CANADA

DEPARTMENT OF MINES

HON. W. A. GORDON, MINISTER; CHARLES CAMSELL, DEPUTY MINISTER

GEOLOGICAL SURVEY

W. H. COLLINS, DIRECTOR

MEMOIR 165

Studies of Geophysical Methods, 1928 and 1929

OTTAWA
F. A. ACLAND
PRINTER TO THE KING'S MOST EXCELLENT MAJESTY
1931

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Studies of Geophysical Methods, 1928 and 1929

PART I

INVESTIGATIONS MADE IN CO-OPERATION WITH RADIORE COMPANY OF CANADA, LIMITED, SCHLUMBERGER ELECTRICAL PROSPECTING METHODS, AND SWEDISH AMERICAN PROSPECTING COMPANY OF CANADA

CHAPTER I

INTRODUCTION

By J. B. Mawdsley

The great development experienced by the Canadian mining industry in the last few years has aroused general interest in methods of prospecting that promise to aid the determining of geological conditions, or the locating of valuable mineral deposits. Geophysical methods have been watched with interest and especially electrical methods which, at present, seem better adapted than other geophysical methods to Canadian needs when prospecting for metalliferous ore-bodies. This report (Part I), based on field work carried out in conjunction with prospecting companies using electrical methods, is an attempt to meet the general demand for unbiased information concerning prospecting by electrical methods.

Geophysical methods of prospecting make an especial appeal to those who are concerned with the Canadian mining industry because large areas that hold valuable ore deposits are difficult to prospect owing to a widespread overburden of glacial origin.

Geophysical prospecting methods have been experimented with for many years. There are ways of detecting various physical differences that exist between different rocks and different ores. The most important methods are classed as gravitational, seismic, magnetic, and electrical. The gravitational methods are based on the differences between the specific gravities of various components of the earth's crust; the seismic, on their elastic properties; the magnetic, on their magnetic properties; and the electric, on their electrical properties.

Gravitational and seismic methods have not been used in Canada, although extensively employed elsewhere, as in the oil fields of the southern United States and Mexico. Magnetic methods have long been used in many countries; in Canada they are an important aid in detecting bodies of magnetic minerals such as magnetite and pyrrhotite. Refinements in the use of magnetic methods have been made in the past few years and work, mainly in other countries, has indicated their value, under certain conditions, as a means of locating geological structures and formations. Electrical methods, during the past thirty or forty years, have been the subject of much research in many countries. They have been the means of locating valuable deposits that have electrical characteristics markedly different from those of the containing rocks, as in the cases of deposits of certain of the metallic sulphides; and, in recent years, they have been employed to aid the deciphering of geological structures and the estimating of the thickness of drift covers. Electrical methods have been used quite extensively in Canada during the past seven years, chiefly in attempts to locate sulphide ore-bodies. The Quebec Department of Mines, in its records of assessment work done up to March, 1928, lists some sixty mining companies for whom electrical surveys were made during the past four years, chiefly in northwestern Quebec. Considerable areas have also been electrically surveyed in Ontario and similar work has been done in Manitoba, Alberta, and British Columbia.

The technical literature has reflected this activity and many articles, as well as advertisements dealing with electrical prospecting methods, have been published in Canada and elsewhere. On the whole, this literature has been unsatisfactory from the point of view of the mining companies and the general public. Although many of the articles are excellent in every way, it is exceedingly difficult for the average reader to evaluate this comparatively new and important phase of prospecting technique. The highly technical nature of parts of the subject, the withholding of many trade secrets, and the apparently biased nature of much of the information, has in the minds of the public cloaked the subject with an unnecessary and harmful air of mystery. A feeling of distrust was fostered by this air of mystery and by the obviously incorrect statements contained in some advertisements published by certain of the prospecting companies. This distrust has been heightened by the use made by certain mining companies and stock brokers of maps made by the prospecting companies. These maps, which indicated electrical conditions, were in many cases presented to the not too critical public as indicating potential or proved ore. Further work on many of these properties brought disillusionment and resulted in the electrical prospecting companies being the object of a largely undeserved distrust on the part of the public.

