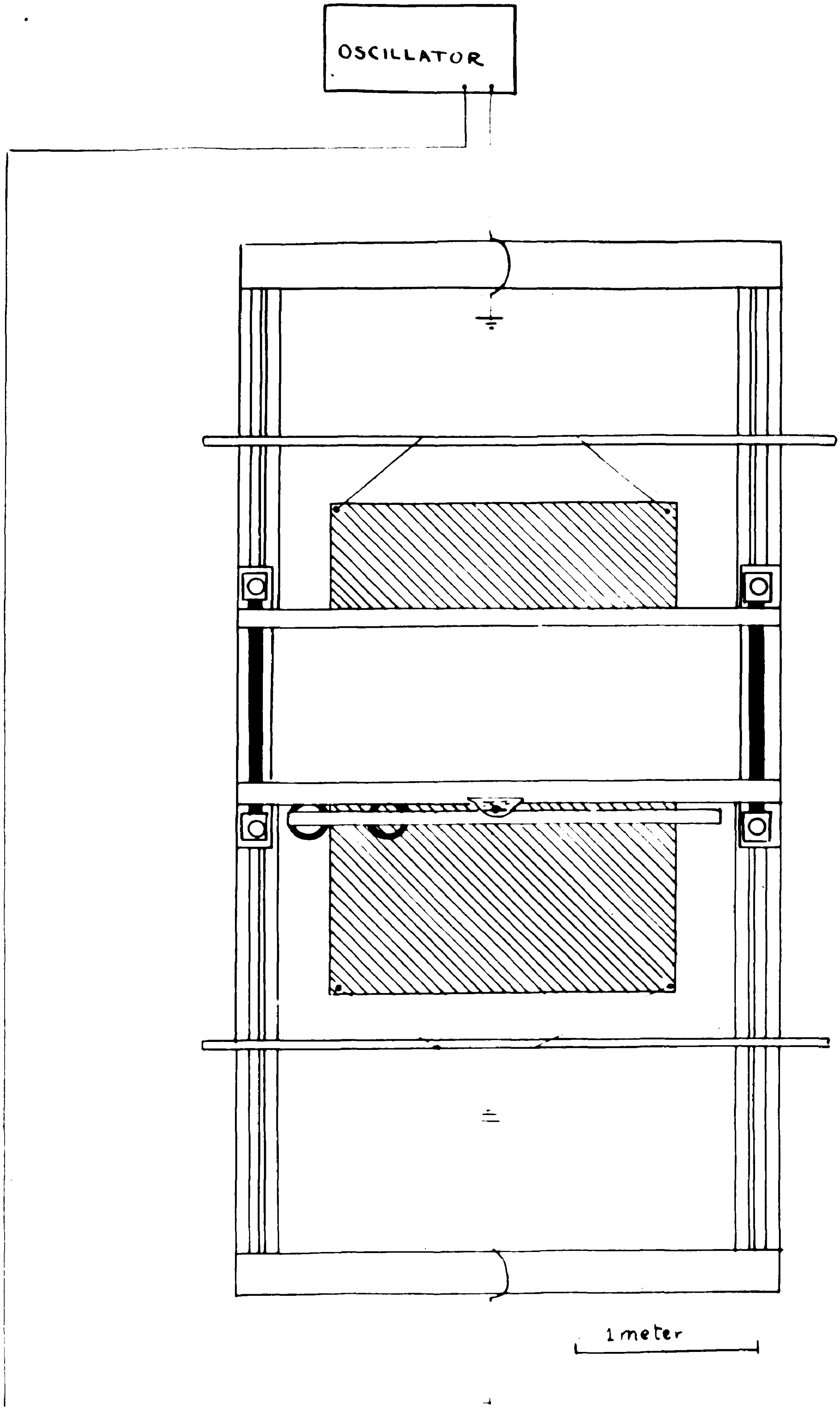


Fig. 1 - PLAN VIEW OF THE TANK, CONDUCTIVE LAYER, DETECTION COILS, OSCILLATOR, AND POINT ELECTRODES.

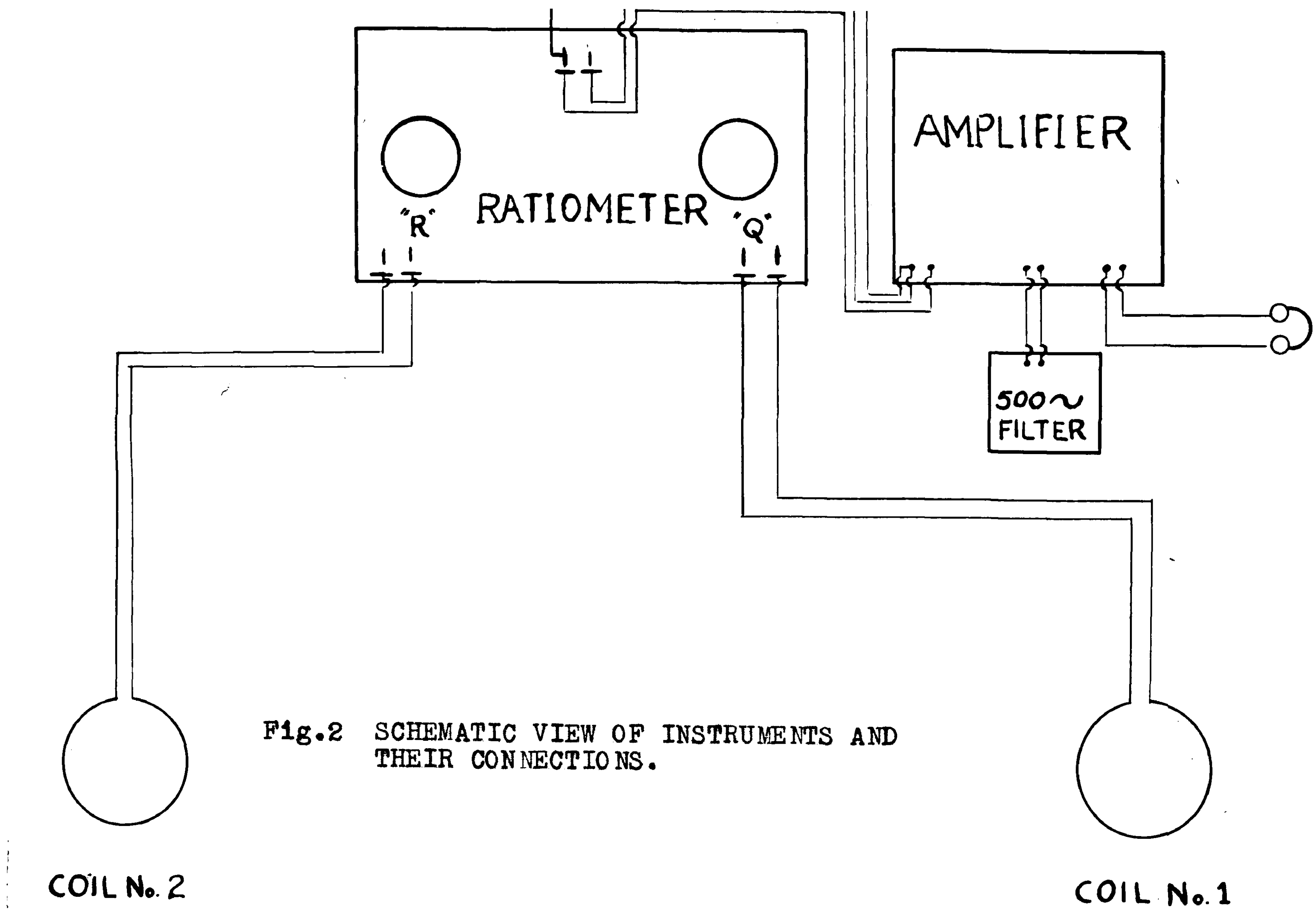


Fig.2 SCHEMATIC VIEW OF INSTRUMENTS AND THEIR CONNECTIONS.

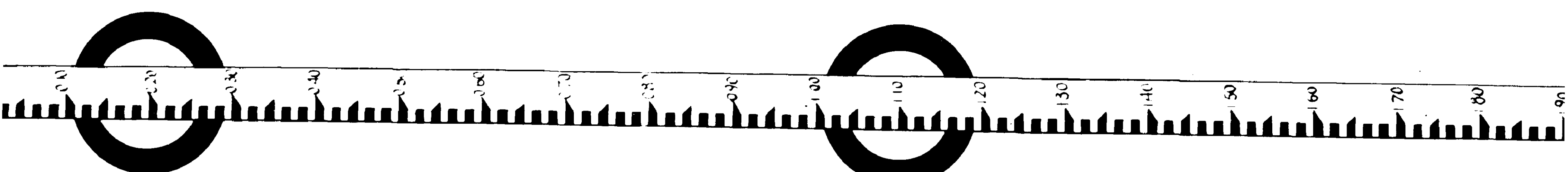


Fig. 3 THE WOODEN BEAM AND THE COILS.

