MODEL EXPERIMENTS ON THIN SHEETS USING A HORIZONTAL LOOP METHOD

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C E R T I F I C A T E

CERTIFIED that the dissertation entitled ' Model experiments on thin sheets using a horizontal loop method' being submitted by Shri RAJENDRA PRASAD KACHHARA in partial fulfilment for the award of the Degree of M.Sc. Tech. in Applied Geology of the University of Roorkee is a record of student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other Degree or Diploma.

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A B S T R A C T

Model experiments on thin sheets simulating a Beiler - Watson system of prospecting at a frequency of 513 c/s constitute the subject presented in this dissertation. The equipment was fabricated and tested in the laboratory and responses of thin sheets have been investigated with its help for different value of their dips, orientations, widths and resistivities , including cases of a fault, a syncline and an anticline.

The theory of electromagnetic similitude has been considered and responses of sheets as a function of ($w\sigma$ ad) have been studied.

C O N T E N T S

CHAPTER I

INTRODUCTION

Electrical methods exploit marked differences in the electrical properties of rocks in adjacent geological formations as a clue to changes in their lithological character. If a source of electrical energy is applied to the earth, currents will spread in it guided by the paths of least resistance. In an inhomogeneous ground the course of these currents will be governed by the distribution of conducting regions, and therefore be irregular much like that of a stream flowing in a rugged country. Measurements on the surface of the electrical potentials produced by these currents or of their magnetic fields can then be interpreted in terms of regional concentration of currents or otherwise. This, in turn, will help elucidate regions bounded by materials of varying conductivities.

Depending upon the availability of theelectrical source, electrical methods can be classified into two groups. The first of these depend upon naturally occuring electrical fields and currents, whilst the second involve actual energization of the ground by an external source.

Naturally occurring electrical currents, have been known to flow in the earths upper regions for a variety of reasons. These occur as undirectional spontaneously polarized sources appearing under certain geological conditions conducive to electrochemical activity. The other constitute periodic currents on a world wide scale and are related to geomagnetic variations. The use of spontaneous polarization is naturally limited to the cases favourable for its production but the latter can be used to delineate conducting or resistive regions upto considerable depths.

In the above methods the distribution of the sources causing the current flow are not known and have to be either deduced or assumed thus increasing the number of variables. By using an external source which offers a control on the conditions of energisation, this limitation can to some extent be removed and the resolvability of the data improved. Currents are induced in the ground either conductively by means of a pair of grounded electrodes or inductively by means of a varying magnetic field produced by a coil carrying alternating current.

In a homogeneous ground energized conductively the distribution of currents depends on the distance between the current electrodes. A well known result shows that the current density at a depth equal to a third of this distance is about 50% of what it is at the surface, and it has been suggested by some investigators that the sensing limit of most techniques using this method of energization lies at this depth. The electrode spacing thus provides a useful control by varying which responses from various depths may be resolved. The configuration of energizing and measuring electrodes are often unique for the nature of the problem involved and for this reason electrical methods have been given rise to a large variety of techniques aimed at improving the information content of the data obtained, and at simplifying the interpretation. Like all geophysical methods, electrical methods are naturally susceptible to the resistivity contrast in adjoining rocks, but for methods employing external energisation another circumstance is effective. This is the coupling between the body sought to be located and the rocks surrounding it on the one hand, and that between the latter and the source, as these will determine the magnitude to which the body to be detected will be energized. If therefore a good conducting ore body is surrounded by highly resistive rocks one may fail to locate it inspite of the large contrast in their resistivities simply because enough energy does not reach the ore body. In such cases energization can be improved by using alternating magnetic fields or electromagnetic fields which find a highly resistive overburden almost transparent. However, if the overburden has a finite conductivity the energization of the ore body will depend on the inductive coupling between the source and the overburden as well as on that between the latter and the ore body.

Inductive methods further differ from conductive methods in that they donot necessitate a direct contact with the ground. This makes it convenient for this method to be employed even on board an aircraft. Airborne electromagnetic methods have been used extensively for location of ore bodies during the past decades and it is expected that modification of these will provide a powerful remote sensing tool for terrain evaluation. Obviously the simple method of controlling the depth by varying electrode spacing cannot be applied to this method but as is shown latter the effective penetration of electromagnetic fields in conducting media are governed by their frequency. The latter therefore can be chosen properly for obtaining responses from a desired depth.

Interpretation of most electrical methods can be reduced to the problem of intergrating the equation which expresses the divergencelessness of the current density vector i.e.

$$\nabla \cdot J = 0$$

or $$\nabla \cdot (\sigma E) = \nabla \cdot (\nabla V) = 0$$

where $J = \sigma E$ is the Ohm's law, or to the solution of the diffusion equation $\nabla^2 A = \mu \sigma \frac{\partial A}{\partial t}$, with appropriate boundary conditions.

Slichter has shown that these solutions can be obtained uniquely under certain conditions but the procedure involved is rather tedious. Other solutions pertaining to specific cases have been presented by several authors particularly to layered formations. However, a relatively simpler approach to geoelectric interpretation lies in the use of models. As the equations expressing electric and magnetic phenomena are linear when ionized and ferromagnetic media are excluded, a linear scaling of the units of space, time and conductivity in the model system with respect to those in the full scale field system which they are designed to simulate, render the model a direct reading reproduction of the field parameters. The conditions for modelling are discussed in a later chapter. Model experiments simulating conditions encountered while using the Beiler - Watson method of proppecting have been included in the present work mainly to test the equipment which has been fabricated in the laboratory.

Applications:

Electrical Methods have been applied to varied types of probelms relating to engineering and mining but its use in the search for oil has been rather limited. Firstly because oil sands have ordinarily a lower resistivity contrast and secondly because of the difficulty of energizing a vary deep section of the earth by an external source. Only electrical sources of global scale such as the telluric currents are able to penetrate the great depths. These have consequently been the only ones to be exploited in oil prospecting. However, electrical methods are extensively used in wells for stratigraphic and lithological correlation and play an important part in the development of oil fields.

In mining, ground water and civil engineering problems on the otherhand electrical methods prove to be a valuable tool as both these kinds of problems involve investigations of only the upper thousand feet of the earths surface.

CHAPTER II

REVIEW OF ELECTRICAL METHODS AND OF ELECTROMAGNETIC METHODS IN PARTICULAR

All geoelectric methods are aimed at elucidating the subsurface distribution of electric currents. In order to achieve this, surface measurement have to be made either of the electrical potentials which they produce or of their magnetic fields. Electrical methods are also classified according to the particular quantity measured. Methods utilizing the former are called surface potential methods whilst those utilizing the latter are called electromagnetic methods. Further they are known as D.C. methods, A.C. methods or radio methods depending upon the frequency of the electrical fields involved.

Spontaneous Polarization:- One of the sources of naturally occuring electrical potentials in the earth is furnished by the various electrochemical actions which take place in certain geological environments. These can be briefly enumerated as follows:-

1. Oxidation Potentials:- These are produced where electronic conductors such as a sulphide ore body comes into contact with ionic conductors such as formation waters or ground water.

2. Electrofiltration Potentials:- These are generated when a liquid is forced through a porus dielectric medium such as sands.

3. Electroosmotic Potentials:- These are produced when the electrotypes of differing ionic concentrations come into contact with each other.

The spontaneous potentials produced on the surface by polarized geological bodies may range from a fraction of a millivolt to a few tens of millivolts and in some cases even to a few hundreds of millivolts, but their use in prospecting is naturally limited to the geological environments favouring the production of Self Potentials.

The electroosmotic and the electrofiltration potentials are extensively made use of in subsurface measurements of potentials in wells as not only are these potentials brought into being when the drilling mud comes into contact with the formation waters but they can also be controlled by varying the pressure and the conductivity of the drilling mud. When so used, the method is referred to as S.P. logging and proves very useful in checking the permeability of formations at different depths and also resistivity of the solutions held by them, with results obtained on the basis of other criteria.

Apart from its occurrence in wells under the influence of the drilling mud, electrofiltration potentials have also been observed where sea water permeates shore formations under pressure.

The spontaneous polarization of ores of pyrite and anthracite have been the most quoted although graphite, pyrrhotite, magnetite and even quartz have been reported to be associated with these potentials. Pyrite is invariably found to be polarised in a manner as to have a negative polarity on its top. This causes positive ions to flow upwards through the surrounding waters causing a potential valley just above the body or, the use a conventional term, a negative center. Anthracite on the other hand is always associated with a positive center proving thereby ~~indicating~~ that its top is positively charged. For a long time the polarisation of ore bodies was explained as arising from its differential oxidation caused by an increase in the oxygen content of the water in the upper regions, even though these were two serious difficulties. Firstly the explanation fails to account for S.P. of graphites which do not normally undergo oxidation and secondly, oxidation of the top of the sulphide ore should librate electrons at that end rather than the reverse situation betrayed by the negative center. Recently sato and Moorey have proposed that the ore bodies merely act as a catalyst whereas the actual source lies in the oxidation potential difference between substances in solution above the water table and those below;

S.P. surveys have been used for locating ore bodies, corroding pipelines, and also for tracing ground water movements. One of the chief sources of interference which S.P. potentials encounter arise from the topographical effects. The normal upward potential gradient of atmospheric electricity tends to produce a current flow from lower ground to more elevated regions and it is not always possible to resolve this effect from the true S.P. potentials. Interpretation of S.P. anomalies is based on the assumption that polarised bodies behave as an electric dipole. The inverse problem of relating the anomaly to its source therefore suffers from the fundamental ambiguity of potential theory, and renders the method incapable of depth control.

S.P. anomalies are usually presented in the form of an equipotential map or a potential profile. Potentials may be measured at various points with respect to a base station or between two electrodes separated by a fixed distance. The latter arrangement is usually exploited to produce a potential gradient map, which is diagnostic of the dip of the body, the gradient being greater in the direction of dip. Either a high impedance voltmeter or a potentiometer can be used to determine potential differences though the latter being null instruments are more accurate. However, in order to ensure that the potential differences measured do not include the effects of electrochemical activity at the earth-electrode contact, non - polarisable electrodes have to be used.

2-i, 3-i

Non-Polarisable Electrodes.- These electrodes are designed to ensure that no potential difference exists between them and the ground whose potential they are intended to assume. This is accomplished by interposing between a metal electrode and the ground, a solution of its own salt e.g. copper sulphate solution for a copper electrode. The solution is contained in a porus pot through which it seeps and contacts the ground. It is assumed that the potential between the solution and the ground moisture is negligible, both being electrolytes, though sometimes an additional outer poruspot containing a dilute solution of the same salt is interposed between the ground and the inner poruspot electrode.

In addition to the S.P. potentialsproduced by electrochemical activity large sheets of world wide currents have been known to flow along the earth's surface. These are called Telluric currents[4-i,1-ii] and unlike the unidirectional S.P. oscillate at frequencies ranging from a few seconds to a few minutes. The actual mechanism whereby these currents are produced is not yet clearly understood but they exhibit a diurnal and seasonal variation strikingly similar to those of the geomagnetic field. Geographically their configuration follows the sun shifting along the earth's surface as it spins.

The time variations of telluric currents over large regions have a similar form, but their amplitudes and directions vary with position depending upon the resistivity of media involved and the time of the day. Mapping of the consequent potential variations with reference to a fixed station thus indicates regions of good or poor conductivity. As the direction of these currents is constantly changing, directional variations in resistivity can also be obtained.

Of all the electrical methods telluric current methods have been the only one to find application in oil prospecting. Arising from a natural source of great potential they maintain a significant flow even at depth of the order of 20,000 feet.

A modification of the method described above, involves the additional measurements of the magnetic fields produced by these currents, and is known as the magnetotelluric method. Cagniard[1-iii] has produced a complete theory for their interpretation. An analysis of the various frequency contents of the magnetotelluric data can be used to yield information regarding the section of the earth to corresponding depths and can thus be used successfully to delineate the trends of the basement or of bedrocks buried at considerable depths.

Methods depending on external energization.

All geoelectric methods employing external energization consist of an energising system i.e. a source of power coupled to the ground either conductively or inductively and a receiving system to which is connected a detector of the necessary sensitivity. For the measurements of the surface potentials the receiver consists of a single electrode or more than one electrodes, Whereas for the measurement of the magnetic field, a fluxmeter or a search coil may be employed. Theoretically, any energizing-receiving system will serve the purpose, but a few have gained greater popularity in view of their greater facility or resolving power. Interpretation is generally accomplished by comparision of the theoretical responses of assumed geological environments to a given energizing-receiving system with results obtained in the field. The methods employing the measurement of surface potential are mainly of three different types depending upon the nature of measurements.

These are the equipotential method (EP), the earth resistivity method (ER) and the potential drop ratio method (PDR).

The EP method as the name suggests involves the mapping of equipotential lines on the surface in the presence of a pair of grounded electrodes which may form a parallel bilinear, or a circular concentric system. The pattern of E.P. lines caused by a given electrode configuration which is appropriately chosen in order to obtain maximum energisation under given geological conditions, will be regular consisting of a family of curves common with the two energizing electrode lines. Departure of the subsurface region from homogeniety will cause distortions of the predictable pattern and thus lend themselves to detection.

Elliptical polarisation

In all conductive methods both direct and alternating currents can be used. The distribution of the latter, however, differs from that of the former because alternating currents involve inductive phenomena with their attendant phase shifting tendencies. The phases of the various current filaments in the ground are therefore out of step with each other and differ depending upon the nature of the subsurface geology. At different points on the surface, therefore electric potentials as well as magnetic fields differ in phase with each other apart from differing in amplitude thus producing ellipitical polarization. Elliptical polarization naturally becomes more significant with increasing frequency and will preclude the mapping of simple equipotential lines as no two points are likely to be equal both in phase and in amplitude. However at a point, the potential vector can be considered to be made up of a vector of certain amplitude ... in phase with that at a reference point and another of a corresponding amplitude in quadrature with it. Whilst using alternating currents therefore, E.P. mapping have to be completed separately for both the inphase and the quadrature components. They are respectively called the inphase and quadrature equipotential lines.

The contours of anomalous equipotentials closely follow that of the body causing it, and thus a qualitative picture of sub-surface geology is readily discernible. Prospecting with E.P. methods can be carried over large areas fairly rapidly and is also relatively inexpensive. These assets make this method eminently suitable for reconnaissance surveys.

<u>Earth Resistivity Method</u>

In the earth resistivity method, the apparent resistivity of the ground as sensed by suitably positioned potential electrodes, is determined. A simple consideration shows that this can be calculated from the knowledge of the total energizing current entering the ground and the potential at a suitable point or potential differences between two selected points. The versatility available in positioning the energising and potentials electrodes has naturally resulted in a great variety of electrode configurations each with their peculiar susceptibilities. One of the most commonly used arrangement is the equispaced Wenner configuration (C —a— P —a— P —a— C) or the reciprocal configuration (P —a— C —a— C —a— P). This system is not necessarily the most highly resolving but results in a simplified expressions for the apparent resistivity ρ_a being equal to $\frac{\Delta V}{I} 2\pi a$. Where I is the total energizing current and ΔV the potential difference between the two potential electrodes.

As has already been indicated that the resistivity so determined will pertain to the section of material which is effectively energized. For the

Wenner system this depth is equal to the spacing between any two consecutive electrodes.

Measurement of the resistivity at a point for varying electrode system expanding about this point, will thus reflect the variations in the lithological character of the ground with depth. When upto a depth the ground is not homogeneous laterally, the effective penetration will differ at different points with a given electrode spacing. Structural conditions involving lateral variations such as those associated with faults, contacts of different formations and variable depth of a marker bed can, therefore, be revealed by measuring the apparent resistivity at various points along a traverse expected to cross these structures, with a constant electrode spacing.

Asymmetrical electrode arrangements are also used according to the nature of the problem involved but then the resistivity will be given by a different expression.

Measurement of potentials:

Potential at any point is always referred to a reference point, usually that existing at one of the energizing terminals. Alternatively differences in potential between two points or ratios of potential differences existing between two successive intervals of ground are measured when D.C. potentials are involved or elliptical polarization is negligible, these can be measured by means of a voltmeter or a potentiometer. The latter is based on the principle that an unknown potential can be determined by matching it against a known but adjustable potential. The condition of equality can be indicated by a detector connected in series with the two sources of potential. In practice this can be achieved as shown in figure 2.1 (a) and 2.1(b).

A rheostat R is connected across a standard cell of e.m.f. equal to V_s or across a transformer which is coupled to the energizing circuit in order to select the proper phase across R. In the latter case the e.m.f. across the resistance R will be $M_1 \times M_2 \times I$ where I is the energizing current and M_1, M_2 the mutual inductances of the two transformers. The fractional tapping a of the rheostat at which the detector shows null thus directly gives the unknown potential at the point with respect to the desired reference point P_1.

Thus $V_{p2} = a \times V_s$ for the case when standard cell is used.

and $V_{p2} = a \times M \times I$ when a rheostat is used. $(M = M_1 \times M_2)$

A variation of the arrangement shown in fig. 2.1(a), consists of a hand driven commutator which simultaneously interchanges the two current terminals about 25 times a second. The current in the Ammeter and the detector thus still flows in the same direction even when the electrode are interchanged but that in the ground alternates with time thus removing the necessity of using nonpolarizable electrodes. This instrument is called the Gish-Rooney instrument. 2-ii, 5-i

A Handy instrument employed for resistivity determinations in the field is the 4 terminal Megger which has a hand driven 50 c/s generator and is designed to give directly the ratio of the potential differences between any two points and the current drawn from the generator. This is accomplished by coupling together two galvanometer coils, one forming tas part of the energizing circuit and the other of the potential circuit.

When elliptical polarization is significant potential at a point with reference to another has to be expressed in terms of an inphase component with respect to the reference, together with a quadrature component.