It is only natural that the need of improved methods of prospecting and that the expenditures made on, and the interest already shown in, electrical methods of prospecting, should result in a demand for reliable information concerning these methods. The desire for authentic information is expressed not only by the mining industry and the general public, but by the reputable electrical prospecting companies who feel that an unbiased account will help to remove misconception and to place before the public the value of the service that they sell.

The Geological Survey being fully aware of the importance of the situation decided to study electrical methods of prospecting. It was recognized that a report on the subject to be of the greatest value to the industry should be issued at the earliest possible date. This condition precluded any attempt to investigate the whole subject, since an elaborate experimental program would require very much time both to organize and to produce results. Furthermore, such a program could not fail to result in unnecessary duplication of effort, since all the larger prospecting companies maintain research laboratories and have at their command the results of years of valuable laboratory and field experience. Besides this, the United States Bureau of Mines is investigating the subject along experimental lines, and has already issued a preliminary report[1] and a further report is promised. The most promising method of speedily obtaining results of value semed to lie in securing the co-operation of the already fully equipped electrical prospecting companies. Accordingly, the prospecting companies operating in Canada were asked if they would care to co-operate in the following program: the Geological Survey to appoint observers to watch the prospecting companies at work; the observers to study the electrical methods used, the conditions existing, and the results obtained; the observers to prepare a report based on the data thus collected and containing whatever conclusions the observers thought to be warranted. The electrical surveys would be carried out either as part of the ordinary contract work of the companies or on any deposits that could be studied geologically and were suitable for the companies to survey. Such a survey would be made under the field conditions met with by the companies in the course of their routine work and would give a fair idea of what could be expected from such work under similar conditions. It was fully realized that any such program could not be in any sense exhaustive, for it would be impossible within the time available to study all the different methods under all possible geological conditions. This program met with the approval of the companies approached and three of them found it possible to co-operate with the Geological Survey in this program during the short field season available during the summer of 1928.

The invitation to co-operate in the project was extended to the following five companies: Alderson MacKay and Armstrong, Montreal, who control Dr. E. S. Bieler's methods; Physical Exploration Corporation (Mason Slichter and Hay) of New York and Madison, Wisconsin; the Radiore Company of Canada, Limited, Montreal; Schlumberger Electrical Prospecting Methods, Toronto and New York; and the Swedish American Prospecting Company of Canada, Toronto. An offer of co-operation was received from all these companies and all evinced considerable interest in the proposed plan. Although desiring to help the Survey's investigation, Alderson MacKay and Armstrong were not able to demonstrate the electrical method which they control, as they suspended electrical work in the summer of 1928. The Physical Exploration Corporation, although undertaking to help the proposed investigation, in the end found themselves unable to co-operate in the field program.

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[1] "Geophysical Methods of Prospecting", by A. S. Eve and D. A. Keys; United States Dept. of Commerce, Bureau of Mines, Tech. Paper 420, 1927.

The two authors of this report were given charge of the investigation: L. Gilchrist, of the Department of Physics of the University of Toronto, to take charge of the electrical part of the investigation; and J. B. Mawdsley, of the staff of the Geological Survey, to conduct the geological work.

Permission was obtained from the officials of the Abana Mines, Limited, to carry out the field program on their property in Desmeloizes township, Quebec. This generous concession assured the electrical prospecting companies of an opportunity to demonstrate their methods on a deposit that promised to be comparatively suitable for mapping electrically and magnetically and that could be studied in detail geologically. Although the Abana property was thus available for study, it was made clear to the electrical prospecting companies that any alternative site would be acceptable, provided the program could be there carried out. Each of the three companies decided in favour of the Abana property.

The Radiore Company of Canada, the Schlumberger Electrical Processes, and the Swedish American Prospecting Company of Canada carried out the demonstration of their various methods at their own expense. Not only was the expense entailed by these companies very considerable, but in co-operating with the Geological Survey they were put to considerable inconvenience, in certain cases involving delay in carrying out their ordinary contract work. The freely given and whole hearted co-operation that they and their staff gave the Geological Survey left nothing to be desired.

The free use of the Abana mine given by the officials of the Abana Mines, Limited, was of the greatest value. Through the efforts of Mr. A. Brambrick, superintendent, and the staff at the mine, everything was done that might expedite the work and make the stop at the mine a very pleasant one.