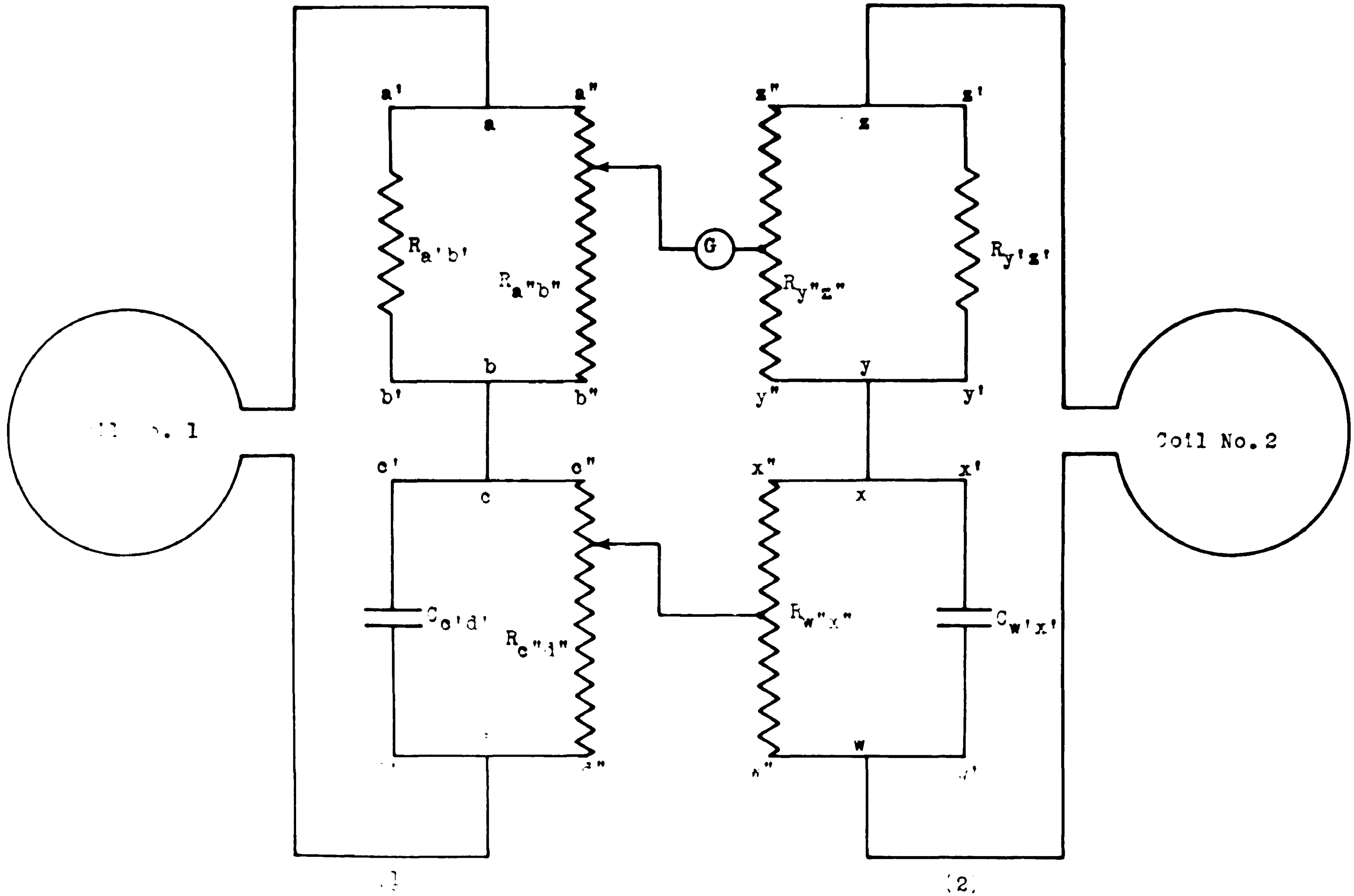


Fig. 4 FUNDAMENTAL DUAL-COIL RESISTANCE-CAPACITANCE

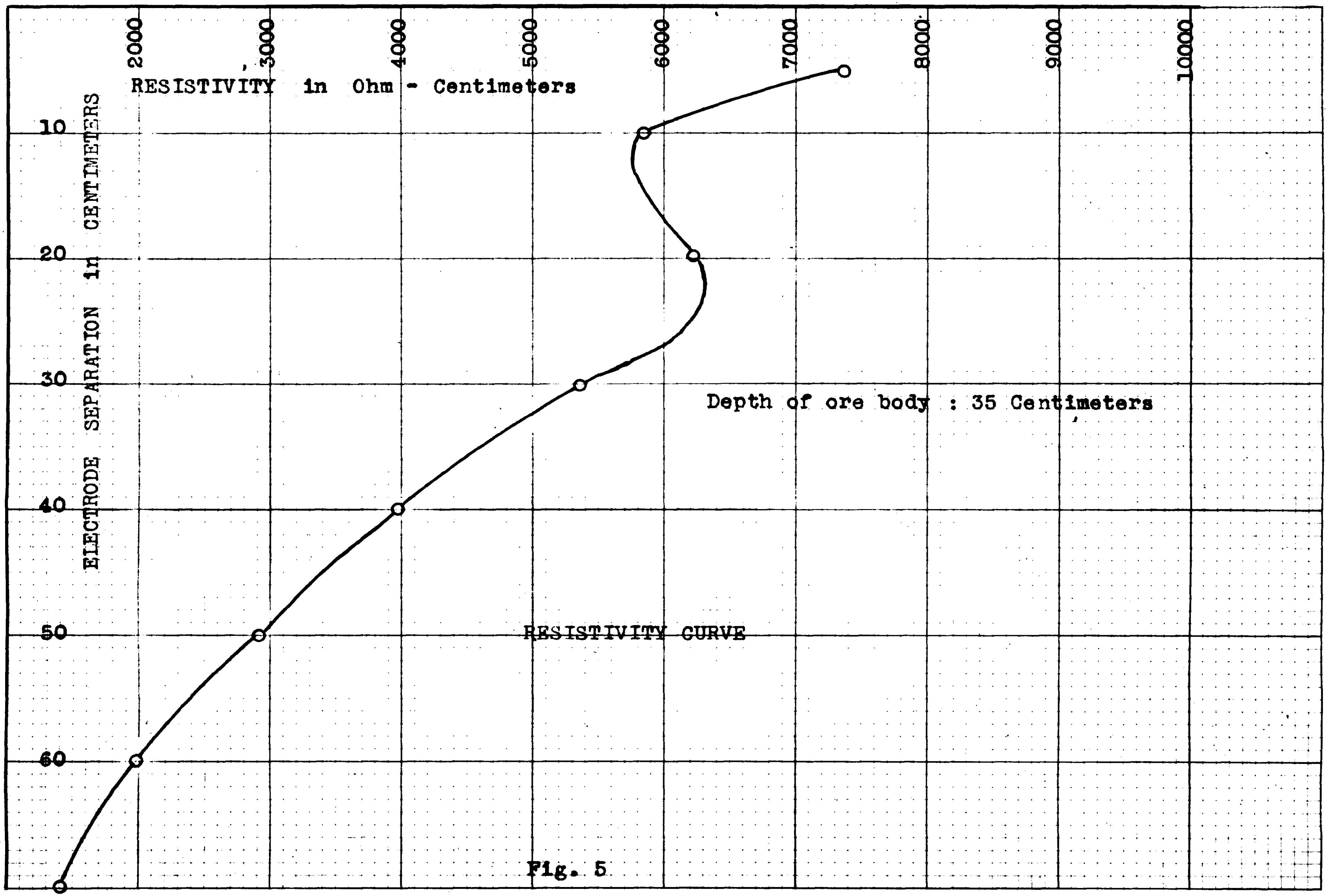

RESISTIVITY in Ohm - Centimeters
2000
3000
4000
5000
6000
7000
8000
9000
10000
ELECTRODE SEPARATION in CENTIMETERS
10
20
30
40
50
60
Depth of ore body : 35 Centimeters
RESISTIVITY CURVE