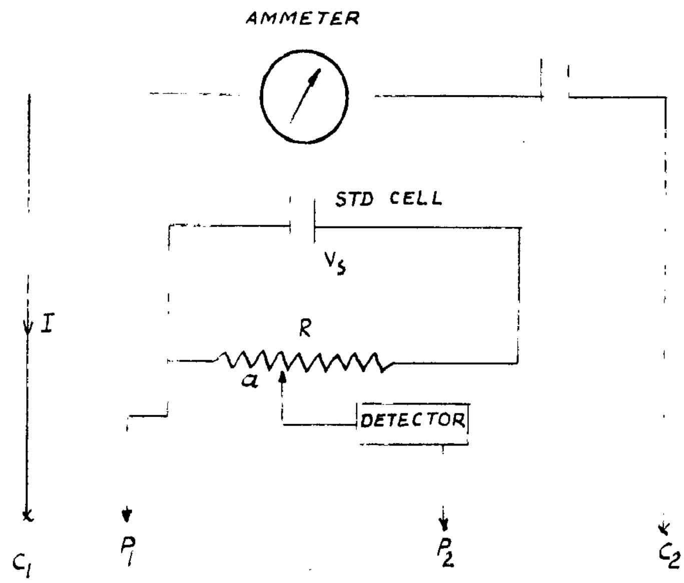


FIG. 2.1 (a)

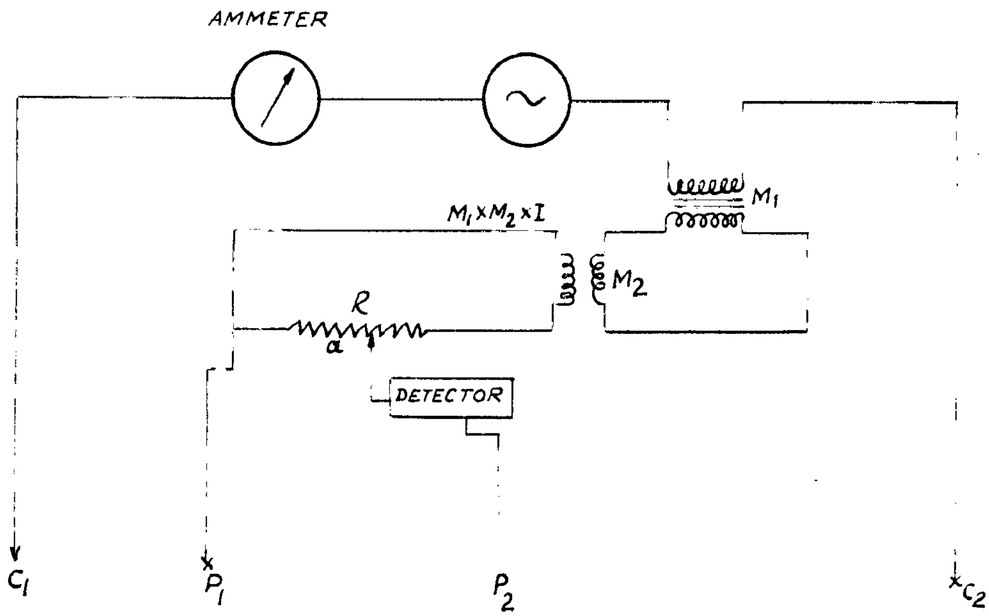


FIG. 2.1. (b)

This is done by obtaining two sources of adjustable potentials, one whose phase always concides with that of the reference and another whose phase is always in quadrature with it. Practically, this is achieved by an arrangement shown in fig. 2.2. Due to inductive coupling the phases of the e.m.f. across the rheostat R_1 and R_2 will respectively be inphase and in quadrature with respect to the energizing current. I.

The fractional tappings a_1 and b_1 on the rheostats R_1 and R_2 give the imphase and Quadrature components of the potential at P_2 with respect to that at P_1.

In some cases it is desired to measure ratios of potential differences between successive intervals of the ground. This can be done by a variety of instruments called the Ratio Compensator or simply the Racom. One such direct reading instrument is shown in fog. 2.3.

Here $V_1 = i\ R_1$

$$V_2 = i\ R_2/1+R_2\ jwC$$

$$\frac{V_1}{V_2} = \frac{R_1}{R_2}\ (1+R_2\ jwC)$$

$$= R_1\ \left(\frac{1}{R_2} + jwC \right)$$

Both R_2 and C can be calibrated according to the last result to give the inphase ratio and the quadrature ratio directly.

The potential drop ratio so obtained can be used (a) to determine absolute potential differences between other points with respect to a reference by multiplying the consecutive P.D.R's.

$$\text{Thus } \frac{V_1}{V_u} = \frac{V_1}{V_2} \times \frac{V_2}{V_3} \times \frac{V_3}{V_4} \text{ ——— } \times \frac{V_{u-1}}{V_u}$$

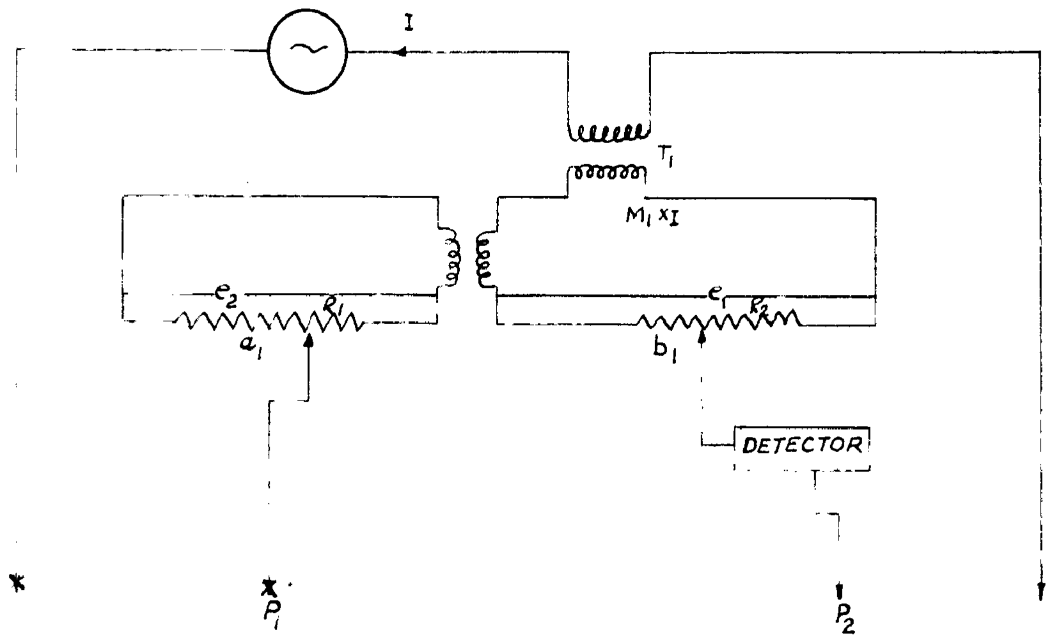


FIG. 2.2

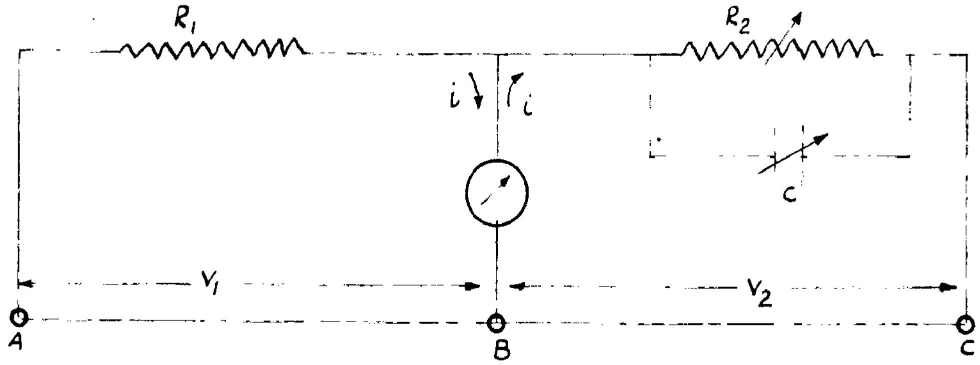


FIG. 2.3

This adjustment is sometimes used in E.P. method to determine potentials at various points before drawing the equipotentials.

Besides, P.D.R's can be used directly for enterpreting the sub - surface geology and often with the highly desirable results. As the P.D.R's resemble potential gradients they have a higher resolving power. When used for direct interpretation they are called the Potential Drop Ratio method and involve measurements of P.D.R's at varying distances from one of the power electrodes and at right angle to the line joining the two current electrodes.

Eltran Method 1-IX

A widely used method in America uses energization of the ground by means of transient current or magnetic pulses instead of continuous electromagnetic fields. These pulses may be of square shape or saw toothed. The signals returning to the surface through the ground are analysed by a receiving system, which consists of two potential electrodes separated by a distance of 300 meters, the distance between the two pairs (energising and receiving electrodes) being much larger than 300 meters.

The method is based on the dispersion and differential attenuation of electromagnetic fields of different frequencies in conducting media. The Fourier components of the transient pulses are not only dispersed after their passage through the earth but are also attenuated to varying degrees. They, therefore recombine on the surface to produce a pulse of different shape than that of the transmitted wave. This deviation is in turn used as a measure of subsurface variation in conductivities. The distortion will naturally increase with increasing frequency. However, one great disadvantage of this method is the relatively small penetrability of high frequency components of a pulse. Thus a greater resolvability at the same time also leads to a blunting of the edge of Eltran methods, and as in other electromagnetic methods an optimum frequency has to be chosen for a given region.

Induced Polarisation method:

If a current flowing into the ground is suddenly intercepted it is observed that the voltage does not drop to zero instantaneously and some fraction of the initial value still persists even after a few seconds. This phenomena is termed as induced polarization or over voltage and its varying propensity for different geological conditions renders it a potential exploration technique.

The magnitude of overvoltage may be expressed in two ways i.e. (i) by $\frac{\Delta V}{V}$ (millivolt per volt of initial voltage or as percentage) where ΔV is the magnitude of the voltage persisting at a definite time t after the interception of the current, and (ii) in terms of the area under the decay curve.

It is also observed that on introducing a current in the ground the potential grows to its maximum value after a definite time. If, therfore, an alternating current is applied to the ground, the potential will be found to lag on the current. The ground therefore will appear to behave as a medium whose impedance varies with the frequency. The overvoltage at different frequencies can be measured in terms of its value for D.C. i.e. in terms of $\frac{Zo}{Zf}$ where Zo is the impedance at zero or near zero frequencies and Zf that at frequency f.

The relaxation curves although resembling dielectric behaviour often show a hyperbolic decrease and not exponential as characterised by dielectrics.

The origins of overvoltage is related to the back e.m.f. or electrode polarization commonly observed at conductor - electrolyte interface. However overvoltage seems to be normally present even in non-conducting materials particularly where clay particles are present. This is termed the 'normal effect' and has to be corrected for whilst interpreting overvoltage anomalies.

Electromagnetic Method:

Electromagnetic methods differ from other electrical methods in that the magnetic field is measured rather than the electrical potentials. However the energization may be conductive or inductive. The former are called conductive electromagnetic methods and the latter inductive electromagnetic methods.

An essential difference between the electrical and electromagnetic methods is the increased sensibility of the latter to currents flowing in deeper regions. The variations in the surface electrical potentials caused by sub-surface inhomogenities, in fact, reflect the degree to which inhomogeneous conditions have squeezed together or drawn apart the current lines near the surface. Thus the currents flowing in deeper regions have only an indirect influence, on the surface potentials. In contrast with this the magnetic field at the surface will contain the direct effect of all current lines, even though their relative contributions decrease with the depths at which they are flowing. Conductive electromagnetic method thus show less sensitivity to superficial inhomogenities and greater awareness of the deeper current flow than the resistivity methods.

Another difference between electric potentials and magnetic fields at thesurface arises from the absence of the vertical component of the electric field which ensures that the ellipse of its polarization lies in the surface of the earth. The ellipse of polarisation of the magnetic field on the other hand will have any arbitrary disposition in space and will therefore require six quantities for its complete definition i.e. the plane of the ellipse, the major and minor axes and the inclination of one of the axes with the horizontal. The plane containing the ellipse is known as the plane of silence and can be easily determined by using a direction finding coil, free to move in azimuth and dip.

If the coil is now set prependicular to the plane of silence and rotated about an axis also prependicular to the plane, it will produce a maximum and a minimum signal which will yield the magnitudes and direction of the major and minor axes of the ellipse.

The method thus provide a complete determination of the elliptically polarised electromagnetic field, but proves to be rather tedious in practice. Besides, the accuracy obtained is very low, as unlike the e.m.f. induced in a coil by a linearly polarised field which produces a sharp minima expressed by the famous 'figure eight', the elliptically polarised field produces an e.m.f. described by a degenerate 'figure eight' with ill defined maxima and minima.

Fortunately, however, it is seldom necessary to determine all the parameters of the ellipse, and measurements are restricted to those of the strike and dip of the ellipse, or of the phase and amplitudes of the fields produced by the inhomogeneous bodies. These are called secondary fields and can be measured absolutely by means of a valve voltmeter and without reference to phase, or semiabsolutely i.e. in terms of a reference field, usually the primary field. The latter quantities are naturally independent of fluctuations in the energizing current and are therefore usually adopted.

<u>Conductive electromagnetic methods:</u>

As has been already remarked these methods are a variation of equipotential line methods or earth resistivity methods with the difference that magnetic fields are measured. The energizing system ~~is~~ usually consists of a single straight wire carrying a source of power grounded at both ends or a ⊔ shaped lead grounded at the two ends. The latter has the advantage that if the legs of the ⊔ are long, the effect of the current flowing in the leads will be very small on the imaginary line joining the legs, along which measurements are made. The electrode separation may be kept fixed or increased as in theEarth resistivity method depending upon whether lateral variations or depth variations are to be mapped. The legs are usually kept about twice as long as the depth to be worked, and the region near the legs is avoided.

The receiving equipment may consist of a magnetometer if direct currents are used or a search coil when A.C. is used. The former gives the values of field intensities which are plotted against electrode separation for the fixed position of the magnetometer or against the position of the magnetometer for a fixed electrode spacing. The latter produces an e.m.f. which gives the mutual impedance Z. This quantity will naturally differ when the ground involves materials of different conductivities. Further as the mutual impedance is also dependent upon the frequency a plot of Z versus f will reflect variations in the subsurface conductivity.

In another variation of the conductive electromagnetic method due to ELBOF,[2-IV] the strike and dip of the ellipse of polarization is used as a clue to the departure of the subsurface from homogeneity.

<u>Inductive Methods:</u>

The possibility of inducing electrical currents in subsurface conductors lying at depths, by a varying magnetic field has proved to be a powerful tool for external energization in regions where surface rocks are highly resistive and preclude the penetration of currents. This is accomplished by laying an insulated straight cable or loops of wire carrying alternating currents.

Inductive methods have been classified by older authors as Horizontal loop and Vertical loop methods. The former employ large (1 sq. mile) rectangular or circular current carrying coils and insulated from the ground while the latter employ coils wound on a vertical frame. The disadvantage in setting up a vertical coil are mainly that of its restricted size, but this is often offset by the greater energization that it can produce in vertical or steeply dipping bodies and the comparatively small interference from more or less horizontal surface formations. Further more, use of higher frequencies can partially compensate for the decrease in its area.

Vertical loop methods.

All vertical loop methods are primarily one of direction finding though when lower frequencies are used, comparision of the axes of the ellipse may be made. This latter will be described later in connection with the horizontal loop methods.

The direction finding involves the determination of the dip and strike of the ellipse. The strike is determined by rotating the search coil in azimuth about a vertical axis, till it gives a minimum signal and the dip by rotating it about a horizontal axis prependicular to the strike till a minimum is obtained.

3-iii

One of the arrangement usually referred to as 'RADIORE PROCESS' consists in setting up a vertical energising coil above the conducting zone with its plane approximately parallel to the anticipated strike of the zone.

Measurements are made of the strike and dip with a search coil, whose center is aligned with the plane of the energizing coil. In the absence of an anomaly the search coil will show a minimum for that vertical plane (indicating zero strike) which is prependicular to the line joining its centre with that of the energizing coil and lying in the plane of the latter. Strike directions are therefore measured with reference to the line of centres of the two coils. The method has been used both with a moving transmittor called the PARALLEL LINE METHOD, and with a FIXED - TRANSMITTER SYSTEM. In the former both the transmitter and the receiver are first oriented so that the plane of the former passes through the centre of the receiver, then they are both moved at regular intervals prependicular to the strike of the zone, and measurements of dip made at these positions.

When the transmitter is fixed its plane has to be rotated for every new position of the search coil in order to ensure that its plane passes through the center of the receiver. Traverses in this case are taken along a line prependicular to the anticipated strike.

SHOOT BACK METHOD

In uneven terràin, however a slight misalignment of the transmitter receiver system will lead to spurious dips called ' phantom dips'. This can be eliminated by a modification of the method called the 'SHOOT-BACK' METHOD.

This system has two similar units each consisting of a transmitter and a receiver kept a fixed distance apart, which may be about 200 ft. The whole assembly is moved along a predetermined traverse line. To begin with their axes are kept parallel to the traverse. The first coil is then energized and its axis tilted at about 15^{o} below the horizontal, and the other coil is used as a search coil, the angle of dip determined by rotating it about a horizontal axis prependicular to the traverse. The second coil is then energized and its axis facing the first coil inclined at 15^{o} above the horizontal. Now the first coil is used as a passive coil and gives the angle of dip. In the absence of an anomaly the two measurements will give equal results even for very rugged terrain. One the other hand any anomalous effect will appear oppositely in the two sets of measurements. The difference of the two results can therefore be taken to be an index of the anomaly and interpreted in terms of the subsurface geology with the help of type curves.

3- IV

A variation of the 'Radiore Process' is the MASON, SLICHTER AND HAY METHOD in which a vertical energizing coil is set up with its plane approximately parallel to the anticipated strike of the body. Measurements of strike and dip are made along a traverse which is prependicular to the plane of the energizing coil and passes through its center. The zero strike for this case will correspond to the plane of the search coil coinciding with that prependicular to the plane of the energizing coil. The latter, thus provides a reference for the measurement of the strike direction

HORIZONTAL LOOP METHOD

The horizontal lopp method also possess a large family of methods which differ in (a) the quantity measured and (b) the manner in which the measuring points are distributed with respect to the energizing loop.