Much information and help of various kinds were received from many other sources and were fully appreciated by the authors.

CHAPTER II

ELEMENTARY PRINCIPLES OF MAGNETIC, ELECTRICAL, AND ELECTROMAGNETIC METHODS OF PROSPECTING

By L. Gilchrist

MAGNETIC METHODS OF PROSPECTING

Magnetic methods have, for some time, been in more general use than electrical methods. The mineral deposits that may be investigated through the former are chiefly those of the magnetic minerals magnetite and pyrrhotite. The principles associated with these methods, the procedure which is followed in their application, and the interpretation of the experimental results readily become familiar with a little study and experience or, at least, do so if the magnetic conditions investigated are pronounced and simply distributed.

There are numerous articles on the subject by investigators of terrestrial magnetic phenomena, and manufacturers of instruments for magnetic exploration usually issue pamphlets that set forth clearly not only the detailed methods of application of their instruments, but also the principles that form the basis of their construction and use. A brief discussion of typical procedure in order to indicate the difficulties and limitations is, therefore, sufficient for this report.

When the ordinary magnetic needle is suspended it takes up a definite position with respect to the geographical axis of the earth due to the resultant magnetic force associated with the earth. Owing to the existence of local magnetic bodies this position varies greatly at different places. These variations serve to indicate the position and extent of these bodies. In order that experimental results may be readily interpreted the following magnetic elements are usually determined.

(1) The easterly or westerly declination of the magnetic needle. This is the angle that the vertical plane in which the needle rests when freely suspended makes with the geographical meridian plane.

(2) The inclination or dip of the magnetic needle. This is the angle that the needle makes with the horizontal when freely suspended in the magnetic meridian plane.

(3) The intensity of the magnetic field. This is the force exerted on a unit magnetic pole. A unit pole is that pole which, at a distance of 1 cm. from an equal pole, exerts a force of 1 dyne on it. This, together with the inclination or dip, may be used to determine the horizontal and vertical components of the intensity of the magnetic field.

The results of the determination of any or all of these elements may be taken into consideration in the portrayal of local magnetic conditions. In general, for this purpose it is sufficient to determine the variation of these elements from some actual or hypothetical standard conditions.

The following serve to illustrate the methods of procedure.

(1) The declination and the dip may be determined directly by a magnetic needle. For this purpose a magnetic needle is suspended so that

it may move freely both horizontally and vertically. It is placed at a point on the surface of the earth where local bodies do not exist. This is usually designated the standardizing place. The angle the needle makes with the geographical meridian is the declination at this place on the earth's surface. The instrument is rotated so that the needle is in the plane of the magnetic meridian and, therefore, may move freely in the vertical plane. Then if the axis of suspension of the needle passes through the centre of gravity of the needle the angle that the needle makes with the horizontal is the magnetic inclination or dip at the standardizing place. The instrument in this form is spoken of as the "dip needle" or "dipping needle" and may be used to obtain the true dips at any place.[1]

If

H=the horizontal component of the earth's magnetic field
V=the vertical component of the earth's magnetic field
D=the angle of inclination or dip

then, $\tan D = \frac{V}{H}$

The values of D, V, and H for places that are free from the effects of local magnetic bodies may usually be obtained from the reports of magnetic surveys. If they are obtained for the standardizing place they are referred to as the standard or normal values.

(2) If at the standardizing place the needle is weighted in a vertical line directly below the centre of suspension the angle of inclination, or dip, at this place will remain as before, but the centre of gravity will be situated directly below the centre of suspension.

The instrument in this form will not give the true dip at places where the true dip is different from that at the standardizing place. At places where local magnetic bodies exist the apparent dip D′ in the resultant meridian plane will be different from that at the standardizing place and

$$\tan D' = \frac{Z}{R \pm \frac{W_1 g r_1}{M}} \qquad \text{(a)}$$

where W_1=the weight of the system
g=the acceleration due to gravity
r_1=the distance from the centre of gravity to the axis of suspension
M=the magnetic moment of the needle

Z and R are the vertical and horizontal components, respectively, of the magnetic field at the place of investigation. The values of the apparent dips at suitably chosen stations may be used to indicate the position of local magnetic bodies.