Fig. 5

Fig. 54

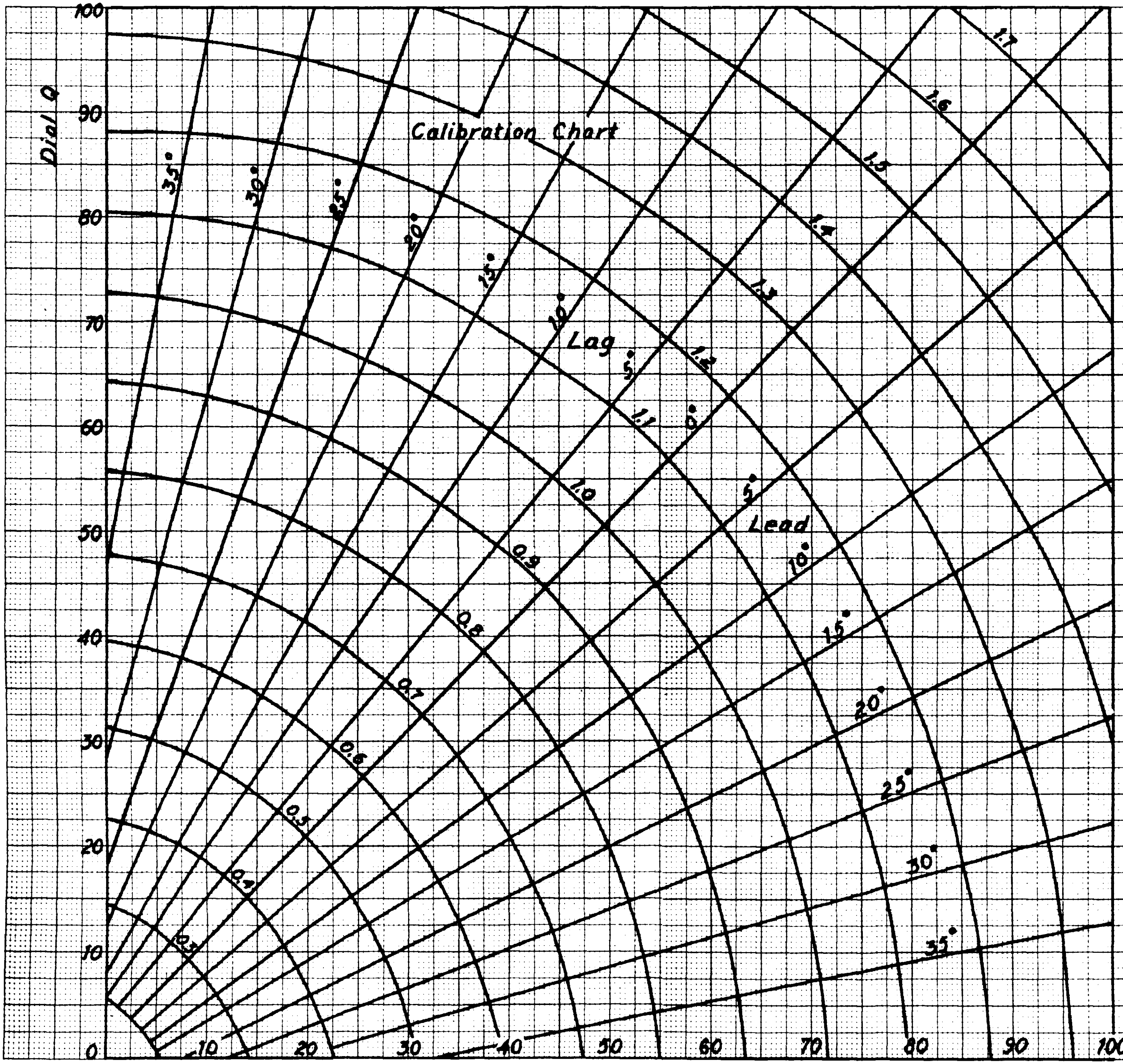
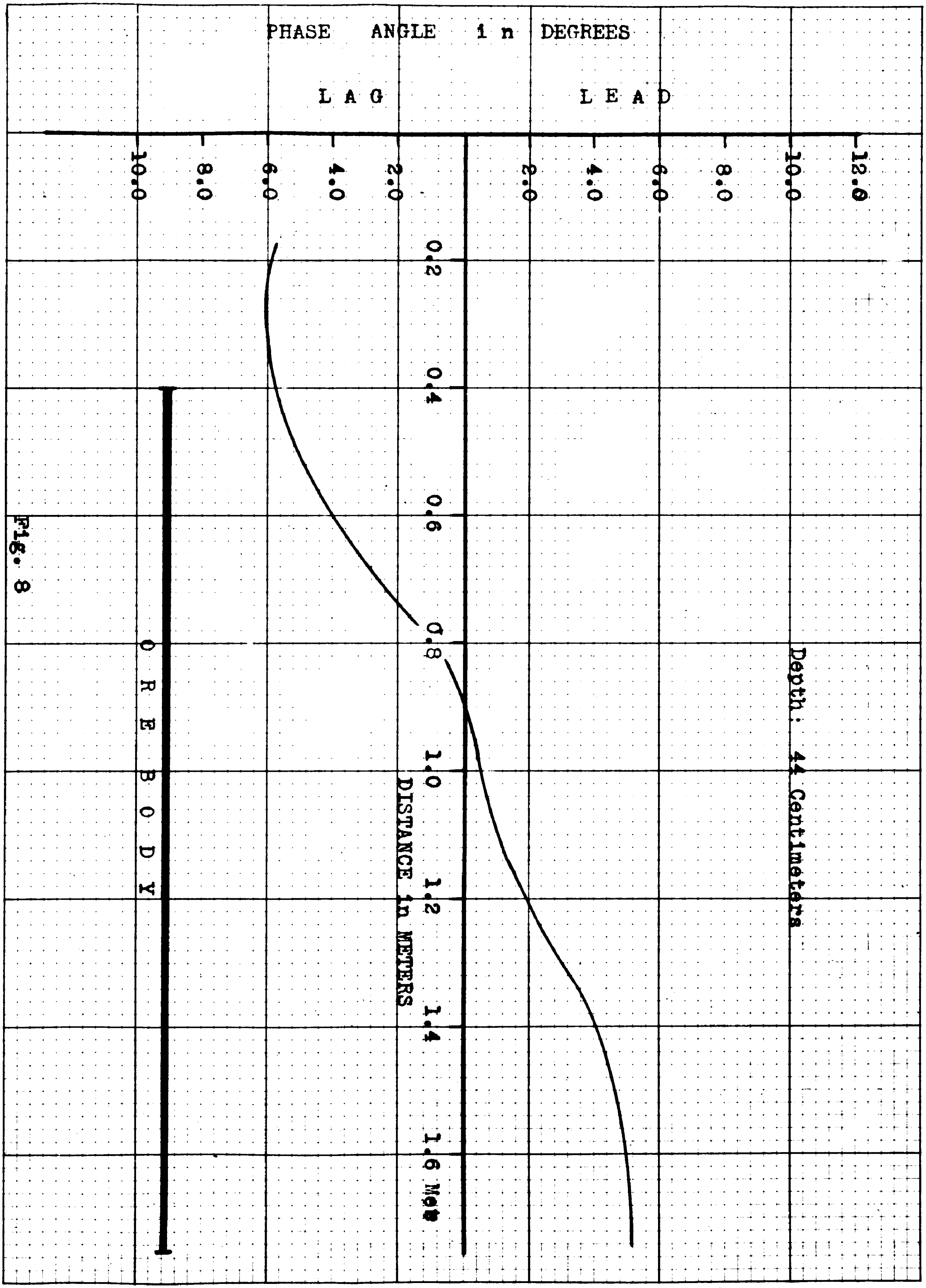
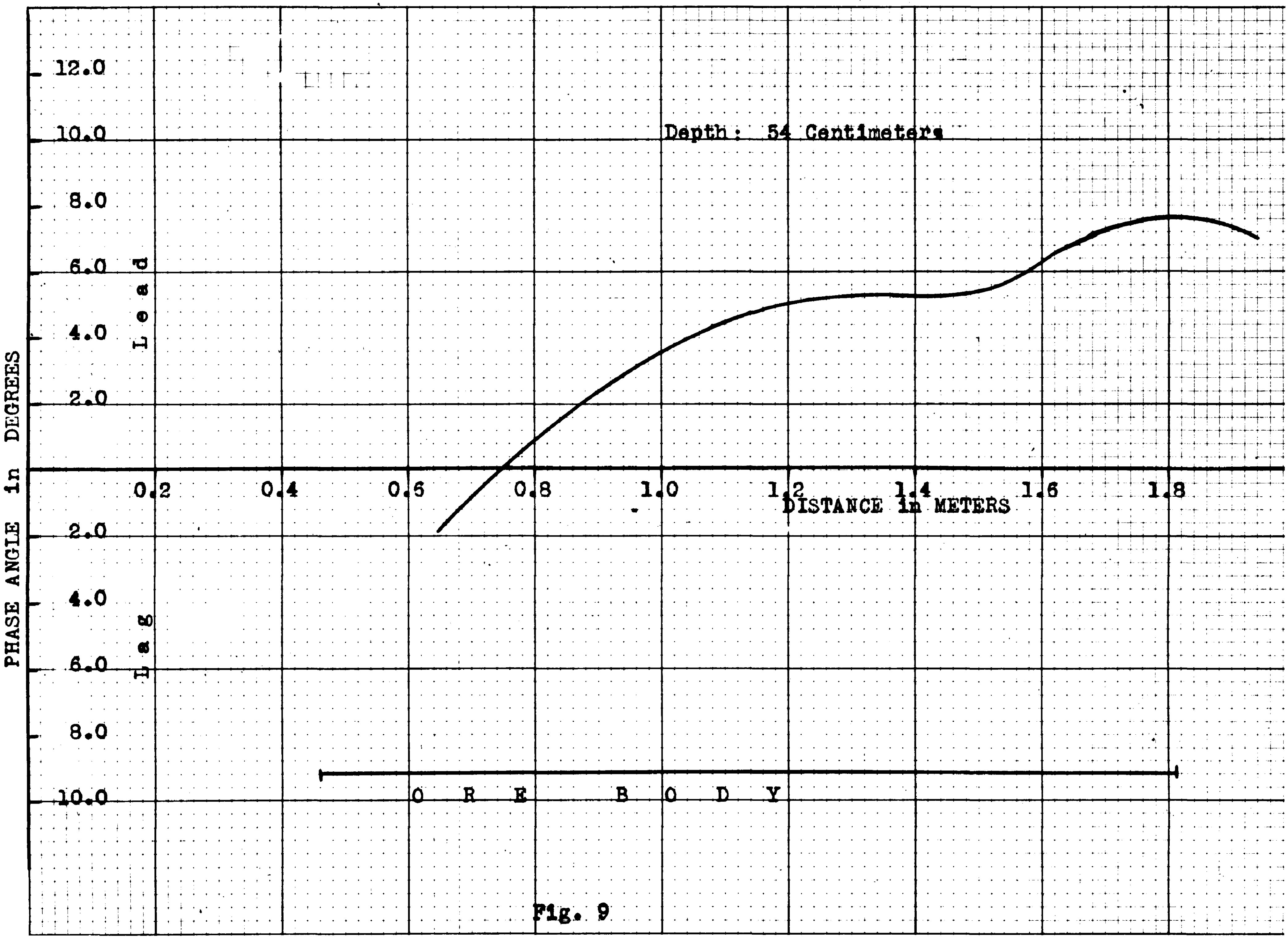