The quantities usually measured in horizontal loop methods are one of the following:

1. Ratio of the quadrature vertical component of the secondary

field in terms of the primary vertical field (KOENIGSBERGER RING INDUCTION METHOD)

2. Ratio of the quadrature horizontal component of the secondary field to the vertical primary field (B EILER - WATSON METHOD)

3. Ratios and phase differences of fields (either vertical or horizontal) in successive ground intervals (TURAM METHOD)

In all these methods a large loop, circular or rectangular is laid on the ground and measurements are made within it and about a quater of the diameter removed from the sides.

The RING INDUCTION method of KOENIGSBERGER has four coils all placed horizontally. In addition to the outermost primary loop which is circular, another smaller neutralizing loop is laid concentric with it and is so disposed as to annul the primary field in a search coil placed inside. The latter therefore only picksup a secondary field in quadrature with the primary, as the inphase component of the secondary field will automatically be backed off in the balancing process by adjustment of the neutralizing coil. The fourth coil carries an adjustable current which is tapped off from the primary energizing system and differs in phase with the primary by 270°. Adjustment of the current in this coil thus annuls the entire field in the search coil and provides a measure of the quadrature component of the secondary field with respect to the primary energization.

In the BEILER-WATSON method a horizontal and a vertical search coils are used, the former picking up a component wholly belonging to the secondary field and the latter picking up a field which will largely represent the primary field. However, as these two components do not really differ exactly by 90° as assumed in the original Beiler Watson System, the ratio can never

2-VII

be determined simply. A direct reading instrument designed by Bruckshaw yields the complex ratio, and is described later. One advantage of the method is that the measured quantity being obtained semiabsolutely i.e. in terms of a reference of the energizing system, is not dependent upon power level fluctuations. Farther more, the horizontal coil output produces purely a component of the secondary field and is consequently more diagnostic of the anomalous bodies.

TURAM METHOD

This method was designed by Hedstrom mainly to eliminate the necessity of taking long leads from the primary energizing system to the points of measurement in order to provide a reference. Alternatively output of two search coils both kept either horizontally or vertically and a fixed distance apart (10-50 meters) are compared in phase and amplitude by a compensator.

LONG-WIRE RATIO DETECTION METHOD

The Turam method has also been applied to measurements outside a rectangular loop along a traverse prependicularly bisecting one of the longer sides of the loop. The energizing field in this case represents that due to a straight cable.

1-VII

THE MOVING TRANSMITTER - RECEIVER SYSTEM

This system consists of horizontal transmitting and receiving coils a fixed distance apart (25 to 100 meters). The e.m.f. picked up by the search coil is measured in terms of the primary field along a traverse. On account of its easy manouverability, the moving transmitter receiver system has evolved a number of its airborne counterparts.

Interpretation of electromagnetic surveys

Interpretation of dip angles is largely qualitative. In general the

the dips are greater when the search coil is on either side of the ore body pointing away from the edge in both cases, and zero just over the edge. Furthermore, the dip curve is highly susceptible to the attitude of the traverse lines to the strike of the conducting body, and the determination of the latter is often a necessary prerequisite for interpreting a profile.

Interpretation of electromagnetic anomalies follows the usual pattern of matching the observed anomalies with type curves. The procedure is common to all potential methods. A large compilation of type curves is therefore indispensable to the task of interpretation. The type curves can be obtained theoritically for a given situation by solving the diffusion equation (the dielectric term in the wave equation being neglected) under the appropriate boundary conditions. However, except for very simple cases the solution is not always easy to obtain. Another means of obtaining type curves is the use of electromagnetic model experiments. Electromagnetic models can be made to simulate the geological conditions absolutely in the sense that the field vectors in the field are reproduced at corresponding points in the model.

Consider that in the field experiment the vector E or H is represented by A which satisfy equation (9) of chapter III without the second term containing ϵ in view of the negligibly small displacement currents. Let σ and μ be the electrical conductivity and magnetic permeability in a given region of the field. Let A', σ', μ' be the values in the corresponding region of the model designed to simulate the field conditions and let the above quantities as well as the unit of spaces a and of time, w be scaled as follows;

7-ii, 8-i

$$\sigma = s\sigma_1 \quad \text{---} \quad (1)$$

$$a = \alpha a_1 \quad \text{---} \quad (2)$$

$$w = \gamma w_1 \quad \text{——} \quad (3)$$

$$\mu = m \mu_1 \quad \text{——} \quad (4)$$

$$A = p A_1 \quad \text{——} \quad (5)$$

$\nabla^2 A = \mu \sigma \frac{\partial A}{\partial t}$ ————(6) expresses the behaviour of the vector A in the field and

$\nabla_1^2 A^1 = \mu_1 \sigma_1 \frac{\partial A_1}{\partial t_1}$ ———(7) expresses the behaviour of the corresponding vector in the model. (See equation 8 page 36)

If the model has to work as a direct reading reproduction of the field system equation (7) must reduce to (6) with the appropriate transformations. As ∇^2 and ∇_1^2 involves double diffrentiation with respect to space coordinates in their respective system.

$$\nabla_1^2 = \nabla^2 \cdot \frac{\partial a_1^2}{\partial a^2}$$

$$= \frac{1}{\alpha^2} \nabla^2 \quad \text{————} (8)$$

Similarly $\frac{\partial}{\partial t_1^2} = \frac{\partial}{\partial t^2} \cdot \frac{\partial t^2}{\partial t_1^2}$

$$= \gamma^2 \frac{\partial}{\partial t^2} \quad \text{————} (9)$$

Rewriting (7) in terms of the transformations (1) to (5) we have,

$$\frac{1}{\alpha^2} \nabla^2 pA = msp\gamma \mu \sigma \frac{\partial A}{\partial t} \quad \text{————} (10)$$

or $$\nabla^2 A = (ms\gamma\alpha^2) \mu \sigma \frac{\partial A}{\partial t} \quad \text{————} (11)$$

Equation (11) will become identical with equation (6) fulfilling the condition necessary for the reproducibility of the model if

$$ms\gamma\alpha^2 = 1 \quad \text{————} (12)$$

For most rocks excluding ferromagnetic minerals, the permeability is approximately the same. The factor m can therefore be taken to be unity. Substituting the values of a, y and α the transformation (1) to (3) in (12) we have

$$\frac{\sigma}{\sigma_1} \times \frac{W}{w_1} \times \frac{a^2}{a_1^2} = 1$$

or $w\, a^2\sigma = w_1\sigma_1 a_1^2$ = constt. ———(13)

A substitution of the dimensions of w, σ and a in (13) reveals that the parameter $wa^2\sigma$ is dimension-less. This is called the modeling parameter. If the value of this parameter in every region of the field system and in the corresponding region of the model system is kept equal, the model becomes a direct reading reproduction of the field system. Once, therefore, the geometrical scale of the model i.e., a has been chosen, w can be properly chosen so that suitable substance of known conductivity may be used to simulate conductivities in the field system. For two dimensional bodies a further facility is available owing to the fact that the controlling factor in their response is the quantity $wad\sigma$ and not $w\ a^2\sigma$ Thus an additional variable that is the thickness d of the model is available for fulfilling the conditions for modelling. Figure 2.4 shows the experimental curve obtained from the model, for the maximum response due to different bodies of increasing value of $wad\sigma$.

In order to understand the significance of the parameter $wad\sigma$, let us investigate the response of an ore body to an arbitrary transmitter - receiver system at an arbitrary ~~transmitt~~ point. The ore body will, for simplicity, be replaced by a closed coil having a resistance R and an inductance L.

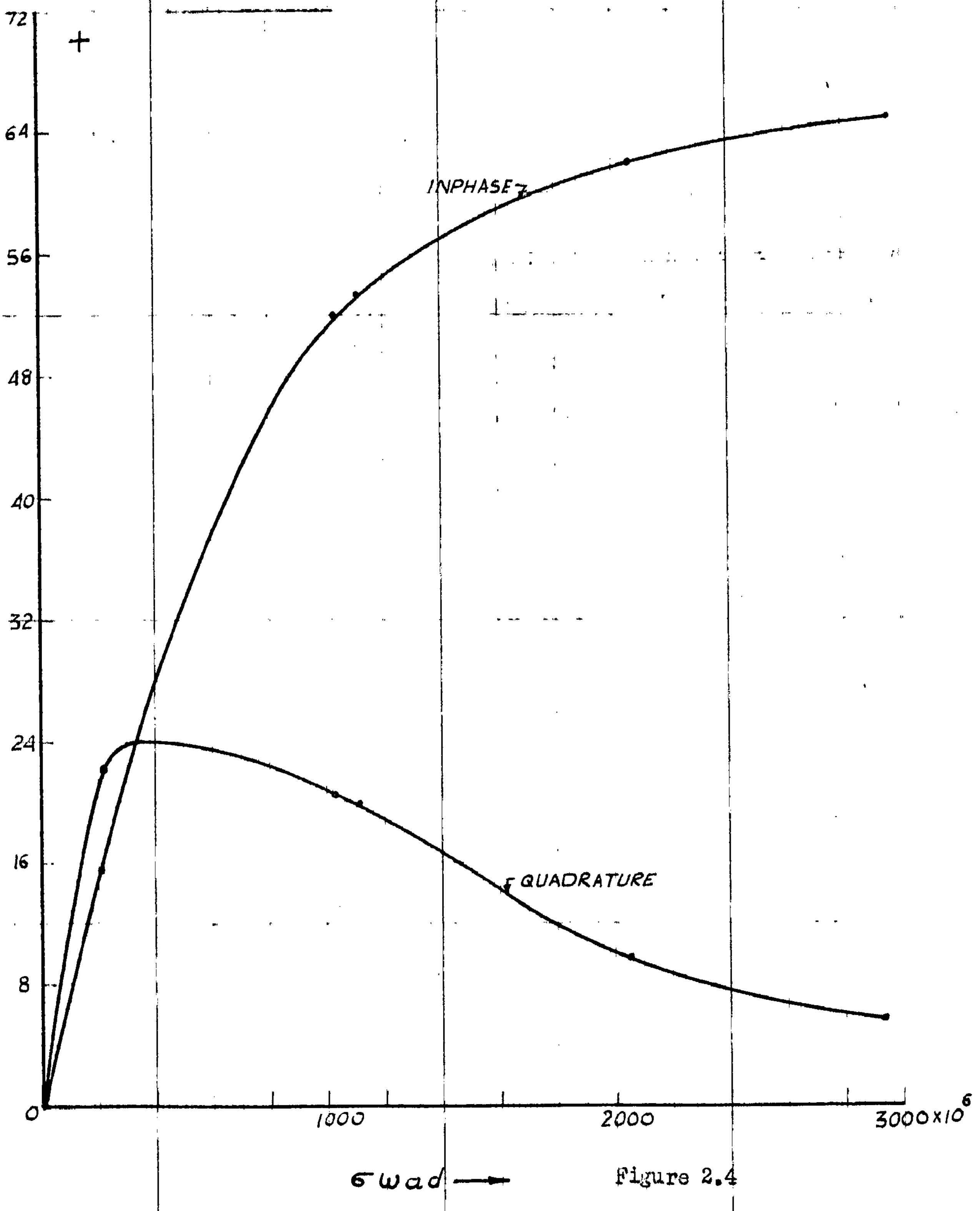

72
64
56
48
40
32
24
16
8
0
1000
2000
3000×10⁶
INPHASE
QUADRATURE
σωad →

Figure 2.4

Let the primary energizing system produce a field in the neighbourhood of the ore body equal to IG_1 where I is the energizing current and G_1 a geometrical factor including coil constants and a furnction of space. The e.m.f. induced in the ore body will then be given by

$$E = \frac{\partial}{\partial t}(IG_1) = jwIG_1$$

The induced current i in the ore body will be

$$i = \frac{E}{(jwL+R)} = \frac{jwIG_1}{(jwL+R)}$$

The magnetic field due to the current i in the ore body at an arbitrary point P in space will be given by, $S = iG_2$ and that due to the primary energization at the same point will be given by $P = IG_3$, where G_2 and G_3 are the appropriate geometrical factors, constant for the same ore body and for a fixed position of the ore body in relation to the energizing system and the point P.

$$\text{The ratio, } \frac{S}{P} = \frac{jwIG_1G_2}{(jwL+R)} \times \frac{1}{IG_3}$$

$$= \frac{G_1G_2}{G_3}\,\frac{jw}{(jwL+R)} = \frac{G_1G_2}{G_3}\,\frac{jw(R-jwL)}{(R^2+w^2L^2)}$$

$$= \frac{K}{L}\left(\frac{w^2L^2+jwRL}{R^2+w^2L^2}\right)$$

where the constants G_1, G_2 and G_3 have been absorbed in another constant K.

$$\text{or } \frac{S}{P} = \frac{K}{L}\left(\frac{(w^2L^2/R^2)}{(1+w^2L^2/R^2)} + j\,\frac{wL/R}{(1+w^2L^2/R^2)}\right)$$

$$\text{or } S/P = \frac{K}{L}\,(x+jy)$$

The real component of the ratio which we shall call 'response' increases parabolically for small values of the parameter ($\omega L/R$), whereas the quadrature component is linear. For $\omega L/R$ equal to unity both components have a value equal to $K/2L$. For very large values of $\omega L/R$ the real component becomes equal to K/L whilst the quadrature component gradually dwindles.

The above results are remarkable in a way that they prescribe a regular behaviour for the response of conducting bodies to electromagnetic fields. Figure 2.4 shows on experimental curve in which the inphase and quadrature response of a horizontal sheet energized by a vertical field are plotted against $wad\sigma$ which has the same dimensions as $\omega L/R$ has, considering that R has the dimensions of $\left(\frac{\rho}{L}\right)$.

The foregoing discussion shows that a single observation can lead to the evaluation of the quantity (σd) pertaining to the body, w and a being known; and that other bodies with the same (σd) and occupying the same position will produce similar responses.

CHAPTER III

8-ii, 7-ii

RESPONSE OF MATERIAL BODIES TO ELECTROMAGNETIC FIELD

Macroscopically, the response of material bodies to an electromagnetic field can be described in terms of three physical properties. These are the electrical conductivity, the dielectric constant and the magnetic permeability.

Effects of an electric field:

Bodies possessing a finite conductivity have enough supply of free electrones or ions, which under the action of an electrical field move and constitute an electric current. The current density J at a point within a liquid or solid medium will depend upon the availability of free charged particles and will be proportional to the applied field E.

$$J = \sigma E \quad \text{------------------} (1)$$

The relation (1) is the Ohm's law. σ is called conductivity or $\frac{1}{\sigma}$ the resistivity of the body.

The conduction of electricity is electronic, where metallic minerals or their ores and intrusions occur as continuous deposits, but in the case of electrolytes it is accomplished by the transport of ions which are librated at one electrode and deposited at the other. The latter, therefore, involves a transport of matter from one point of the body to theother.

On the other hand non-metallic substance of negligibly small conductivities, being defficient in free electrones or ions cannot permit electrical conduction described by (1). However an electric field although unsuccessful in tearing off electrones in such bodies, produces a strain in the normal configuration of atoms and molecules. This strain is termed electric polarization of the medium and can be interpreted, on the basis of a macroscopic theory as an equivalent volume distributed of electric dipoles. If P be the moment of these dipoles per unit volume, it can be written as follows, assuming proportionality with the applied field.

$P = KE$

With analogy to the magnetic field the flux associated with the polarization P will be $4\pi P$. The electric displacement vector D which represents the total flux can be written as

$D = E + 4\pi P$

$= E\ (1+4\pi K)$

or $D = \epsilon E$ ——————(2)

Where K is termed the electric susceptibility and ϵ the dielectric constant.

If the electric field changes with time, so will the polarization. The latter however, will involve a redistribution of charges which can be interpreted as a displacement current Id, where,

$Id = \frac{\partial D}{\partial t} = \epsilon \frac{\partial E}{\partial t} = j\omega\epsilon$ ——————(3)

The dielectric constants of most rocks varies within a narrow range of about 8 to 50 e.s.u. increasing with their moisture content. The displacement currents are therefore unlikely to be significant unless the rate of change or the frequency is extremely large.

To appraise the relative magnitudes of the conduction and displacement currents i.e. $\frac{\sigma}{w\epsilon}$, let us assume ϵ to be equal to 10 e.s.u. or $\frac{10^{-9}}{36\pi}$ Farad/meter and $\sigma = 10^{-1}$ mho/meter. This ratio is 180×10^{-6} for 1 c/s and will be equal to unity at frequency of 180 M c/s. As will be discussed later, the frequencies usually applied in geophysical exploration lies below, 1000 c/s Even at this frequency the displacement currents in general will be only a few thousandth of the conduction current. The former are therefore invariably neglected in geophysical interpretation.

Effects of a magnetic field:

Certain materials acquire an induced magnetisation when placed in a magnetic field. One way of expressing this magnetisation quantitatively is to use the magnetic permeability which is defined as the ratio of the total magnetic flux through the body to that produced by the magnetizing field alone.

$$\mu = \frac{B}{H} \quad \text{———} (3)$$

In a varying magnetic field the induced magnetisation will also varies accordingly and in phase with it, but in addition to this the changing flux will also generate an e.m.f. in the body and drive electric currents whereever a finite conductivity exists. The conductivity of a body usually includes an inductive component which varies with frequency. The effective conductivity at a given frequency is therefore complex causing the currents and their magnetic fields to differ in phase with respect to the primary field.

The effects of permeability and of the conductivities of bodies through which a varying magnetic field has been established appear therefore as additional magnetic fields of similar periodicity with the difference that whilst that due to the first depends upon μ alone. and is inphase with the primary field, that due to the second depends upon the frequency and the conductivity which determine its phase and amplitude.