At the standardizing place an adjustable counterweight may also be attached to the south end of the needle if the instrument is to be used to indicate northerly dips to provide that the needle may be used in the position of maximum sensitivity which is given by Stearn[2] as 12 degrees below the horizontal where the normal dip is about 70 degrees.

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[1] Stearn, Noel H.: Proc. Am. Inst. Min. Eng., Boston, August, 1928.

[2] Stearn, Noel H.: "The Dip Needle as a Geological Instrument"; Proc. Am. Inst. Min. Eng., Boston Meeting, August, 1928.

The addition of the adjustable counterweight on the south end of the needle will displace the centre of gravity of the system a short distance to the south of the vertical line passing through the point of suspension of the needle and produce rotation of the needle so that only apparent dips are given at the standardizing place as well as at other places. The apparent dip D″ is represented by the equation

$$\tan D'' = \frac{Z}{R \pm \frac{Wgr}{M}}$$

where W=the new weight of the system
and r=the distance from the centre of gravity to the axis of the system.

(3) In order to evaluate Z and R the instrument is modified still further. The counterweight is adjusted until the vertical component at the standardizing place is cancelled and the needle rests in a horizontal position. The instrument in this form is usually called a Magnetometer or Field Balance. It is now largely used for investigations of magnetic fields due to local magnetic bodies in which the resultant fields are greater than the normal fields.

If at the place of investigation the dip of the needle in a vertical plane is D_1

$$\text{Then } Z\,M \cos D_1 = (R\,M \cos B \sin D_1 + Wgr \sin D_1)$$

$$\therefore Z = (R \cos B + \frac{Wgr}{M}) \tan D_1 \ldots\ldots\ldots\ldots \quad (1)$$

where B is the angle between the vertical plane in which the dip D_1 is read and the meridian plane of the resultant field at the place of investigation.

(*a*) If the vertical plane which contains the needle coincides with the plane of the magnetic meridian of the earth as determined at the standardizing place, then $Z = (R \cos B_1 + \frac{Wgr}{M}) \tan D_2 = (R \cos B_1 + K) \tan D_2$

where B_1=the angle between the magnetic meridian plane at standardizing place and the magnetic meridian plane at the place of investigation.

(*b*) If the vertical plane containing the needle is at right angles to the plane containing the direction of the resultant force R then

$$Z = \frac{Wgr}{M} \tan D_3 = K \tan D_3 \ldots\ldots\ldots\ldots\ldots \quad (2)$$

where $K = \frac{Wgr}{M}$ which may be considered a constant if the magnetic axis of the needle passes through the axis of suspension and if its magnetic moment does not change.

The method (*b*) may be used alone and the variations in the value of D_3 (=the angle of dip) and consequently of $\tan D_3$ at different places will be a measure of the differences in the value of Z at these places. If these are plotted suitably the position of the magnetic body may be indicated approximately.

If both methods (*a*) and (*b*) are used at each place of investigation then:

$$(R \cos B_1 + K) \tan D_2 = K \tan D_3 \ldots\ldots\ldots\ldots \quad (3)$$

$$\therefore R \cos B_1 = \frac{K (\tan D_3 - \tan D_2)}{\tan D_2} \ldots\ldots\ldots\ldots \quad (4)$$

Now if the instrument is rotated so that the needle moves freely in a horizontal plane the value of B_1 may be measured. Also, if with the needle in this position an auxiliary magnet is placed with its axis always perpendicular to the axis of the needle and deflects it through an angle α, and if at the standardizing place the same magnet in the same position with reference to the axis of the needle deflects the needle through an angle α_0, then R may be obtained from:

$$R = \frac{\sin \alpha_0}{\sin \alpha} H \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

where H=the horizontal component of the intensity of the earth's magnetic field at the standardizing place. From this, together with equation (4) above, the value of K may be calculated and then Z, H_1 ($= R \cos B_1$), and $F \sin B_2$, where F is the resultant horizontal component of the magnetic force due to the local magnetic bodies and B_2 is the angle between the direction of F and the direction of R, may be evaluated. An extensive, well-arranged set of values of Z, H_1, and $F \sin B_2$ will enable the investigator to outline the location of the magnetic zone. $F \sin B_2$ is, of course, $= H \sin B_1$.