Fig. 7 CALIBRATION CHART FOR THE RATIOMETER


PHASE ANGLE in DEGREES
LAG
LEAD
10.0
8.0
6.0
4.0
2.0
2.0
4.0
6.0
8.0
10.0
12.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6 Met
DISTANCE in METERS
Depth: 44 Centimeters
O R E B O D Y
Fig. 8



PHASE ANGLE in DEGREES
Lead
Lag
12.0
10.0
8.0
6.0
4.0
2.0
2.0
4.0
6.0
8.0
10.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
DISTANCE in METERS
Depth: 54 Centimeters
O R E B O D Y

Fig. 9

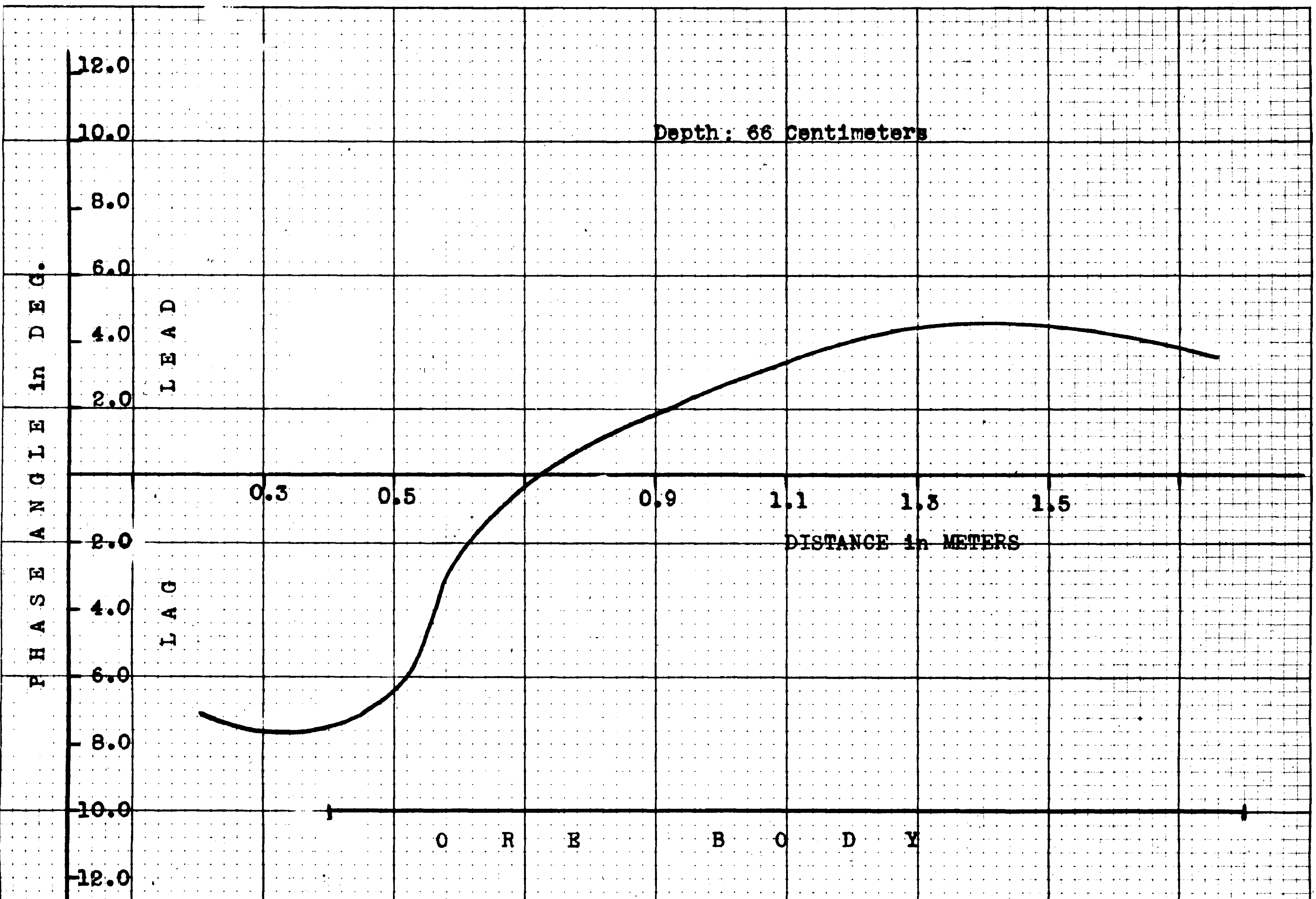

PHASE ANGLE in DEG.
12.0
10.0
8.0
6.0
4.0
2.0
2.0
4.0
6.0
8.0
10.0
12.0
LEAD
LAG
Depth: 66 Centimeters
0.3
0.5
0.9
1.1
1.3
1.5
DISTANCE in METERS
O R E B O D Y