The general behaviour of the field vectors of an electromagnetic field in material media can be described by the following differential equations after Maxwell.

$$\text{Curl } E = -\mu \frac{\partial H}{\partial t} \quad \text{———} (4)$$

$$\text{Curl } H = J + \frac{\partial D}{\partial t} = \sigma E + \epsilon \frac{\partial E}{\partial t} \quad \text{———(5)}$$

where E and H are the electric and magnetic field intensities respectively σ the conductivity, ϵ the dielectric, and μ the permeability of the medium. To these may be added two more expressions expressing the universal divergencelessness of the field of B, and the divergence of the field of D, which by Gauss's theorem is given by the volume density of charges.

$$\text{Div.} B = 0 \quad \text{———(6)}$$

$$\text{Div.} D = \rho \quad \text{———(7)}$$

Elimination of either E or H from (4) and (5) yields similar equation in both E and H. This is of the form

$$\nabla^2 A = \mu\sigma \frac{\partial A}{\partial t} + \mu\epsilon \frac{\partial^2 A}{\partial t^2} \quad \text{———(8)}$$

The equation (8) is easily identified as the wave equation. In order to interpret this equation in relation to the properties of material media we shall reduce it to one dimension by considering a plane wave harmonic in time and propagating along the x-axis. Accordingly,

$$\frac{\partial^2 A}{\partial x^2} = \mu\sigma \frac{\partial A}{\partial t} + \mu\epsilon \frac{\partial^2 A}{\partial t^2} \quad \text{———(9)}$$

Let us now choose a trial solution for A of the following form

$$A = Pe^{\pm \gamma x} e^{-jwt} \quad \text{———(10)}$$

Substituting (10) in (9) we find that γ is complex given by

$$\gamma^2 = jw\mu\sigma - \mu\epsilon w^2 = \alpha + j\beta \quad \text{———(11)}$$

where ~~$\alpha = w \left\{ \frac{\mu\epsilon}{2} \left[1 + \frac{\sigma^2}{w^2\epsilon^2} - 1 \right] \right\}^{\frac{1}{2}}$ ———(12)~~

$$\alpha = \omega \left[\frac{\mu\epsilon}{2} \left\{ \sqrt{1 + \frac{\sigma^2}{\omega^2\epsilon^2}} - 1 \right\} \right]^{1/2} \quad \text{— (12)}$$

and, $= w\left(\frac{\mu\epsilon}{2}\left\{\left(1+\frac{\sigma^2}{w^2\epsilon^2}\right)^{\frac{1}{2}}+1\right\}\right)^{\frac{1}{2}}$ ——————(13)

(10 can now be rewritten as follows for the positive x direction only

$A = P\, e^{-\alpha x}\; e^{-j(wt-\beta x)}$ ——————(14)

The solution for A given by (14) offers a self explanatory interpretation of the quantities α and β. The former can be regarded as an attenuation constant which has the effect of reducing the strength of the field to 1/e of its value at a distance $x = 1/\alpha$, β has the effect of reproducing the function periodically after every successive interval of $x = \frac{2\pi}{\beta}$. This can therefore be interpreted as a phase constant and the quantity $\frac{2\pi}{\beta}$ as the wave length of the wave. The velocity $v = \lambda f$ will be given by v =

$v = \frac{\lambda w}{2\pi} = \frac{w}{\beta}$ ——————(15)

from the value of β in (13)

$v = \frac{1}{\sqrt{\mu_o \epsilon_o}}\left(\frac{\epsilon_m \mu_m}{2}\left\{\left(1+\frac{\sigma^2}{\epsilon^2 w^2}\right)^{\frac{1}{2}}+1\right\}\right)^{\frac{1}{2}}$ ——————(16)

In free space for which $\epsilon_m = \mu_m = 1$ and $\sigma = 0$, v reduces to c that is the velocity of electromagnetic waves in free space.

The reciprocal of the attenuation constant which is the distance where the field drops to 1/e of its value is customarily referred to as the depth penetration d in geoelectric work. As α increases with the conductivity σ, the field will penetrate to a comparatively shorter distance in a better conducting medium, whereas a highly resistive medium will appear to it as being almost transparent.

As has already been pointed out $\frac{\sigma}{\epsilon w}$ is very much greater than unity for frequencies normally used in prospecting. Applying this condition i.e. $\frac{\sigma^2}{\epsilon^2 w^2} \gg 1$ to the expression for α in (12) and replacing μ by the permeability of the free space = $4\pi \times 10^{-7}$ Henry/meter we have

$$\alpha = \beta = \frac{W}{2}$$

$$= 1.987 \times 10^{-3}\sqrt{\sigma f}$$

or $d = 1/\alpha = 503.8\sqrt{\frac{1}{\sigma f}}$ meters ———— (17)

The relation (17) shows that an increase in frequency has the same effect of increasing the attenuation constant α as an increase in conductivity has. However, another effect of the frequency is to produce a proportional energization of the bodies sought to be located and an improvement of signal to noise ratio. A decrease in the working frequency therefore improves the detectability of the deeper lying bodies at the expense of these burried at shallower depths. In particular an optimum frequency will exist at which the response of a body burried at a certain depth will be maximum. For most cases encountered in geophysical exploration this frequency lies between about 10 c/s and 1,000 c/s.

CHAPTER IV

EQUIPMENT USED

The equipment consists of a rectangular energizing loop, a reference coil, a search coil and the measuring bridge and detector (shown in fig.4.1, 4.2 and 4.3). The design is according to Bruckshaw's modification of the Bieler-Watson method. The whole assembly was entirely fabricated in the geophysical laboratory of the department.

Energising System.- The rectangular energising loop (fig. 4.1) is 140 cm.in length and 110 cm. in width and has 6 turns. A sinusoidal current of 513 c/s was passed through the coil by means of a 'PHILLIPS' power amplifier which was in turn excited by a wide range 'PHILLIPS' beat frequency oscillator shown in fig. 4.2. A bridge for measuring the inphase and the quadrature components of an unknown e.m.f. in terms of a reference e.m.f. was constructed earlier to work at 500 c/s. However a re-examination of the bridge revealed that a few components had altered in value. In order to necessitate minimum adjustments of the components the working fequency had therefore to be raised from 500 c/s to to 513 c/s and the experiments were carried out at this frequency.

Search Coil.- It could be moved on a wooden surface with its plane vertical. The wooden surface was marked by a grid system of 5 Cm. x 5 Cm. and simulated the earth's surface. The position of the search coil could thus be easily read with respect to the model.

Reference Coil.- It was fixed in a horizontal position near one of the sides of the energising coil and not along with the search coil as in the Bieler - Watson system in order to afford greater convenience.

The e.m.f. picked by this coil will correspond to the phase of the primary field but will differ from its amplitude in the center of the loop by a constant factor K. This factor was determined once for all from the ratio of

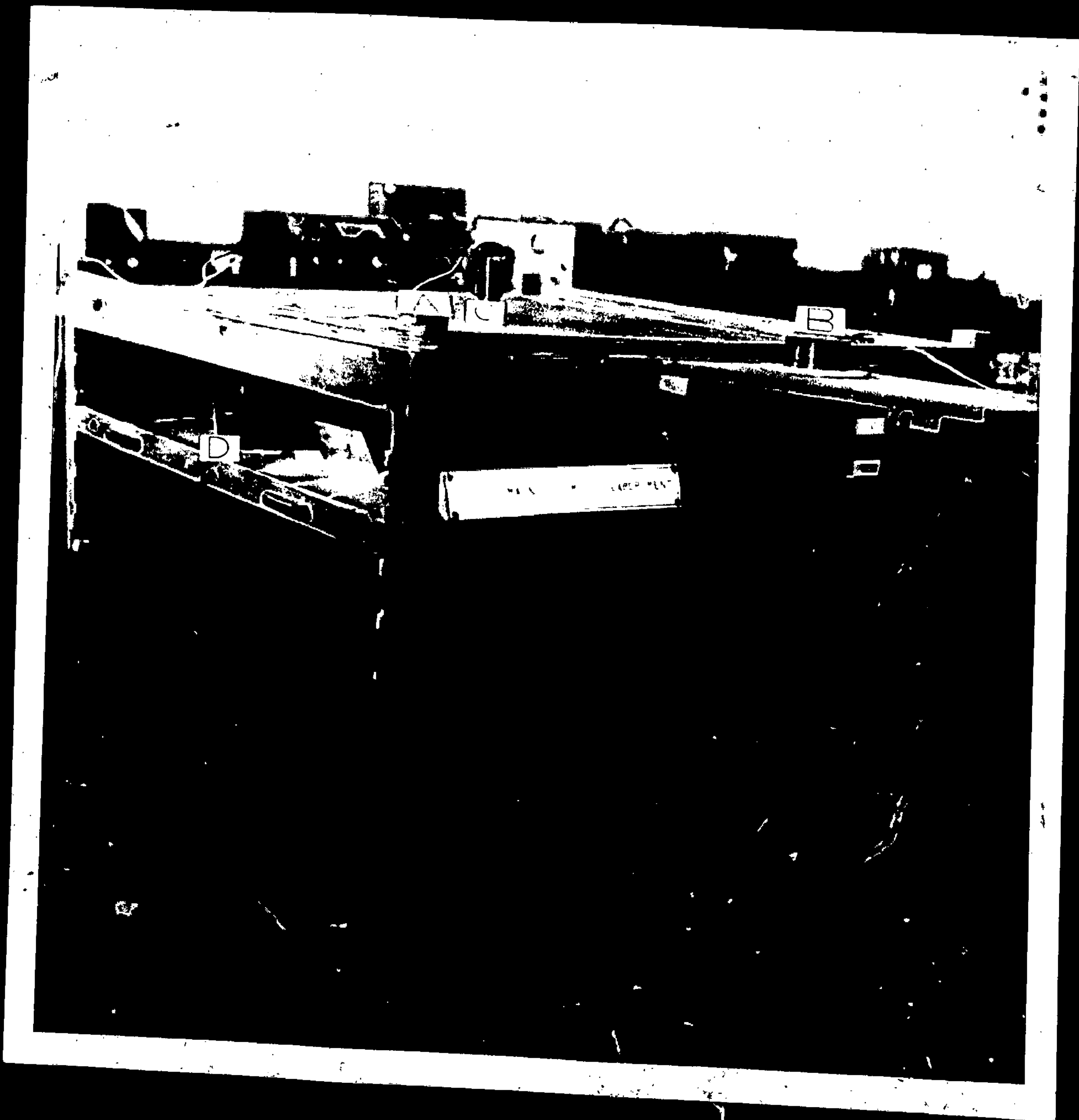
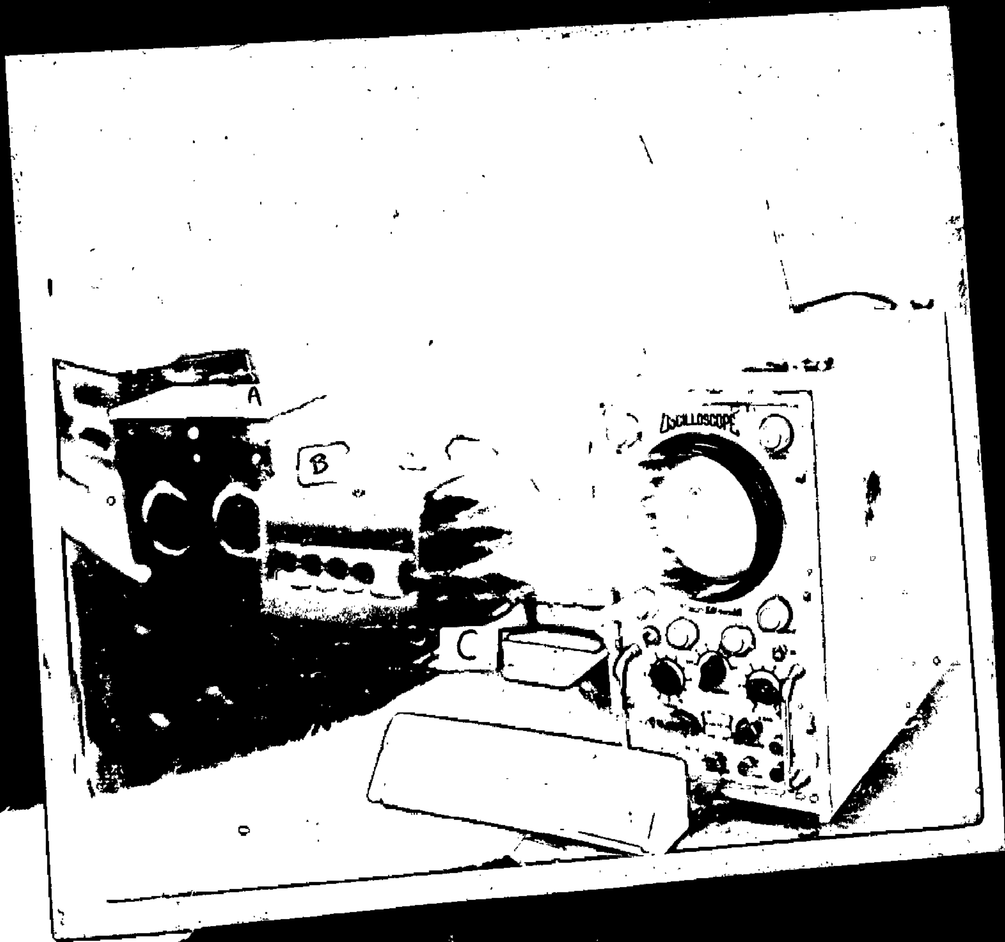

A
C
B
D

Fig 4.2



A. Oscillator

B. Power Amplifier

C. Ammeter

D. Oscilloscope

Fig 4.3

BRIDGE &
DETECTOR

the e.m.f. induced in this coil when placed in the center of the loop to that induced in it when placed in its normal position which it occuppied during experiments. As the latter e.m.f. was used as a reference for the measurement of secondary fields. The ratio of the secondary fields to the field in the center of the loop could be easily calculated by multiplying the observed ratios with the constant factor K.

7-i

<u>The Measuring Bridge</u>:- Thebridge used was of Bruckshaw's design. It consists of two parallel branches connected across the reference coil. The first has a potentiometer of resistance 250 ohms flanked by two equal inductances, and the other has a potentiometer of the same value but flanked by two equal capacitances. (Fig. 4.4)

It the total reactance in each arm is equal to its total resistance which can be ensured by making $WL = R = \frac{1}{WC}$, the phase of the current in it will differ from the phase of the voltage applied across the arm by -45^{o} for the inductance branch and by $+45^{o}$ for the capacitive branch. The phases of the e.m.f. appearing on the potentiometers will follow the phases of the currents in their respective branches and will therefore be 90^{o} out of phase with respect to each other.

An arbitary e.m.f. can be represented as a sum of two e.m.f.s in quadrature. It will therefore be possible to compare an unknown voltage drop $(x+jy)P$ against suitable tappings on the two potentiometers. Where x is inphase with one of them and y with the other.

By constructing the system obsolutely symmetrical it can be further ensured that the e.m.f.'s will drop from a positive value at one end of the potentiometers to an equal but negative value at the other, withoút changing their respective phases along the length of the potentiometer. Thus both will have a zero potential at their centers. By properly selecting the

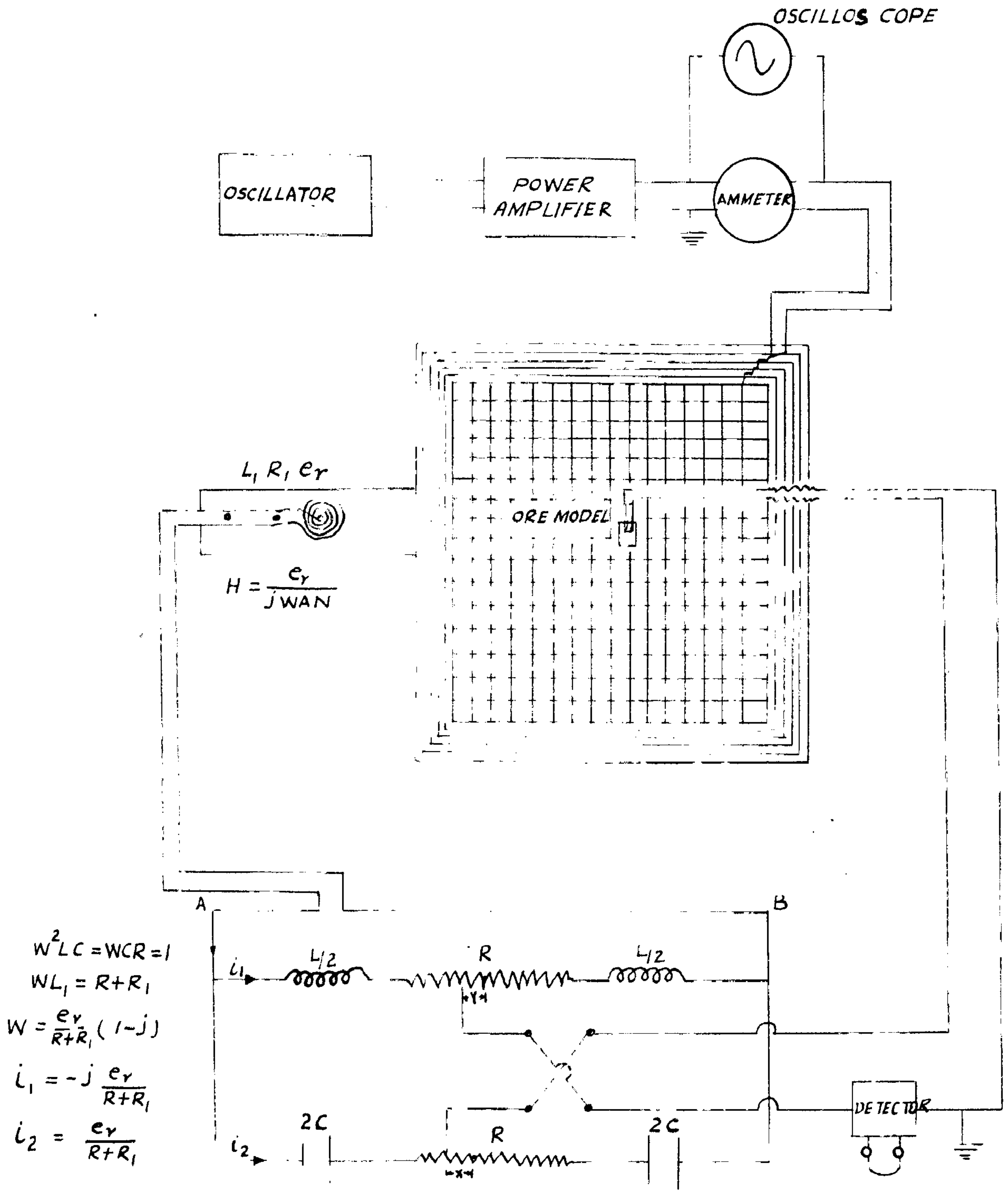

OSCILLOSCOPE
OSCILLATOR
POWER AMPLIFIER
AMMETER
L1 R1 er
H = er / jWAN
ORE MODEL
A
B
W²LC = WCR = 1
WL1 = R+R1
W = er/(R+R1) (1-j)
i1 = -j er/(R+R1)
i2 = er/(R+R1)
i1
i2
L/2
R
L/2
2C
R
2C
DETECTOR

Fig.4.4.

tappings with respect to the center of those potentiometers one could therefore compare a potential drop of any phase angle between 0° to 360°, but limited in magnitude to the value at one end of the potentiometer with respect to its centre.

The two parallel arms together behave as a simple resistance equal to R which can be verified for two extreme cases, when the frequency is zero and when it is infinitely large. In the former case the reactance of the capacitive branch tends to infinity and all the current will flow only through the inductive branch which will behave as a simple resistance R. On the other hand if the frequency of the applied e.m.f. is infinitely large the reactance of the inductive branch will become almost infinite and all current will pass only through the capacitive branch which will now behave as a simple resistance R, the capacitances behaving virtually as short circuits. It will thus appear that the whole net work as looked from the reference coil will behave as a pure resistance of value R.

Now if the reference coil is so wound that its inductance L_1 and resistance R_1, satisfy the condition $\omega L_1 = R+R_1$, the phase of the total current or that of the voltage appearing across the two arms which together behave as a pure resistance of R, will lag on that of the e.m.f. induced in the reference by $\tan^{-1} \left(-\frac{\omega L_1}{R+R_1}\right)$ or -45°. The voltage drops appearing over the potentiometers in the capacitive and inductive arms would now be respectively in phase and in quadrature with reference to the induced e.m.f. The voltage vectors between various points of the bridge circuit are shown in figure 4.5.

An analysis of the bridge shows that if the search coil picking a certain voltage, $(x+jy)P$ is inserted between the two potentiometers with their tapping at $-x$ and $-y$ respectively no current will flow through the coil.

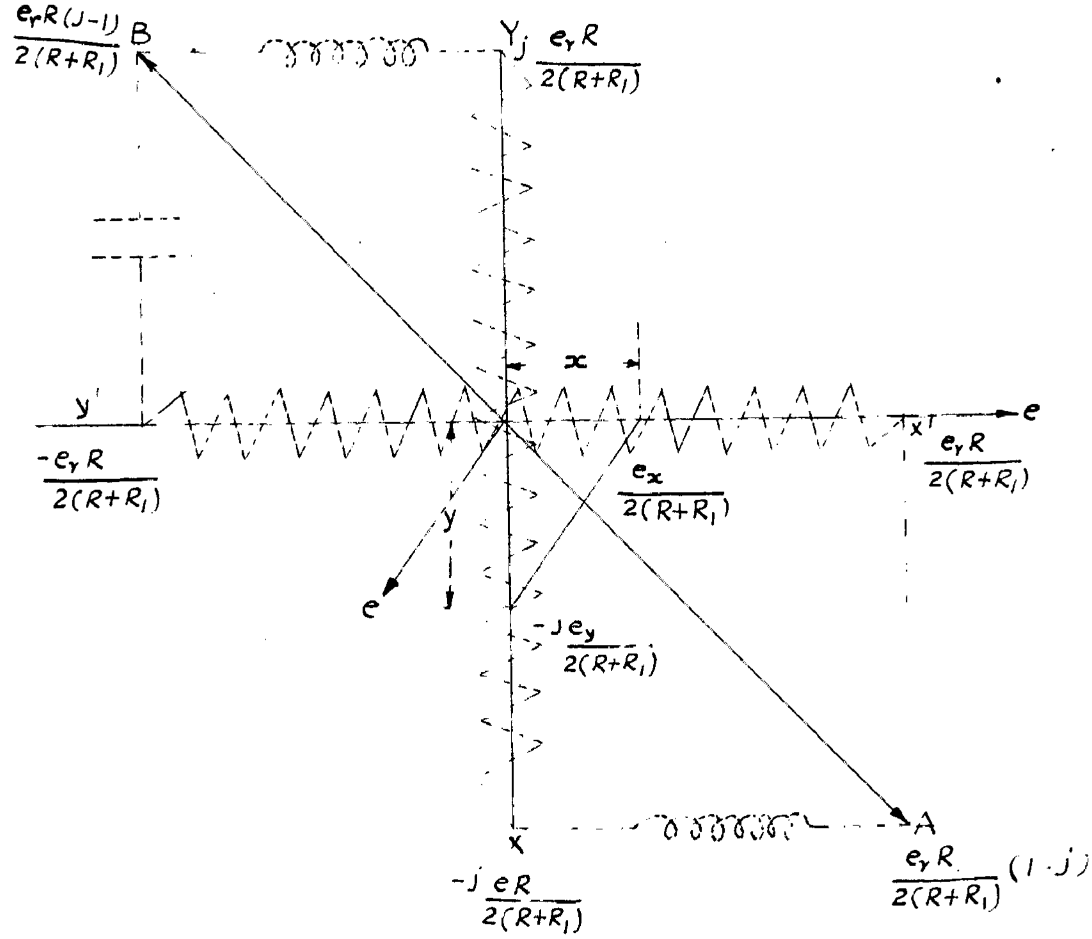

e_r R (j-1) / 2(R+R_1)
B
Y j
e_r R / 2(R+R_1)
x
y'
-e_r R / 2(R+R_1)
e
x'
e_r R / 2(R+R_1)
e_x / 2(R+R_1)
y
e
-j e_y / 2(R+R_1)
A
x
-j eR / 2(R+R_1)
e_r R / 2(R+R_1) (1-j)

Fig. 4.5.

This condition for balance can be determined by putting a detector in series with the search coil. The factor P is given by $\frac{e_r}{2(R+R_1)}$ where e_r is the e.m.f. picked up by the reference coil. The ratio of the unknown e.m.f. e_x, induced in the search coil to the reference e.m.f. $\frac{e_x}{e_r} = \frac{1}{2(R+R_1)}(x+jy)$ where x is the tapping on the potentiometer producing an e.m.f. in phase with that of the reference coil and y that on the other, producing an e.m.f. in quadrature with it. It is easily seen that the e.m.f. on the potentiometer in the capacitance branch is inphase with that induced in the reference coil.

Detector :- A null detector model 931 'APLAB' with a pair of headphones was used. (Fig. 4.3)

Sources of Error

The experimental errors can be divided into two groups viz. systematic errors and random errors.

Systematic Errors:-

1. Errors due to the size of the energizing coil:- However theoretical calculations show that within the region of measurement, the magnetic field produced by the coil was homogenous to within ±5%.

2. Errors due to the size of the search coil:- The search coil must of necessity have a reasonable size and number of turns in order to be able to measure small fields. The secondary field produced by a two dimensional body may be assumed to vary only along the vertical at a given point. It can be shown that this will cause a shift in the effective center of the coil, but this is extremely small.

3. Errors due to the wrong setting of the frequency: - An error in setting of the oscillator frequency will lead to two different errors in the measured values.

a) A change in working frequency amounts to a change of the effective conductivity of the model. The secondary field will therefore be modified in the general way indicated in figure (2.4). The error will also depend upon the point on the curve to which the ore model happens to correspond. Further an error in the operating frequency of δf will result in errors in the inphase and quadrature readings amounting to $\frac{dI}{df}\,\delta f$ and $\frac{dQ}{df}\,\delta f$ respectively.

b) Since the reactance of the bridge is dependent upon the frequency, any error in the latter would alter the amplitudes of the currents in the two arms of the bridge, and also their respective phases with respect to the of the induced e.m.f.

<u>Random Errors:</u>

1. <u>Errors due to frequency drift of the oscillator:</u> - A beat frequency 'PHILLIPS' oscillator GM 2308/90 type was used and it is believed that its accuracy is = 1%.

2. <u>Errors in setting the potentiometer control:</u> - The potentometer dial could only be adjusted within 0.25 of a division. This adjustment would tend to vary between readings and would introduce errors depending on the particular dial reading. There is obviously no control on this error but its effect in most cases would be small.

<u>Experimental procedure:</u>- The equipment was allowed to stablise for about an hour after being switched in order to ensure that drift has been minimized. The platform holding themodel was then adjusted to the predetermined height and measurements made.

The ratio of the secondary field to that threading the reference coil due to the ore model at any position on the platform is given by the algebraic differences between the potentiometer readings with (a) the model in position and (b) the model removed.

CHAPTER V

RESULTS AND CONCLUSION

Results of model experiments are presented in the form of curves showing the inphase and quadrature components of the secondary field arising from conducting sheets with reference to the prim-ary inducing field. The abscissae denote the positions of the search coil with reference to the sheet, one edge of which marks the zero.

Since it is impracticable to investigate the response for all possible configurations of the ore body the ore model was oreinted to simulate simple geometrical relationship with the line of traverse.

The working fequency for all these experiments was fixed at 513 c/s.

Experimental results are recorded in figures 5.1 to 5.15. Figure 5.1 to 5.4 show the responses of aluminium and brass sheets with varying depth for different positions of the search coil with respect to the sheet. These sheets are striking prependicular to the line of traverse. Effects of varying orientations of the ore model with respect to line of traverse was also investigated. The responses of a horizontal sheet for skew traverses is plotted in figures 5.5 and 5.6, where the orientation is defined as the angle between the strike of the sheet and the line of traverse. A comparision of the responses due to three horizontal sheets of identical thickness and lengths but of differing widths is shwon in figures 5.7 and 5.8. Similarly a comparision of the responses due to three horizontal sheets of identical lengths and widths but of different conductivities is shown in figure 5.9 and 5.10. The responses of a horizontal sheet for a given position of the search coil for varying depths of burial shown in figure 5.11. These suggests a logarthmic decrease of response with depth. A plot of these on a log paper is presented in figure 5.12 which directly gives the order whereby the response decreases.

Finally responses along a traverse were also determined for the case of a fault, a syncline and an anticline all of which were striking prependicular to the traverse. The latter two were slightly asymmetrical which clearly appears in their respective responses. The results of these are shown in figures 5.13, 5.14 and 5.15 respectively.

CONCLUSIONS

With the results of the above mentioned model experiments some of the following general comments can be varified.

(1) On variation of the dip angle from 0^{o} to 90^{o}, the maximum responses of the sheets tend to decrease becoming a minimum for a vertical sheet.

(2) As the orientation of the ore model with respect to line of traverse departs from 90^{o} the peak value of responses shift from the center of the model depending on the direction of approach with respect to the strike.

(3) Responses of horizontal sheets having equal thicknesses and lengths but different widths, show these increase non-linearly.

(4) Responses for horizontal sheets of different metals show that the inphase component is greater for more conducting sheets, as predicted by the curve shown in figure 2.4.

(5) The responses of a horizontal sheet at a fixed point for varying depths of burial decreases with increasing depth as the $(2.6)^{th}$ power of depth.

(6) In case of the anticline and the syncline the inphase components becomes less than the quadrature component although the shape of the profile remains the same as for horizontal sheets.

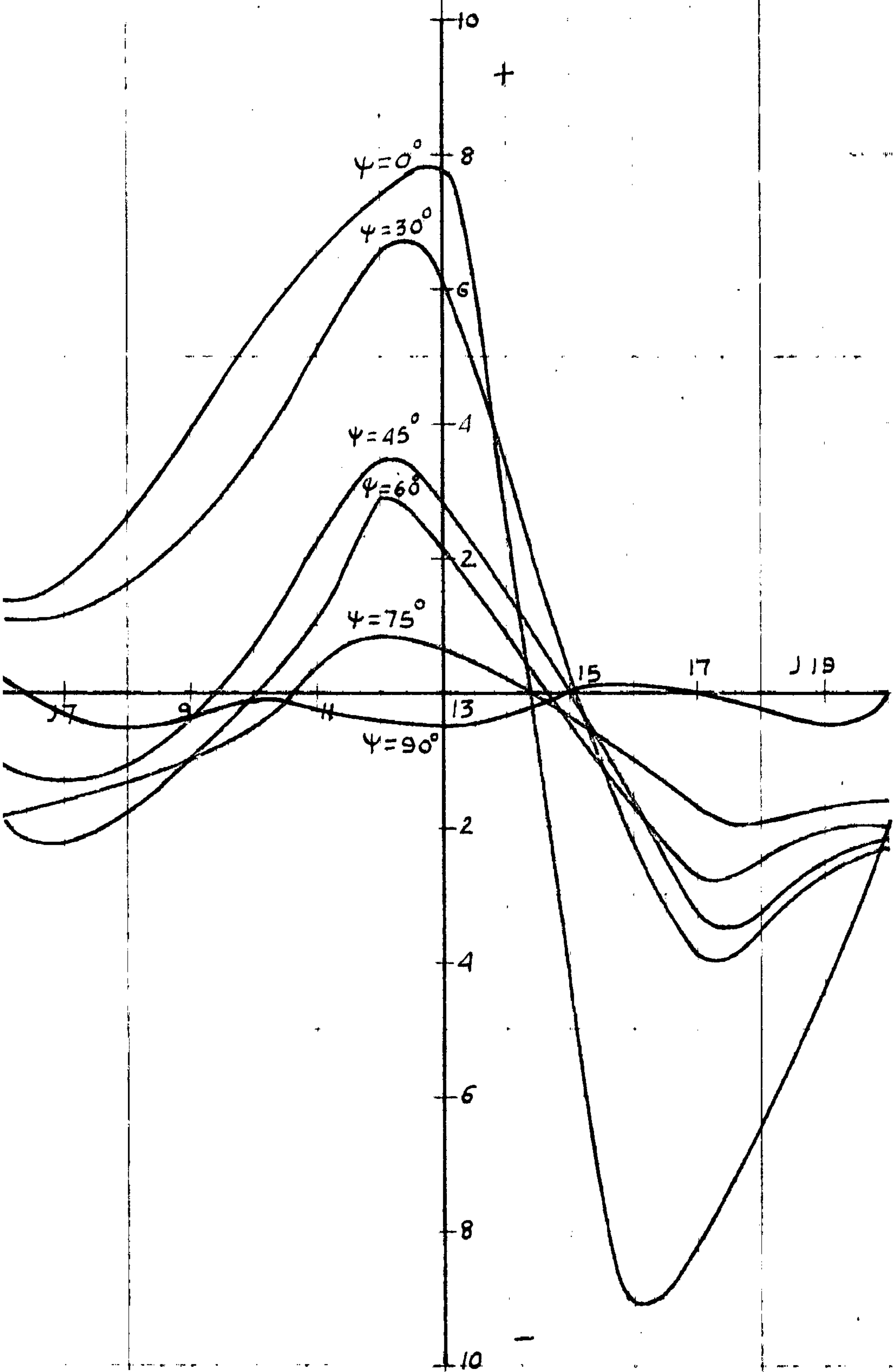


Figure 5.1?