Fig. 10

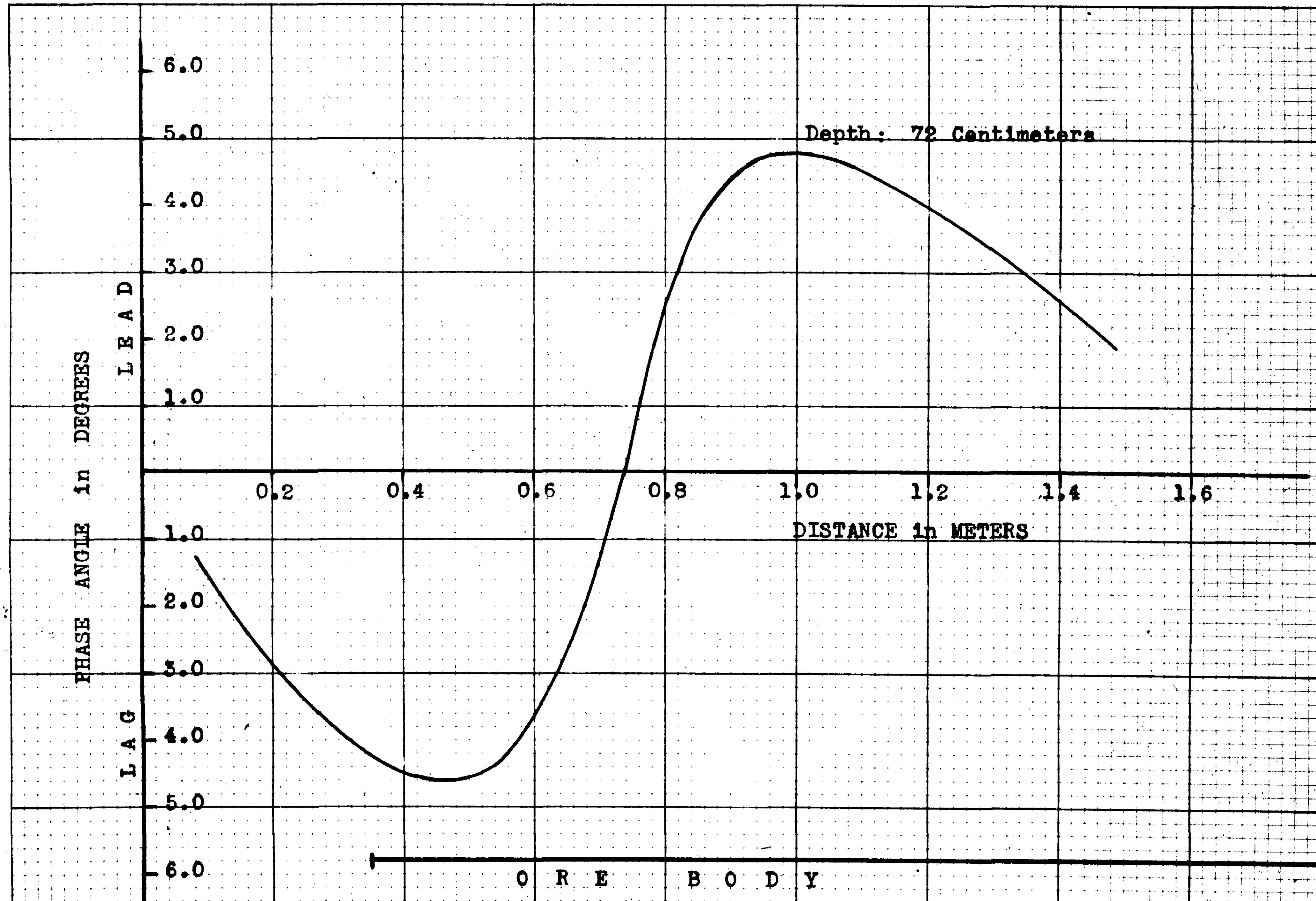
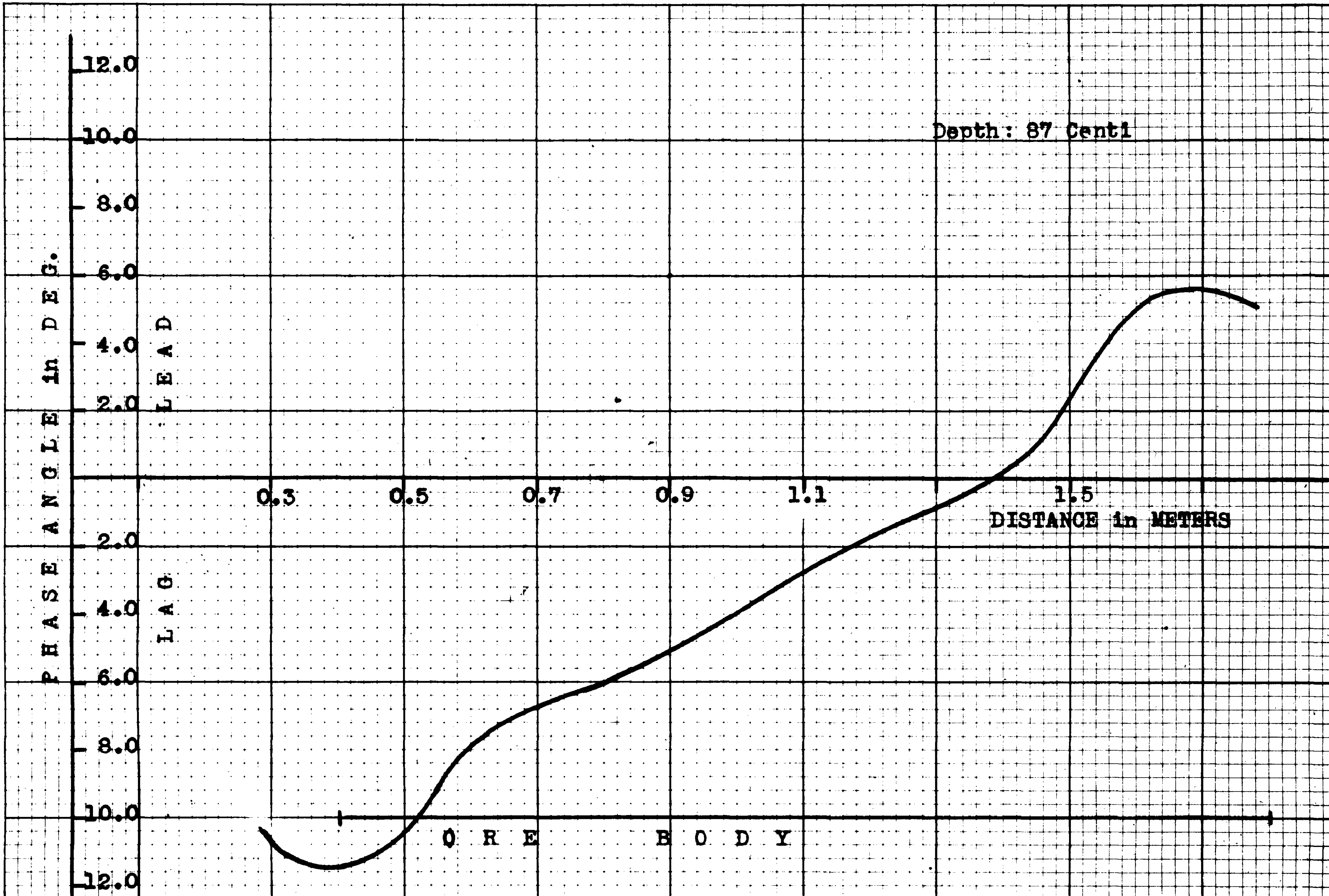

PHASE ANGLE in DEGREES
LEAD
LAG
6.0
5.0
4.0
3.0
2.0
1.0
1.0
2.0
3.0
4.0
5.0
6.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
DISTANCE in METERS
Depth: 72 Centimeters
O R E B O D Y

Fig. 11



PHASE ANGLE in DEG.
LEAD
LAG
12.0
10.0
8.0
6.0
4.0
2.0
2.0
4.0
6.0
8.0
10.0
12.0
0.3
0.5
0.7
0.9
1.1
1.5
DISTANCE in METERS
Depth: 87 Centi
ORE BODY

Fig. 12

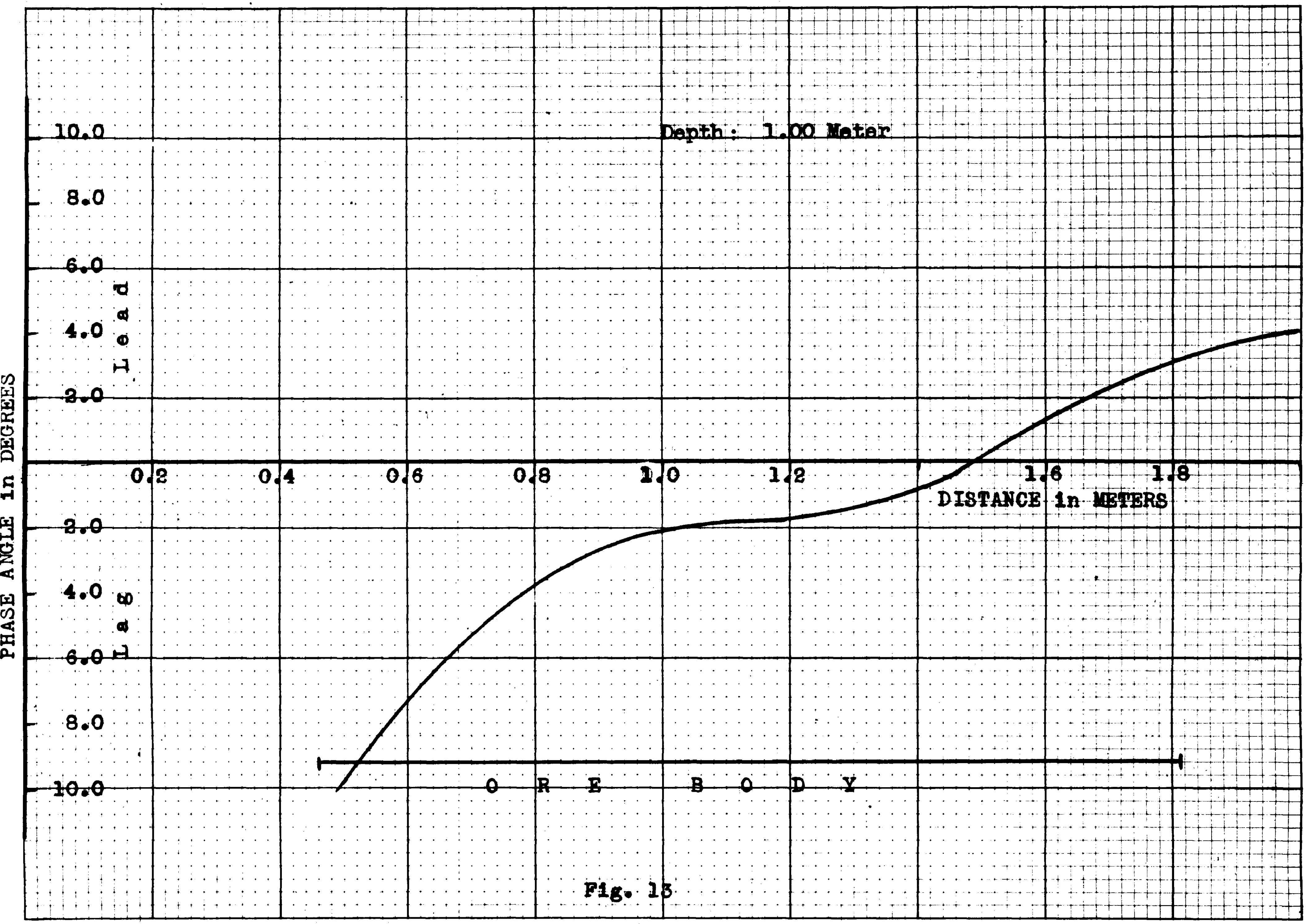

PHASE ANGLE in DEGREES
10.0
8.0
6.0
4.0
2.0
Lead
2.0
4.0
6.0
8.0
10.0
Lag
Depth: 1.00 Meter
0.2
0.4
0.6
0.8
1.0
1.2
1.6
1.8
DISTANCE in METERS
O R E B O D Y

Fig. 13

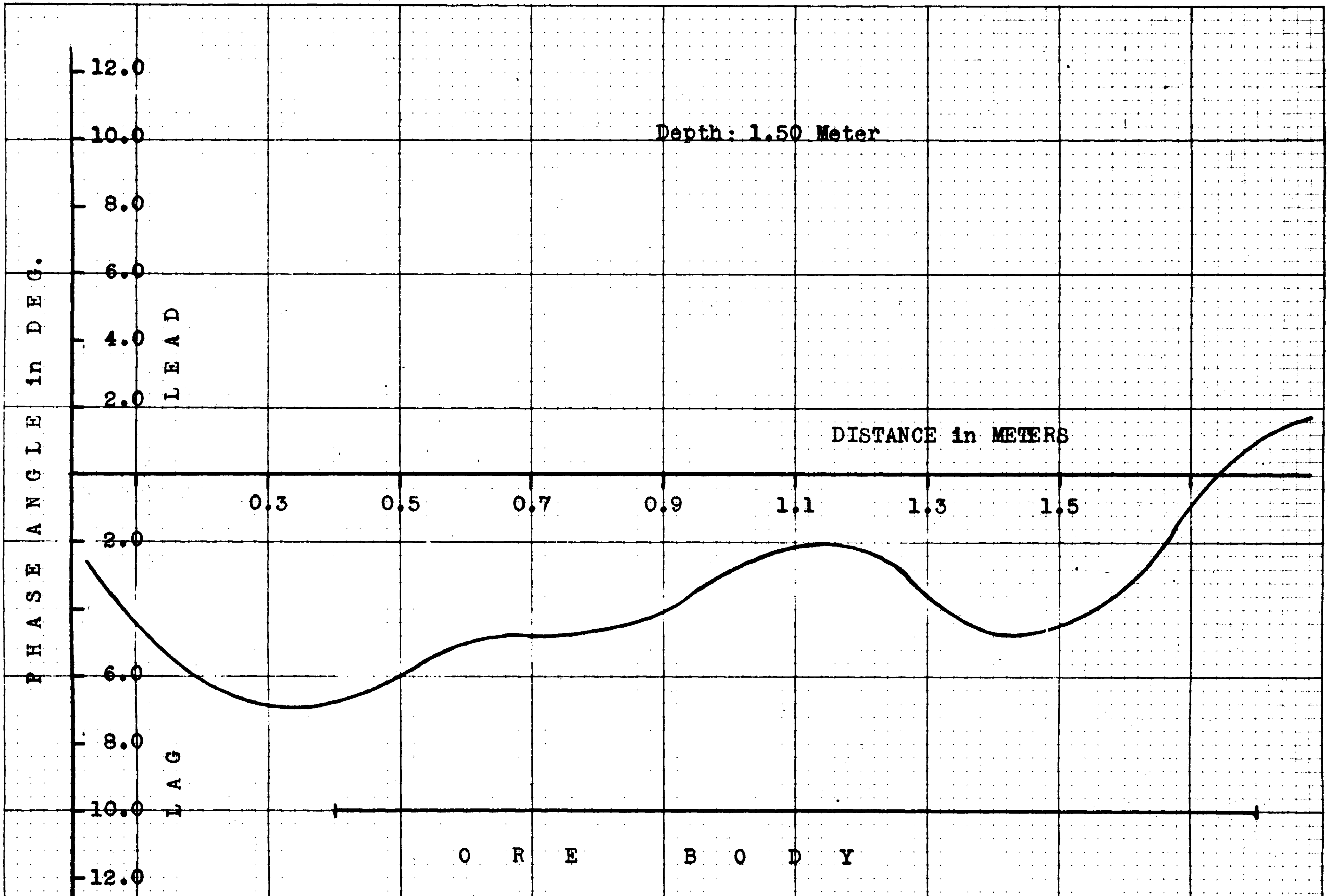

PHASE ANGLE in DEG.
12.0
10.0
8.0
6.0
4.0
2.0
2.0
6.0
8.0
10.0
12.0
LEAD
LAG
Depth: 1.50 Meter
DISTANCE in METERS
0.3
0.5
0.7
0.9
1.1
1.3
1.5
ORE BODY

Fig. 14

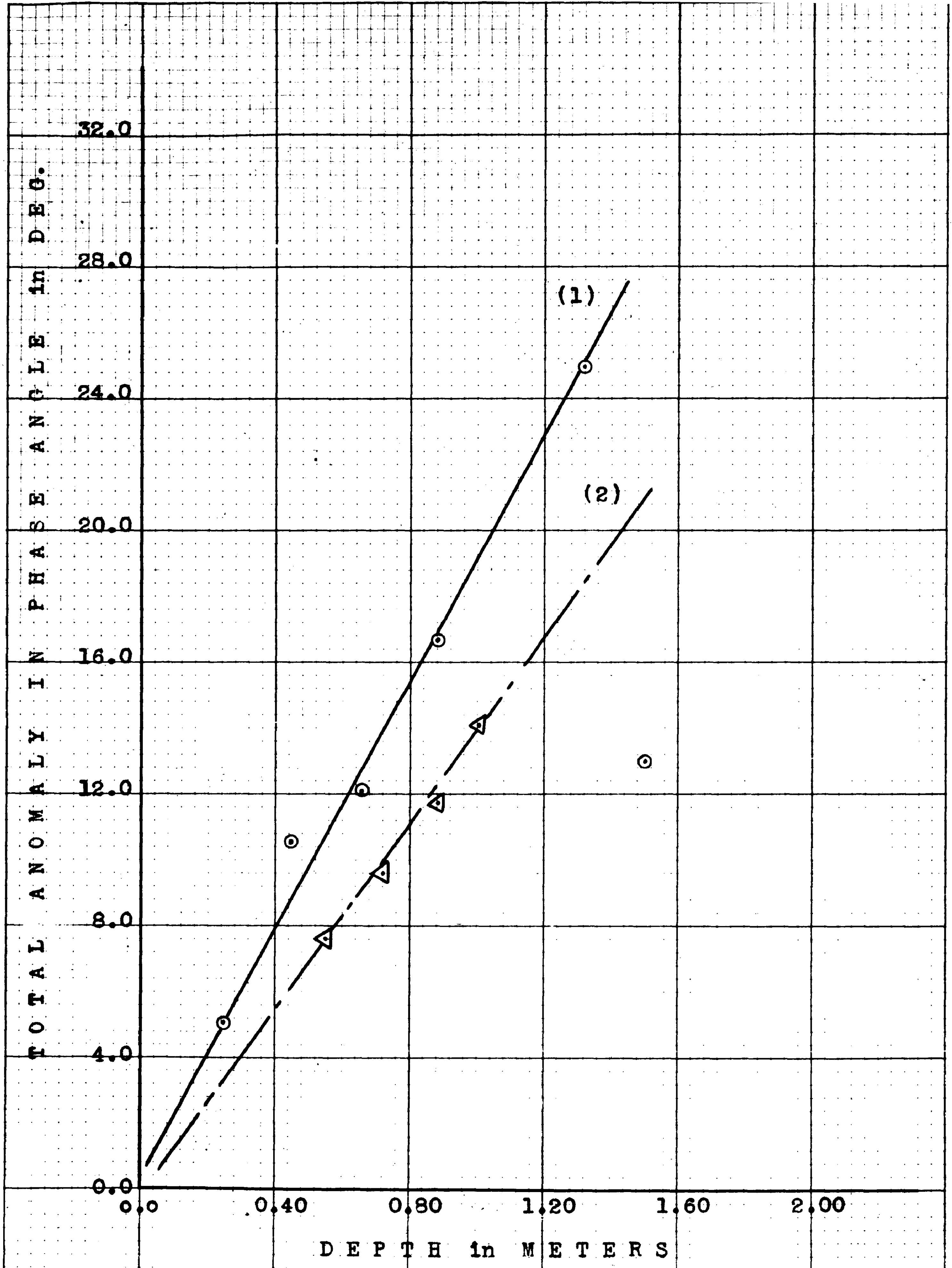

TOTAL ANOMALY IN PHASE ANGLE in DEG.
32.0
28.0
24.0
20.0
16.0
12.0
8.0
4.0
0.0
0.0
0.40
0.80
1.20
1.60
2.00
(1)
(2)
DEPTH in METERS