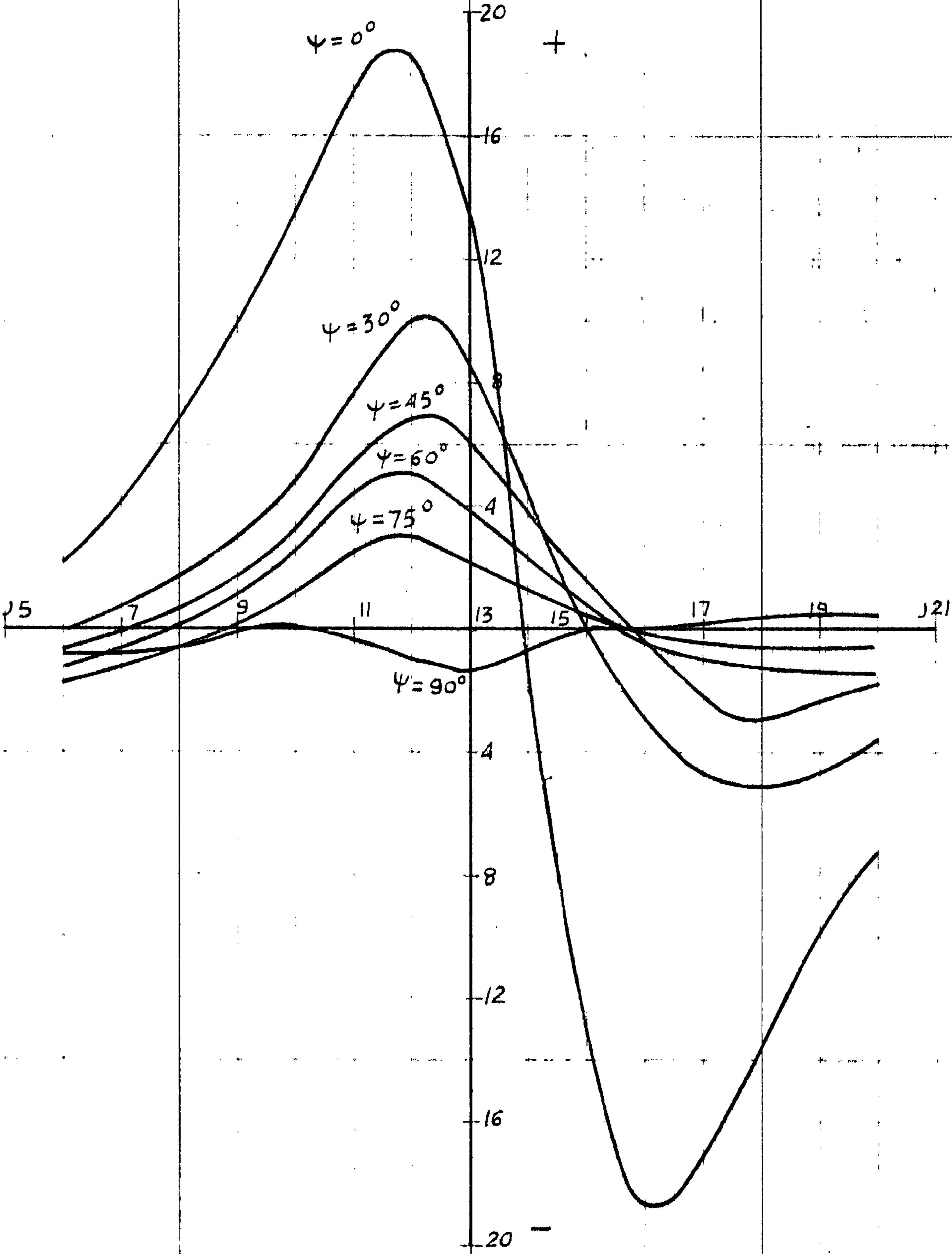


Figure 5.2

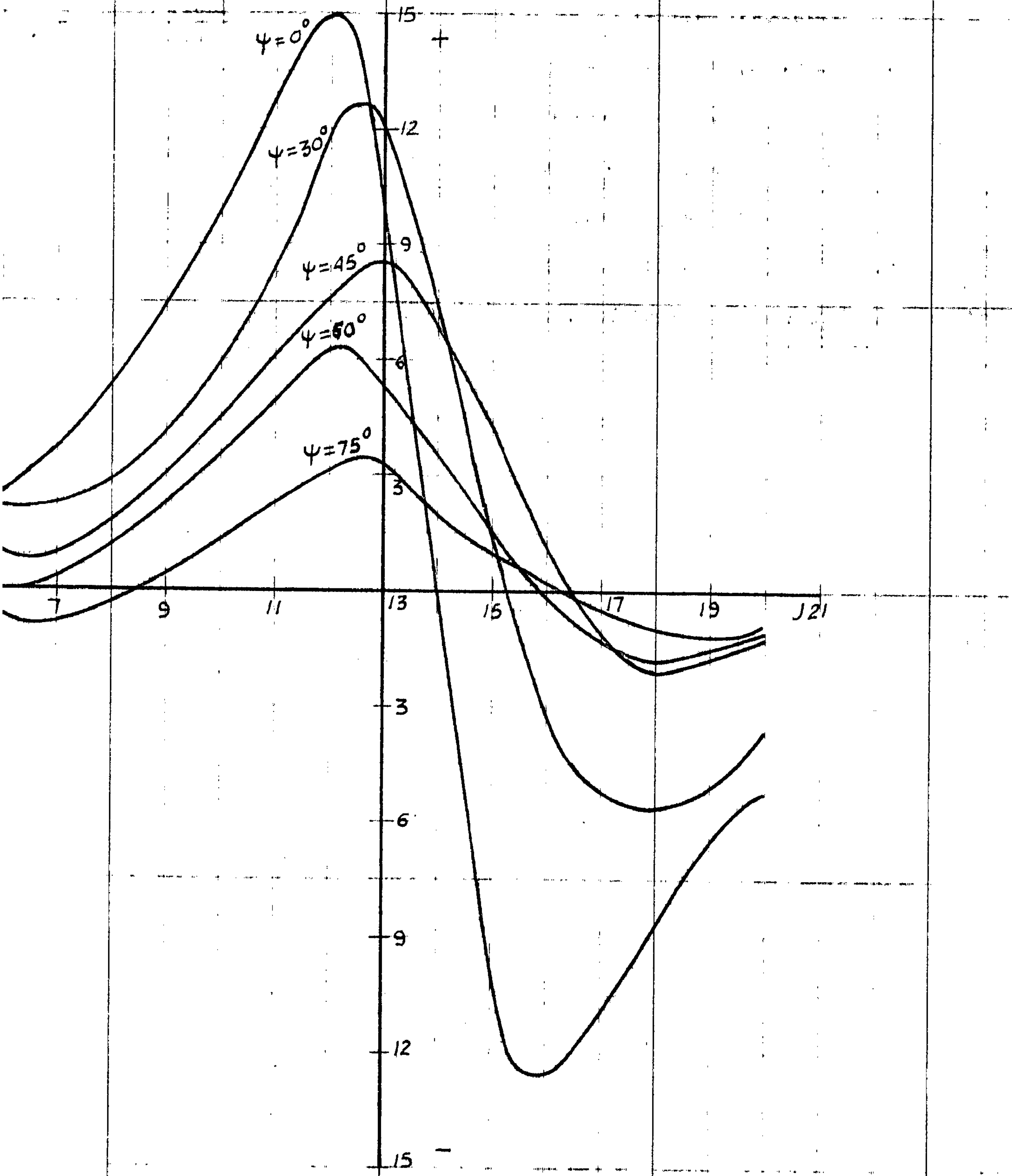


Figure 5.3

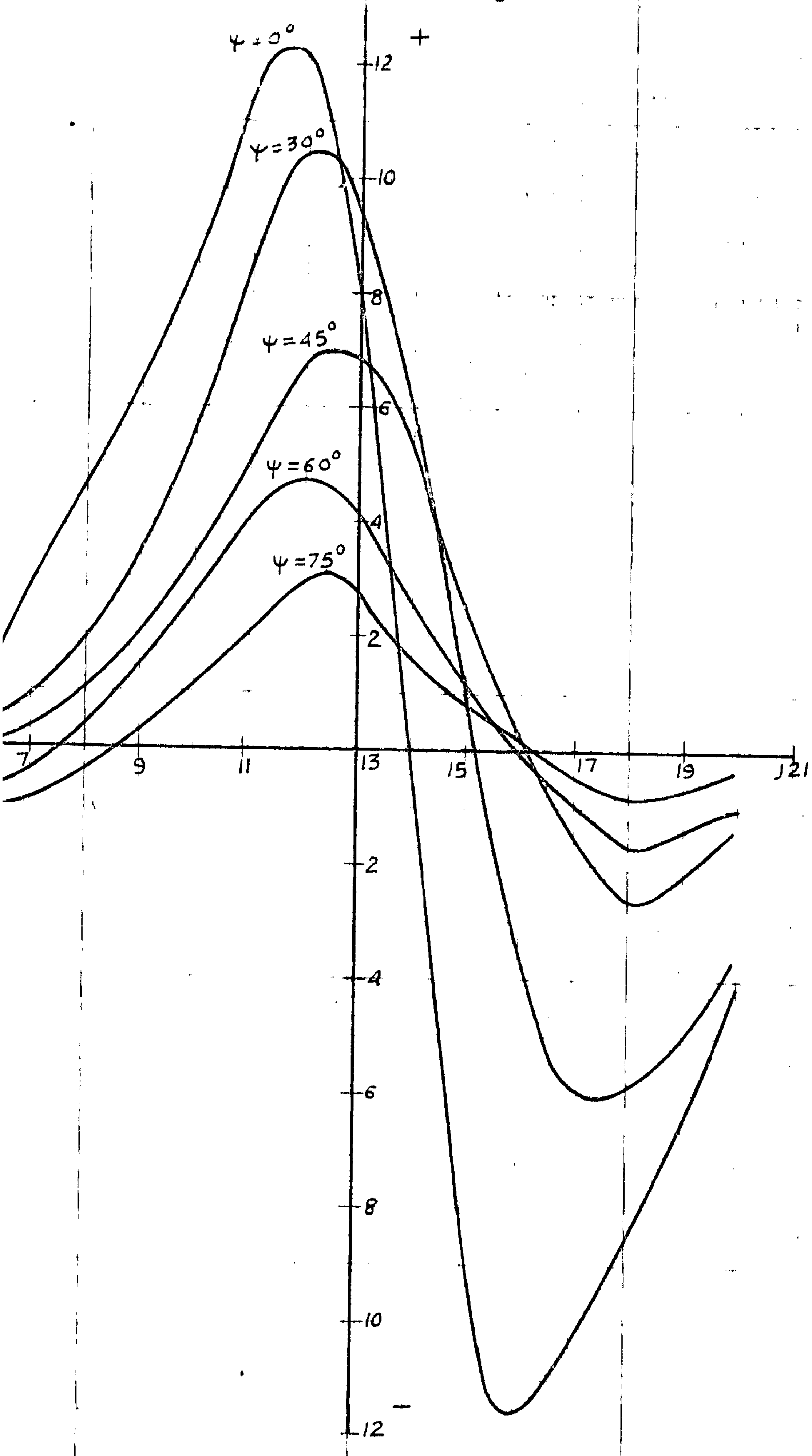


Figure 5.4

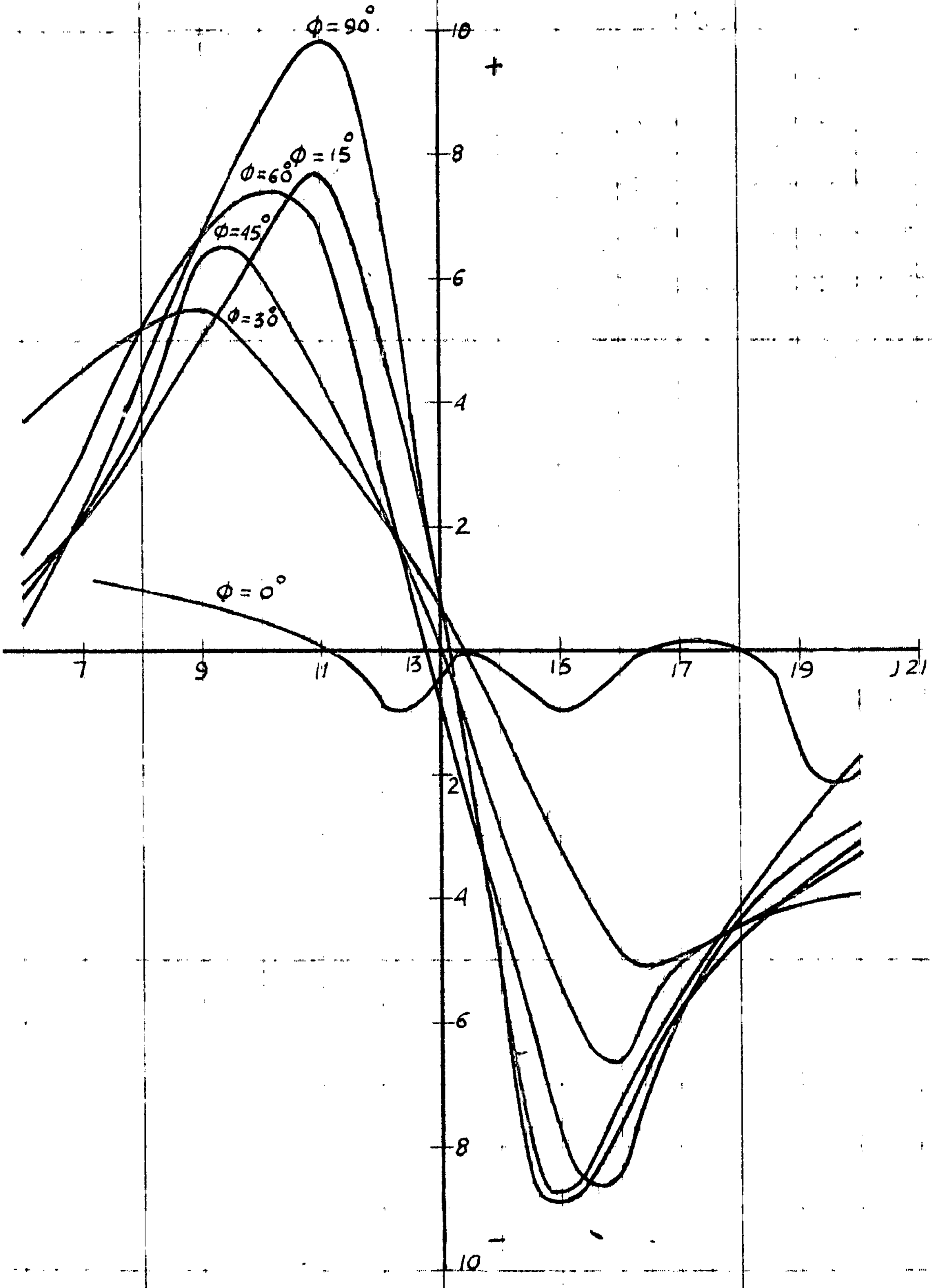
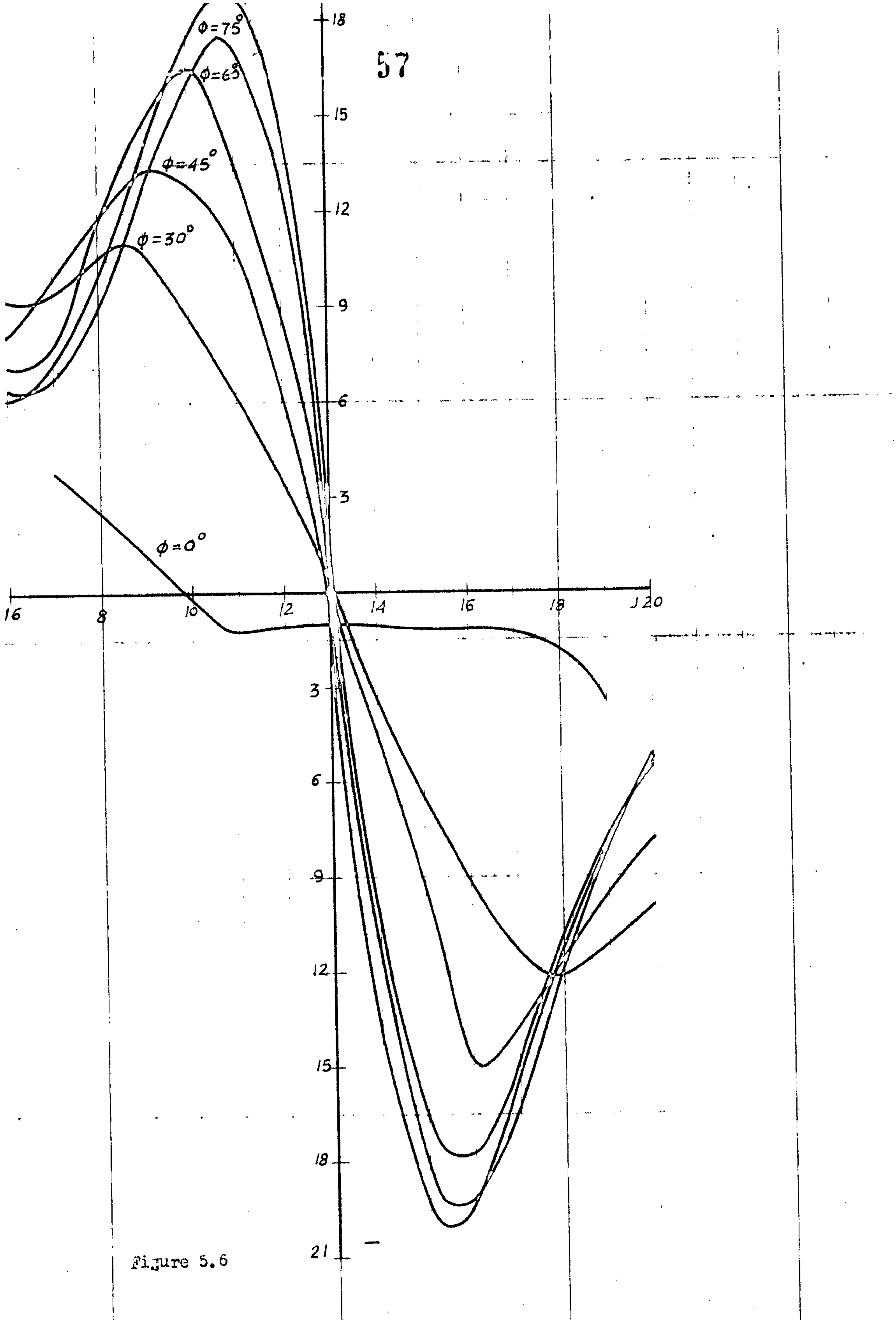


Figure 5.5



φ=75°
φ=65°
φ=45°
φ=30°
φ=0°
18
15
12
9
6
3
16
8
10
12
14
16
18
J 20
3
6
9
12
15
18
21

Figure 5.6

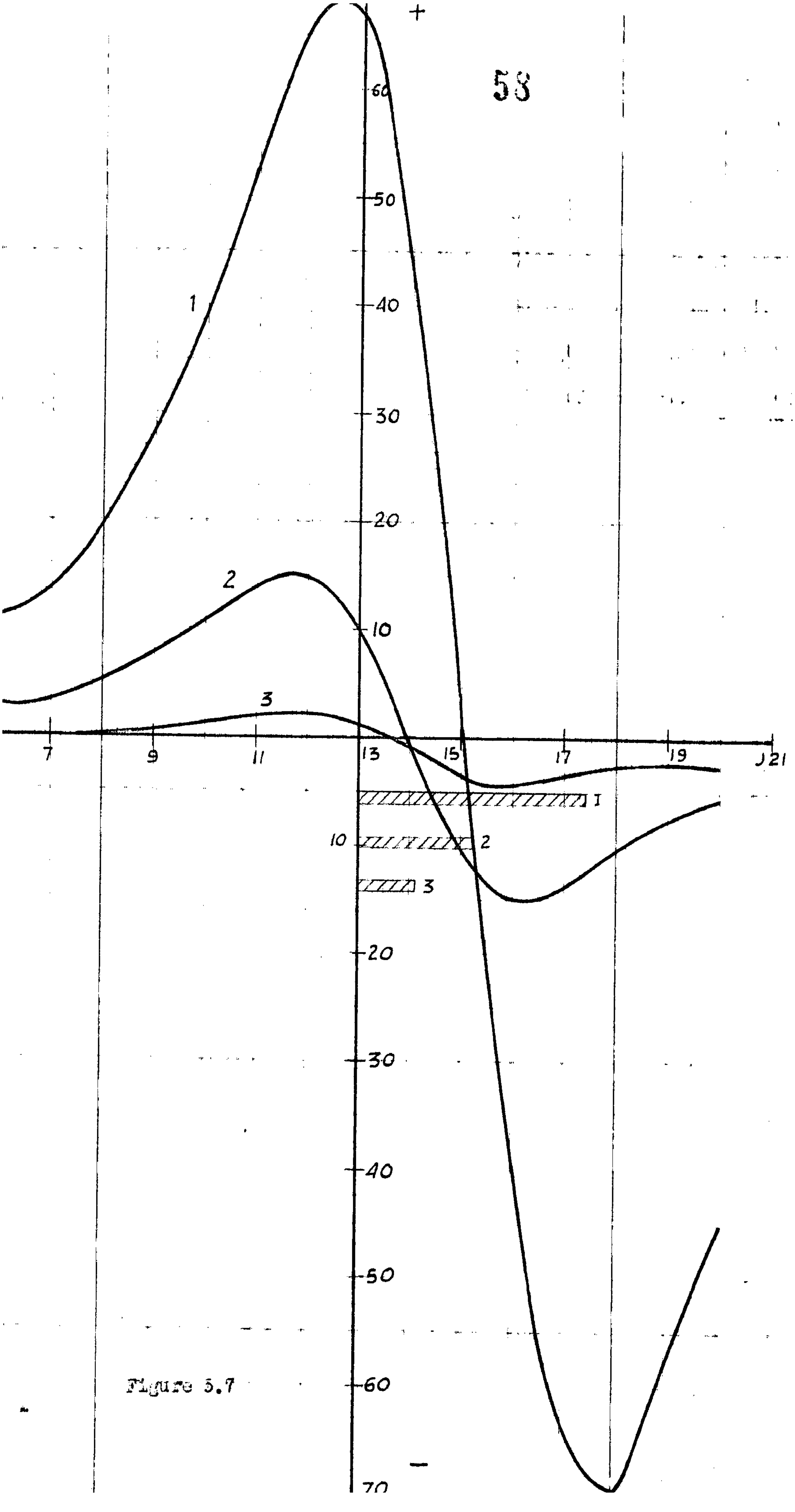


Figure 5.7

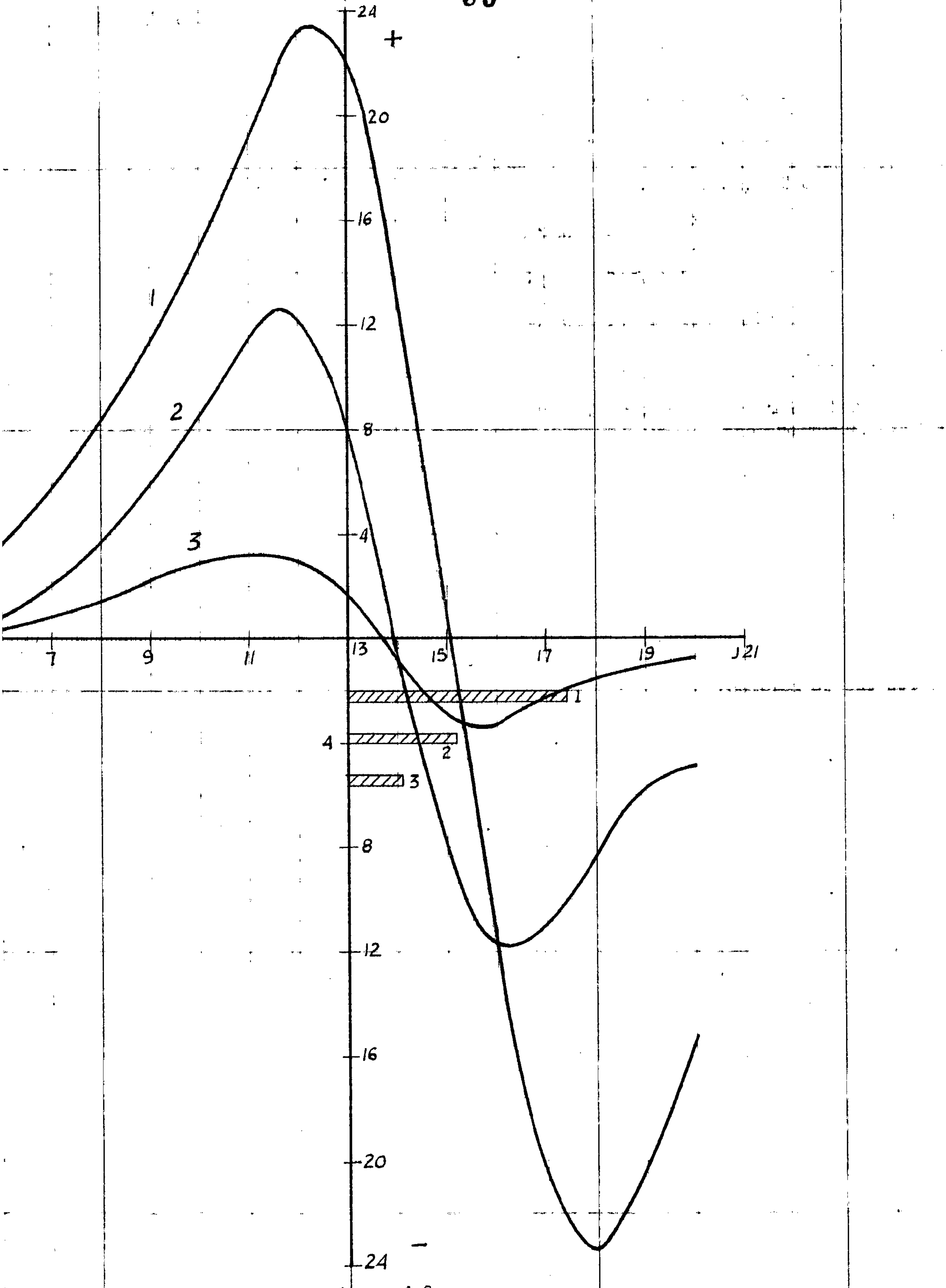


Figure 5.8

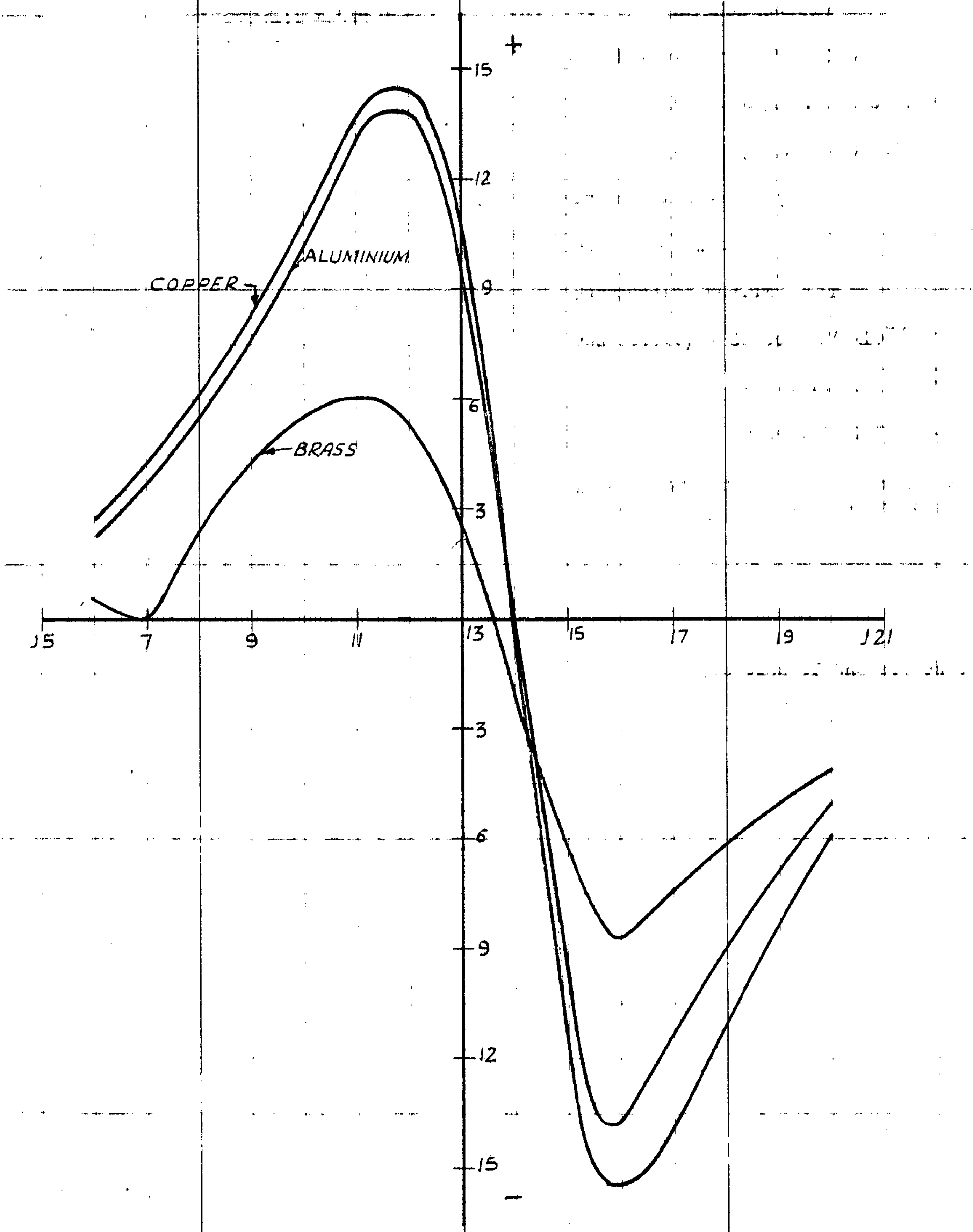


Figure 5.9

61

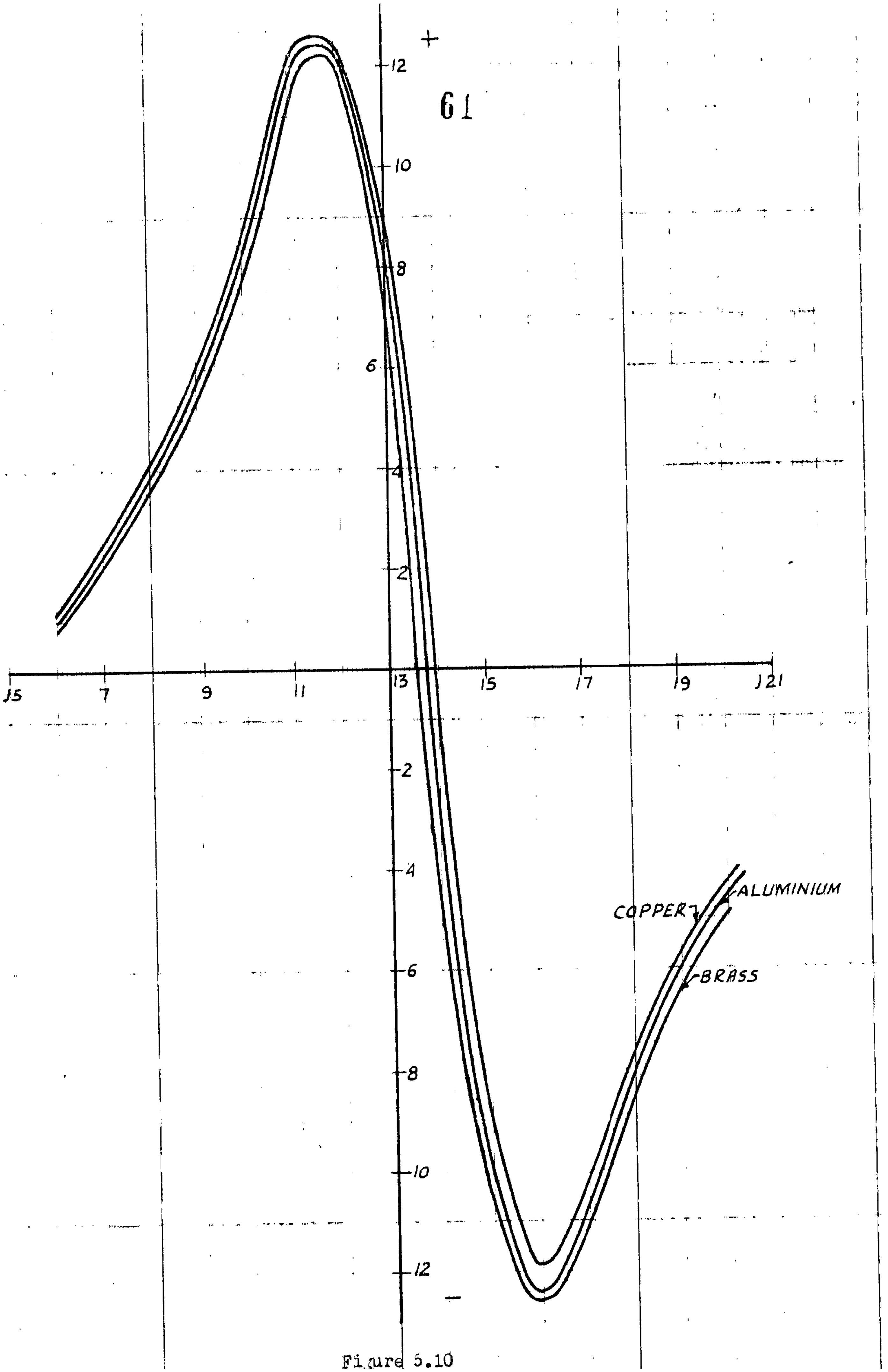


Figure 5.10

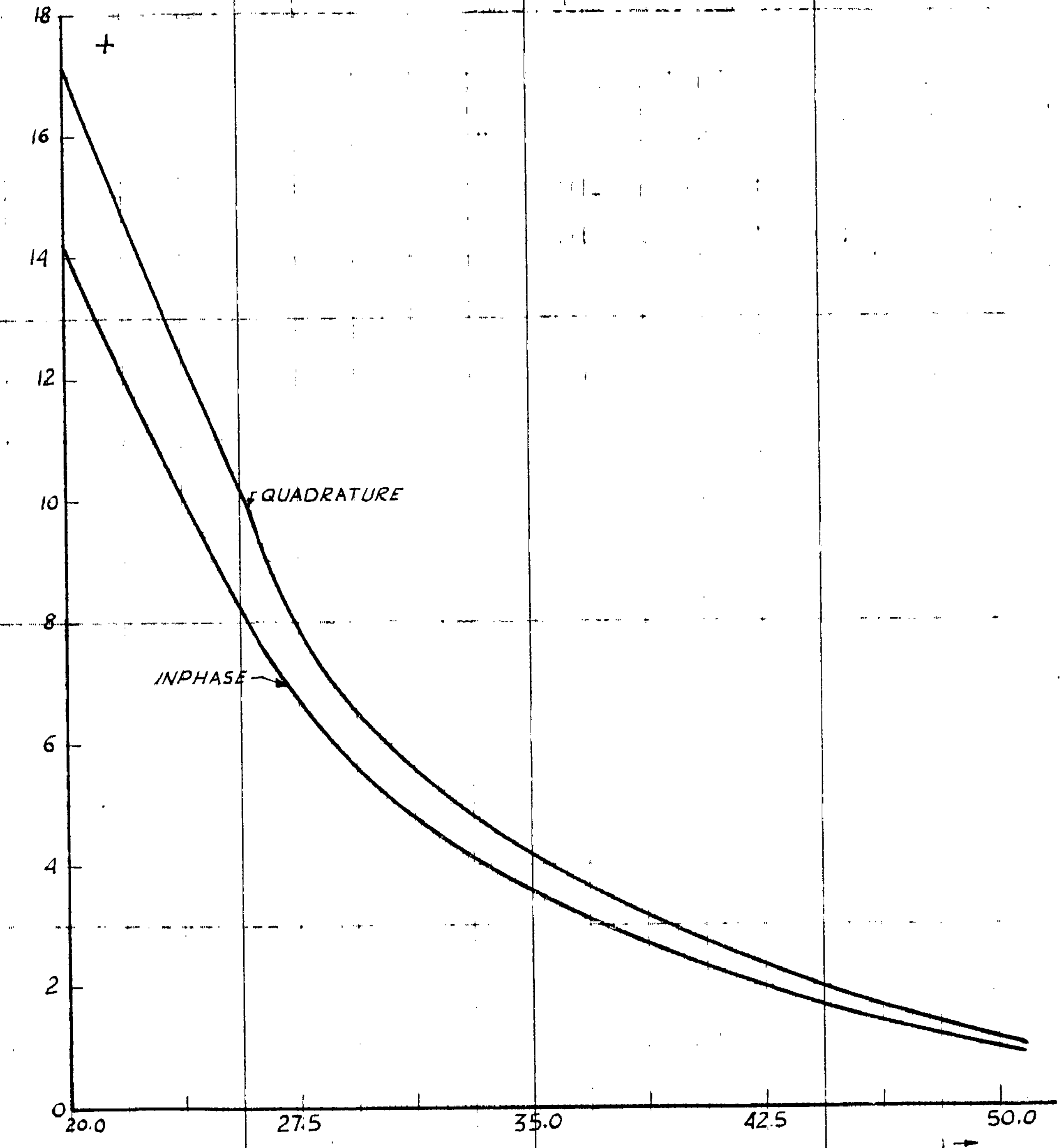
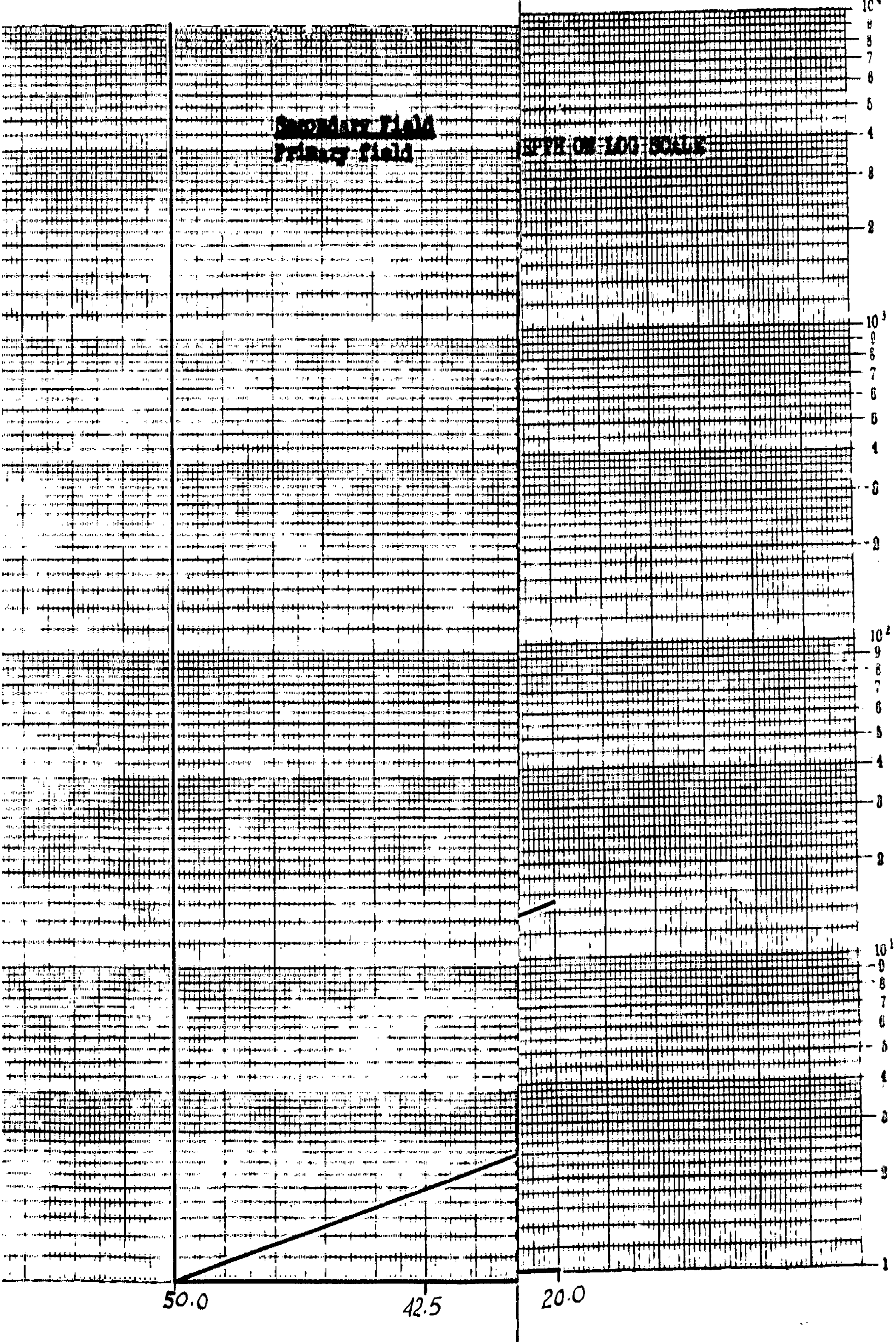