Fig.15

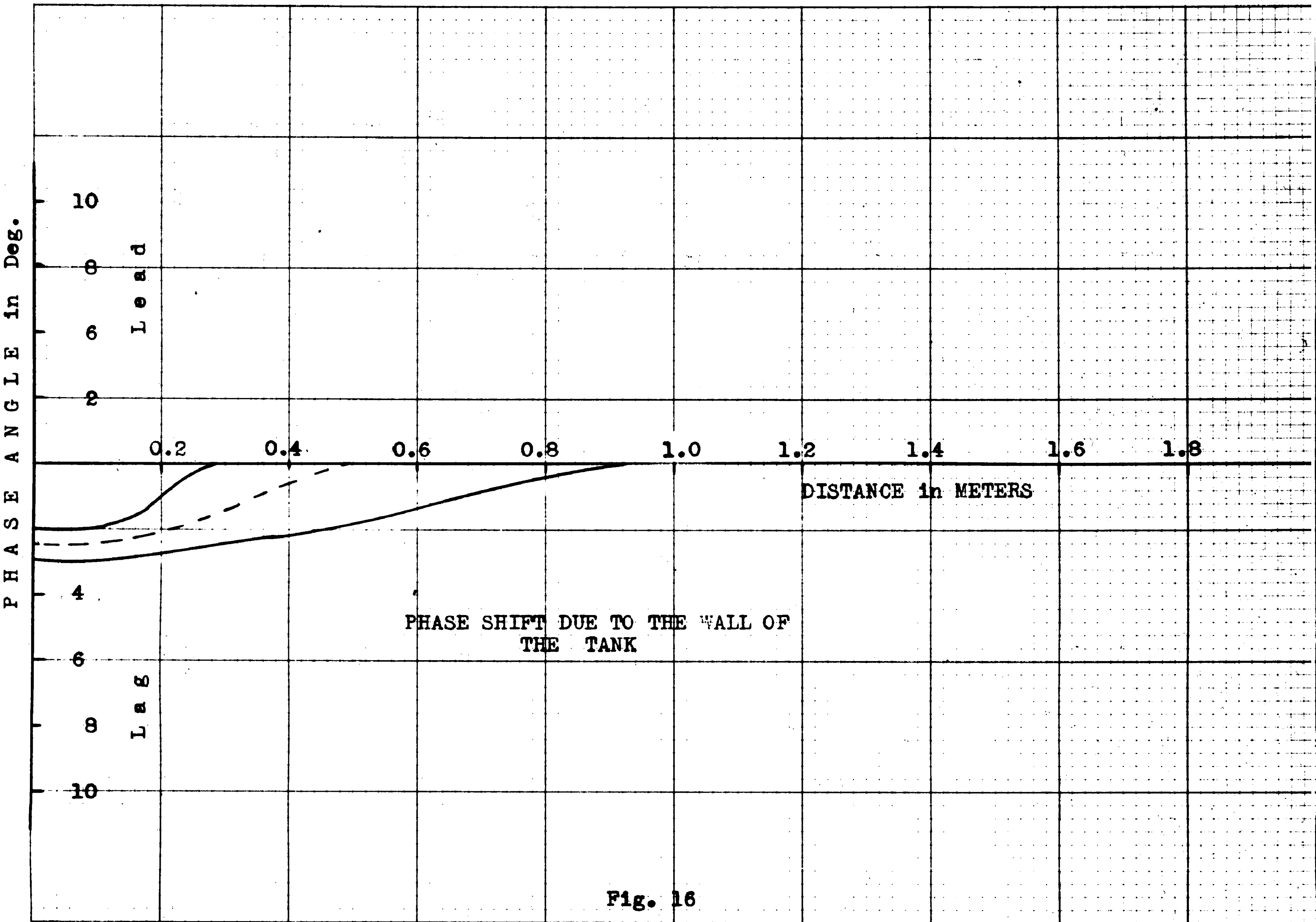
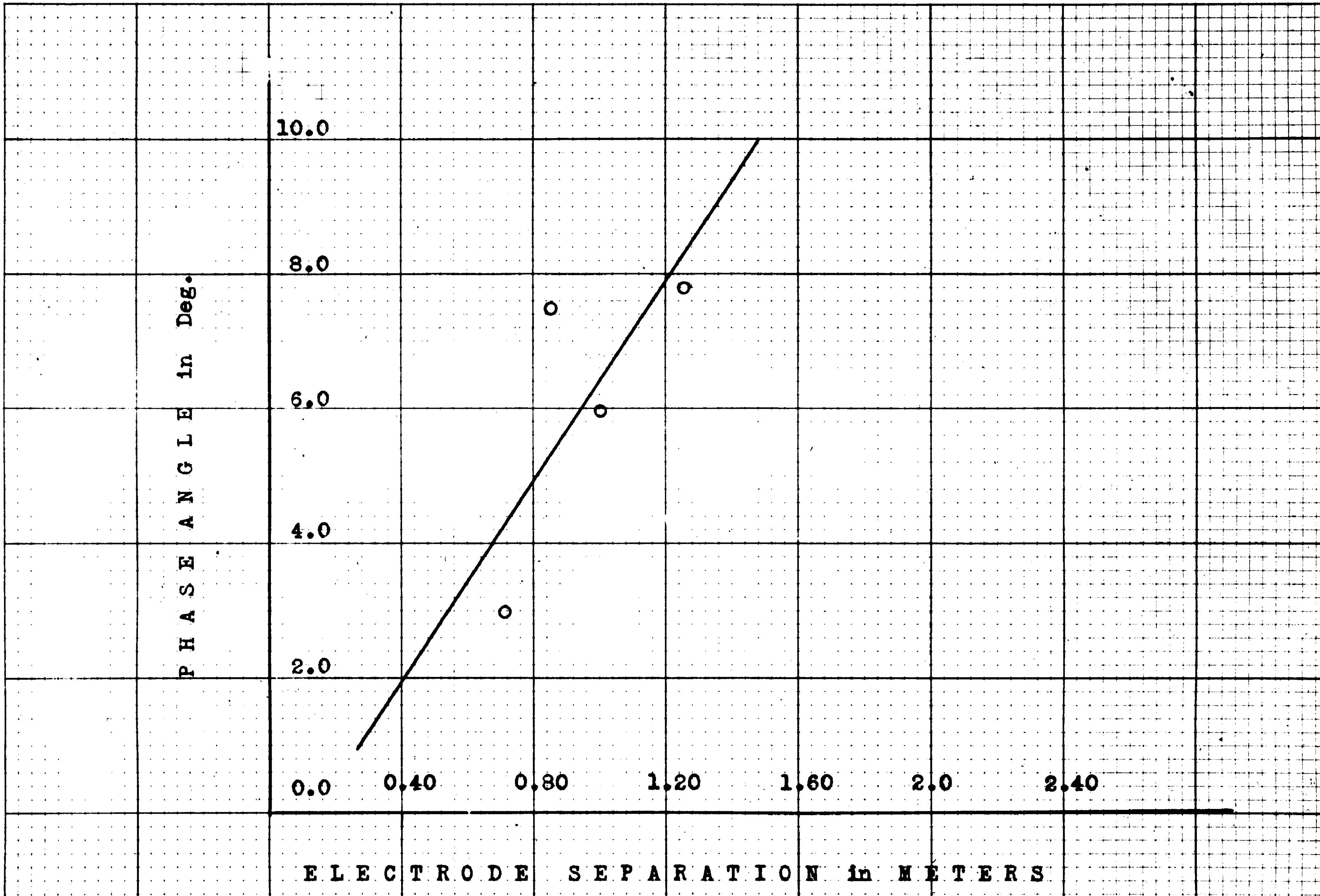

PHASE ANGLE in Deg.
Lead
Lag
10
8
6
2
4
6
8
10
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
DISTANCE in METERS
PHASE SHIFT DUE TO THE WALL OF THE TANK