Figure 5.11


Secondary Field
Primary Field
DEPTH ON LOG SCALE
50.0
42.5
20.0
10^4
10^3
10^2
10^1
1

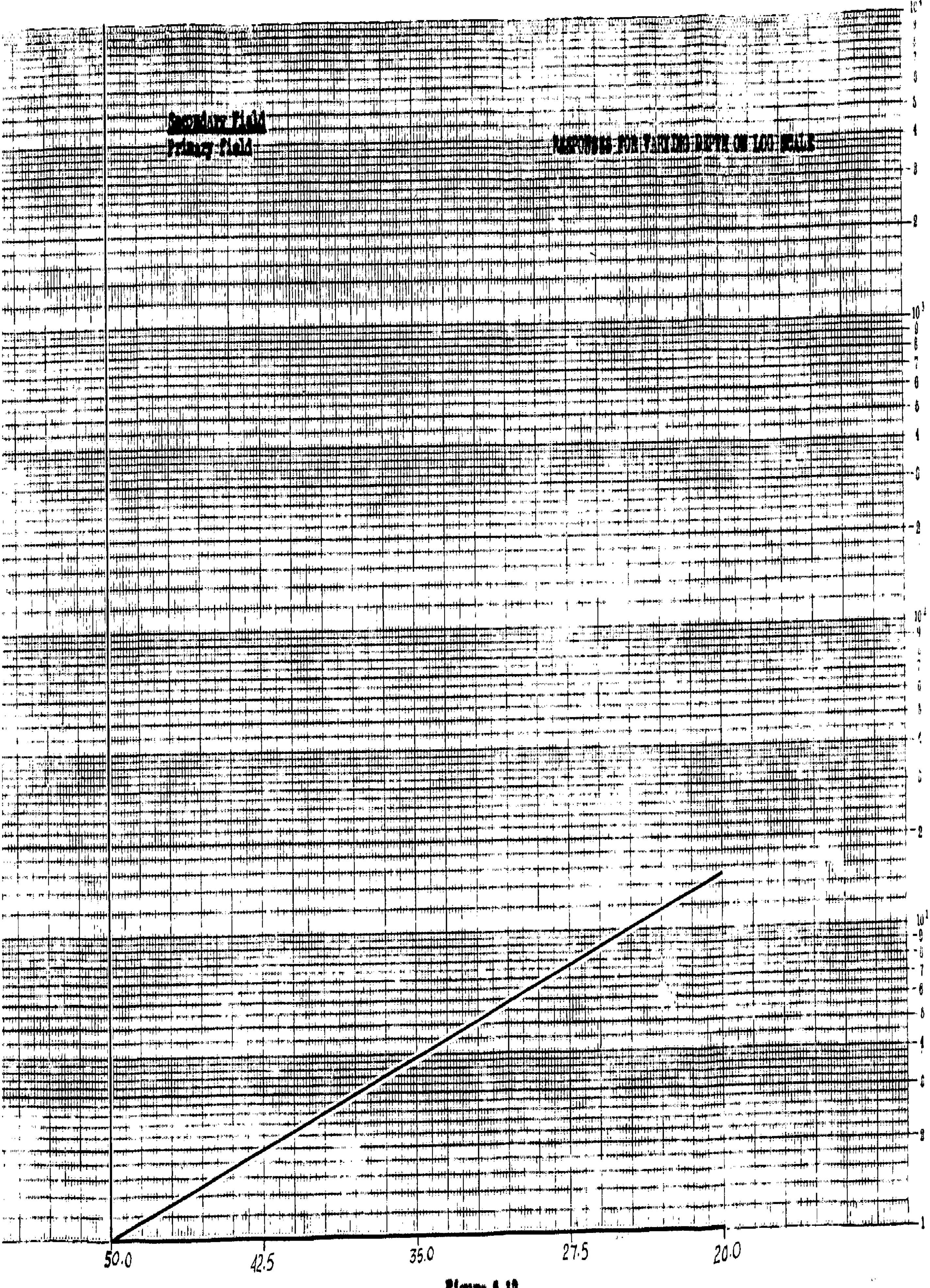

Secondary Field
Primary Field
RESPONSES FOR VARYING DEPTH ON LOG SCALE
10^4
10^3
10^2
10^1
1
50.0
42.5
35.0
27.5
20.0

Figure 5.12

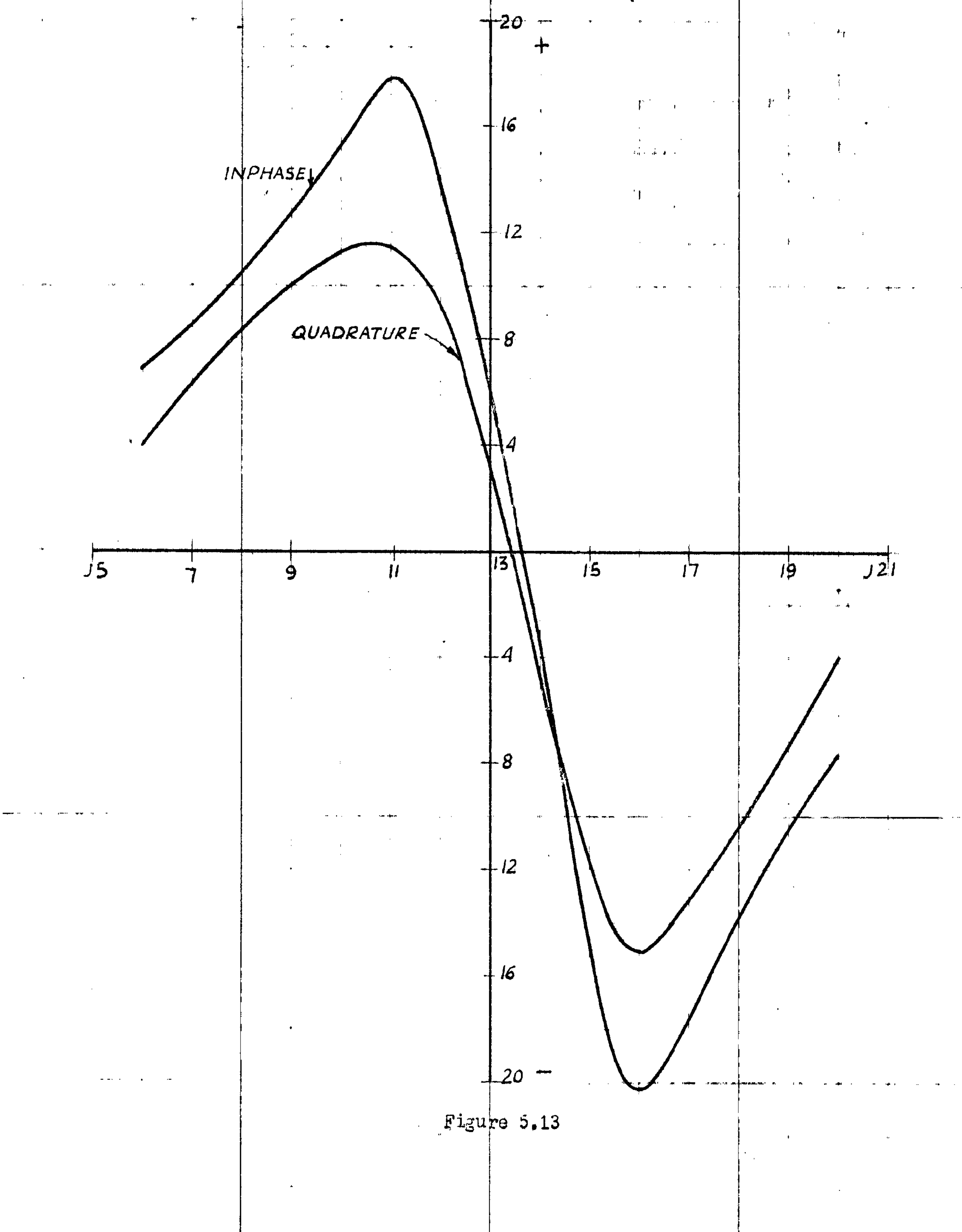


Figure 5.13

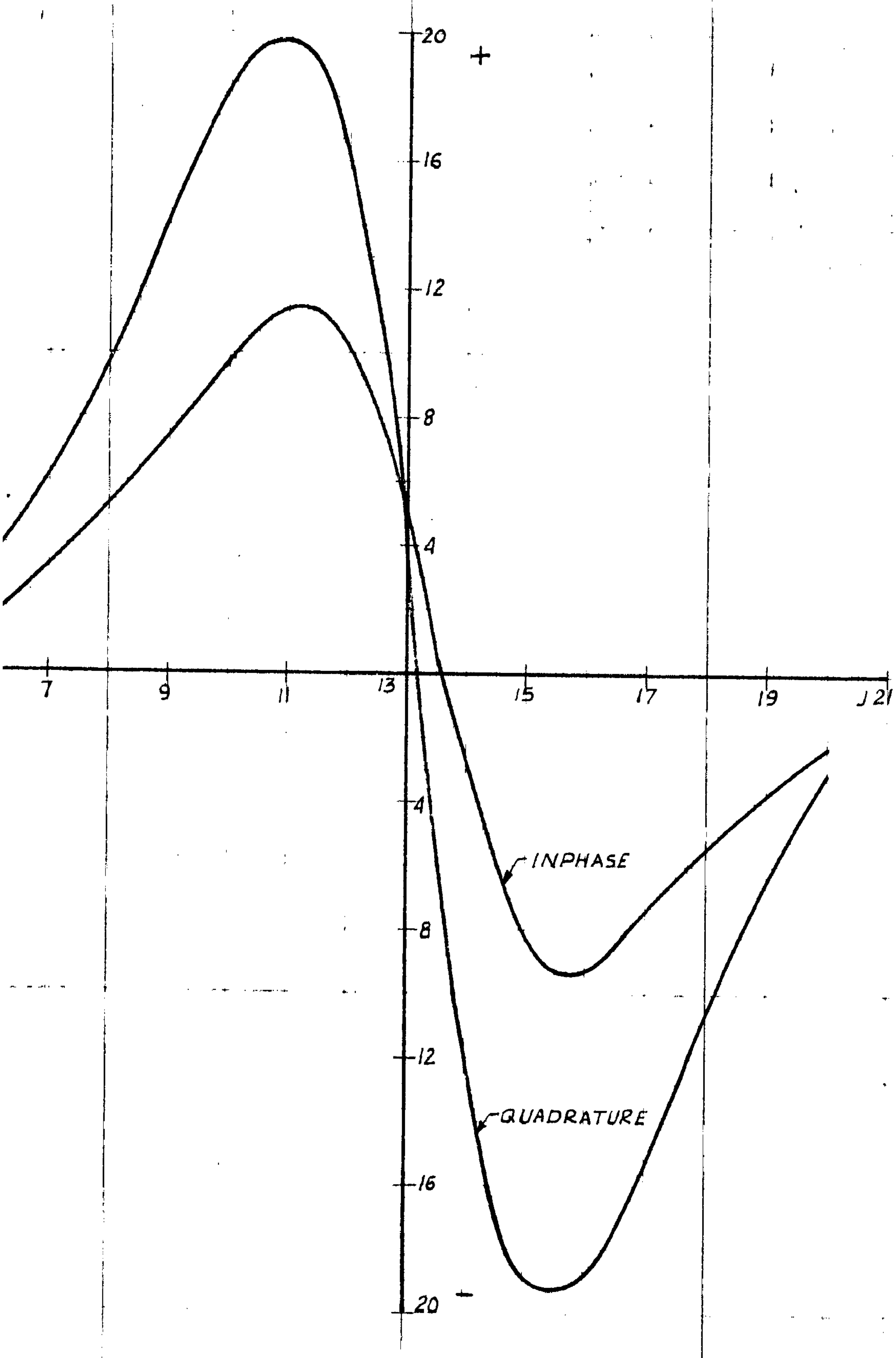


Figure 5.14

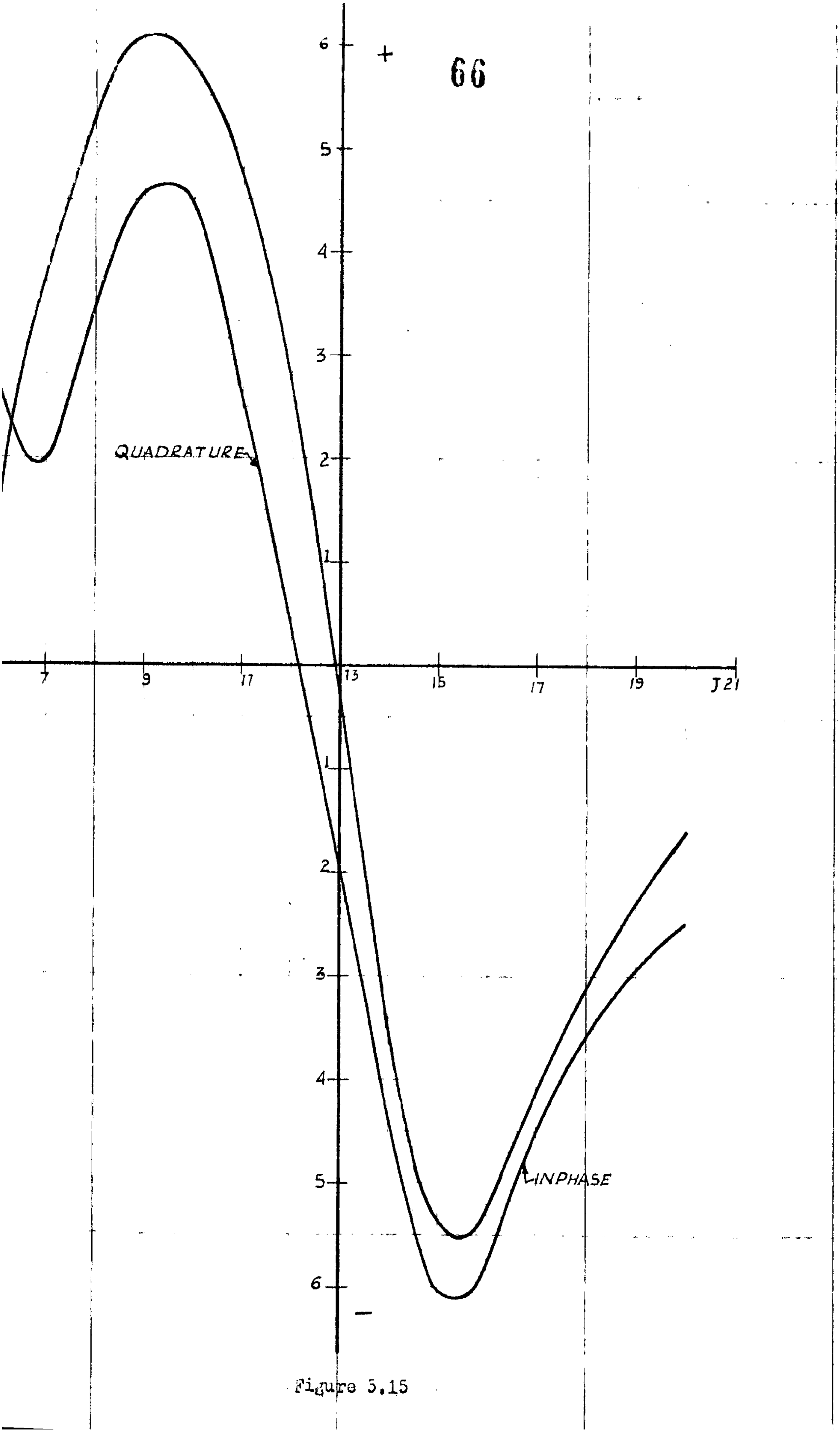


Figure 5.15

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