Fig. 16



PHASE ANGLE in Deg.
10.0
8.0
6.0
4.0
2.0
0.0
0.40
0.80
1.20
1.60
2.0
2.40
ELECTRODE SEPARATION in METERS

Fig. 17

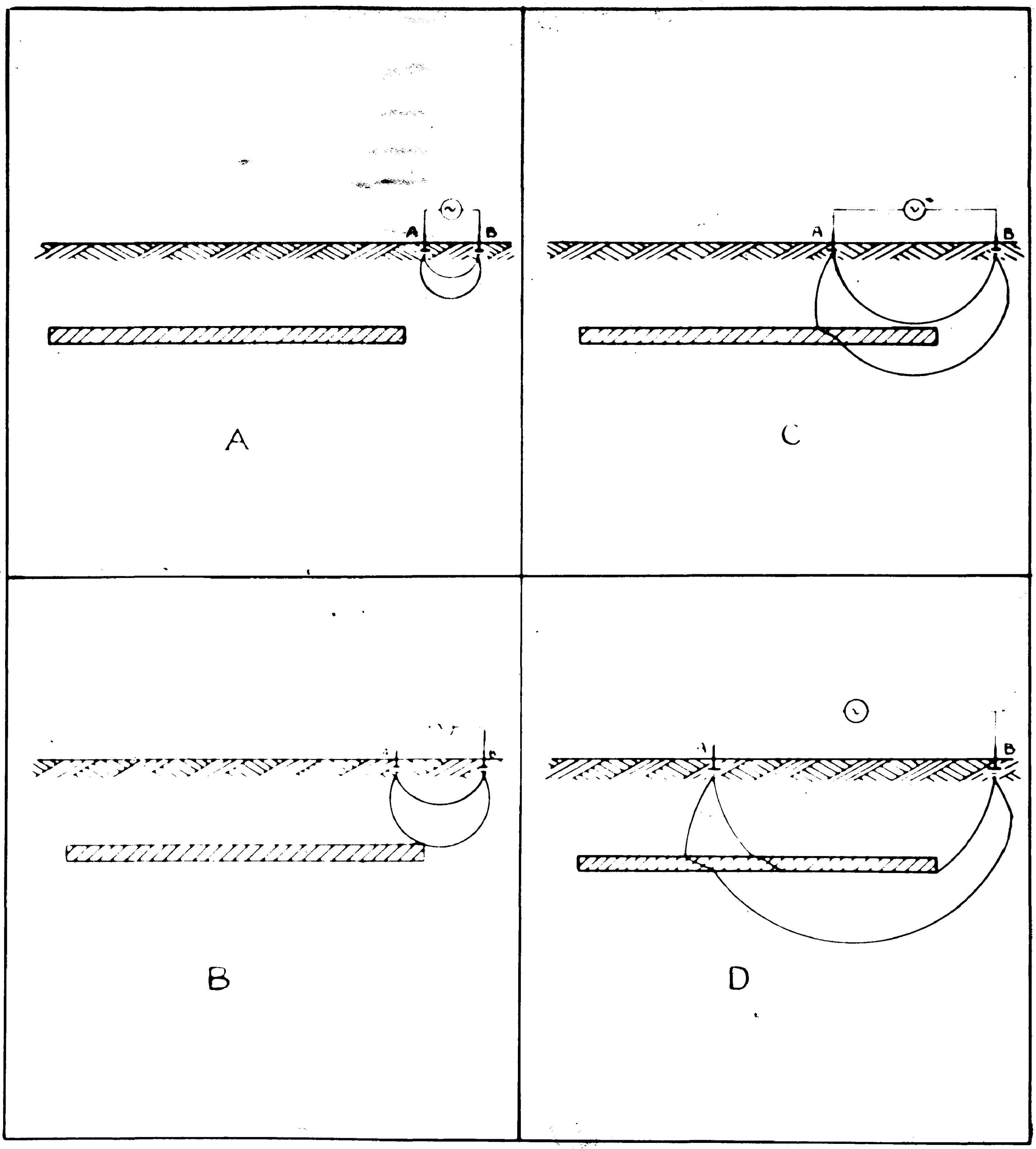


Fig. 18 IDEALIZED CURRENT FLOW LINES
(A) & (B) no phase shift;
(C) & (D) phase shift detected.

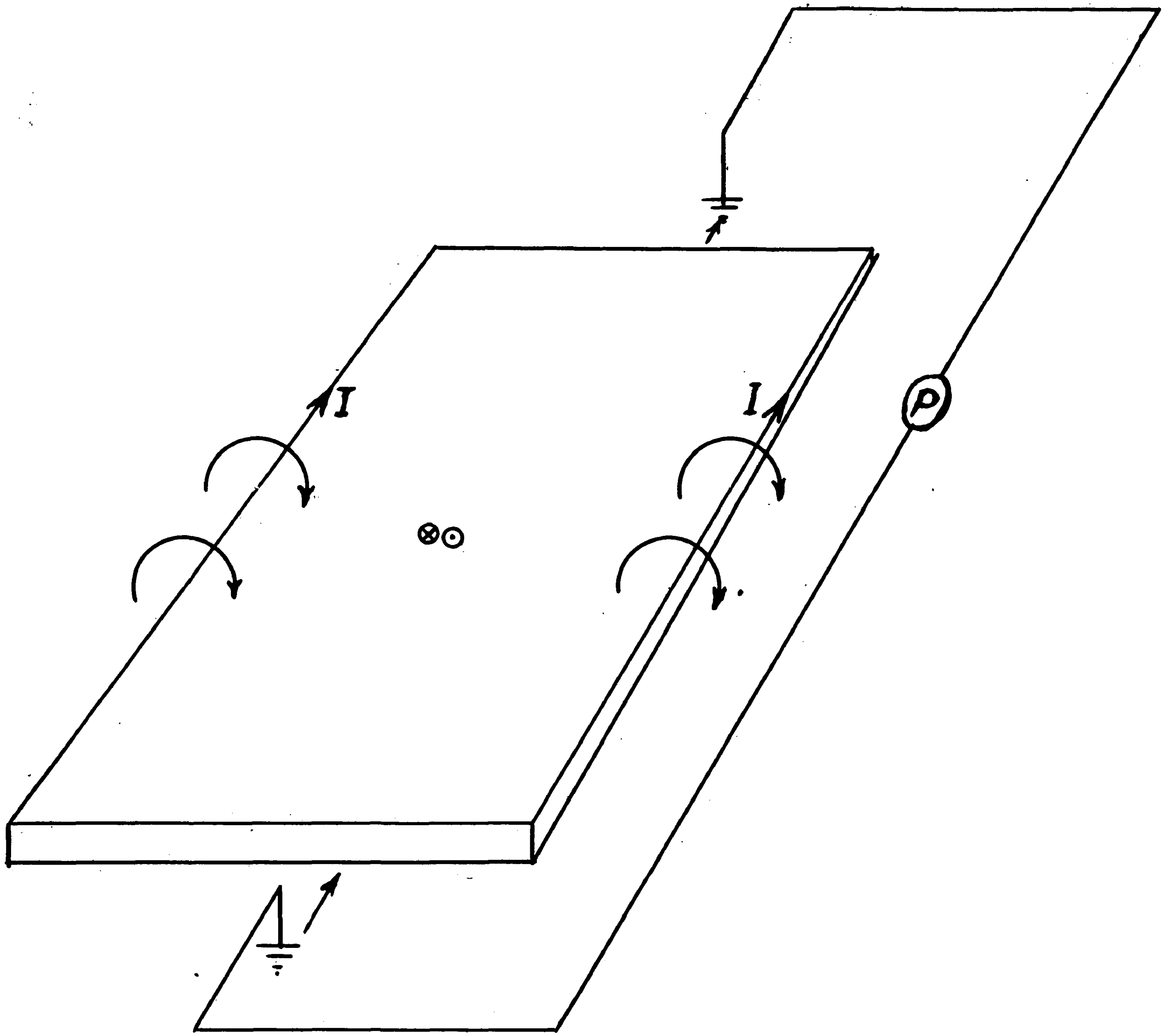


Fig. 19

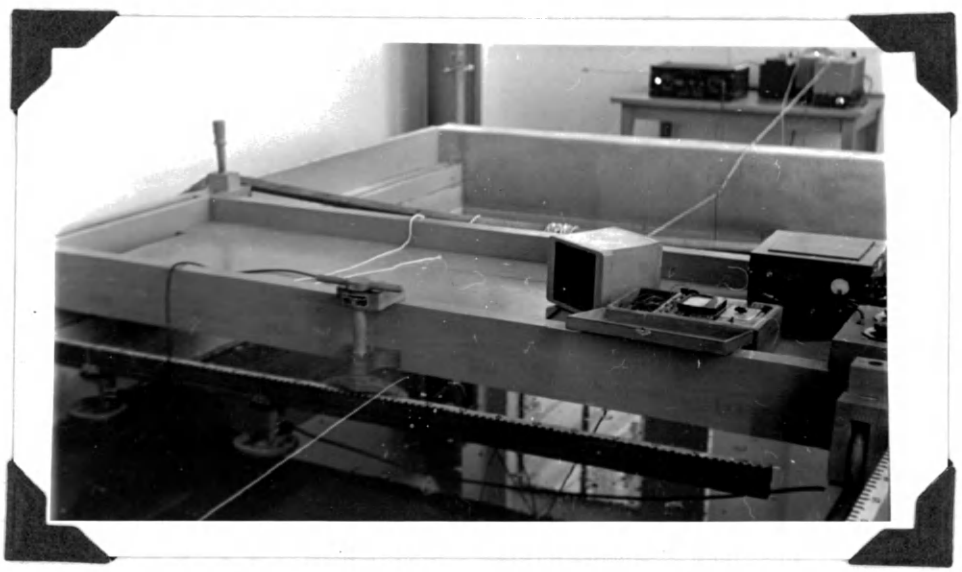


Fig. 20