(*c*) In many places of investigation it may not be convenient to determine the position of any other vertical plane (e.g., the geographical meridian plane) than that in which the resultant magnetic force is situated. In such circumstances measurement (*a*) cannot be made and consequently B, and H_1 cannot be determined. However, sufficient information for the location of the magnetic body in simple conditions is still obtainable.

If the vertical plane containing the needle is made to coincide with the vertical plane containing the resultant force R then

$$Z = (R + K) \tan D_4 \ldots\ldots\ldots\ldots\ldots \quad (6)$$

where D_4 is the angle of dip.

From equations (2) and (6)

$$K \tan D_3 = (R + K) \tan D_4$$

$$\therefore K = \frac{R \tan D_4}{\tan D_3 - \tan D_4} \ldots\ldots\ldots\ldots\ldots \quad (7)$$

Since R may be obtained from equation (5) then K and Z may be evaluated from (7) and (6) respectively. If values of R and Z are determined in numerous, well-chosen positions the location of the magnetic zone may be outlined approximately.

In weak fields the value of $F \sin B_2$ will be small and in order that D_2 and D_3 may be sufficiently large for accurate measurement a highly sensitive instrument must be used. Sensitivity is obtained by providing that W and r are small and M large. In largely sensitive instruments, which are used in weak fields, it is necessary to make certain that the movement of the needle is unhampered and also to take account of variations of H and V with time and variations of M with temperature.

When only weak magnetic fields which are due to the presence of magnetic mineral are to be investigated by a very sensitive instrument such as the Schmidt Balance, it is in general only the variations from the normal magnetic field at the standardizing place that are registered and the horizontal and vertical components of the actual intensities are not measured. When the instrument is constructed for this purpose it is sometimes described as a variometer.

When magnetic methods are used for the investigation of weak magnetic fields of complex distribution, or if the results are to be used in conjunction with the results of an electrical or an electromagnetic exploration, very close study and extensive experience, as well as experimental skill and care, are imperatively necessary in order to reach dependable conclusions.

It seems to be unnecessary to describe methods that are modifications of the above or to give examples of others that make use of elastic forces in order to determine Z and F. The construction, theory, and use of the various instruments, together with the results of investigations in which they have been applied and the interpretations of these results, are discussed in detail in the following:

Haanel, Eugene: "On the Location and Examination of Ore Deposits". Ottawa, Canada, 1904.

Pautsch, E.: "Methods of Applied Geophysics". Houston, Texas (Minor Printing Co.), 1927.

Heiland, C. A., and Duckert, P.: Zeitschrift fär angewandte Geophysik, Bd. 1, Heft 10, August, 1924, pp. 289-315; Bd. 1, Heft 11, January, 1925, pp. 321-329.

Heiland, C. A., and Courtier, William H.: "Magnetometric Investigation of Gold Placer Deposits"; Proc. Am. Inst. Min. Eng., Boston Meeting, August, 1928.

Heiland, C. A.: "Theory of A. D. Schmidt's Horizontal Field Balance"; Proc. Am. Inst. Min. Eng., Boston Meeting, August, 1928.

Heiland, C. A.: "Constitution, Theory, and Application of Magnetic Field Balances"; Bull. Am. Assoc. of Petroleum Geologists, December, 1926.

Schlichter, Louis B.: Technical Publication No. 120, Am. Inst. Min. Eng.

Ambronn, Richard: Methoden der angewandten Geophysik, pp. 47-84. Theodor Steinhoff, Dresden and Leipzig, 1926. English Translation, McGraw Hill Co., New York, 1928.

Stearn, Noel H.: "Background for the Application of Geomagnetics to Exploration". "The Dip Needle as a Geological Instrument"; Proc. Am. Inst. Min. Eng., Boston Meeting, August, 1928.

Aldrich, H. R.: "A Demonstration of the Reflection of Geologic Conditions in Observed Magnetic Intensity"; Proc. Am. Inst. Min. Eng., Boston Meeting, August, 1928.

Hazard, D. L.: "The Earth's Magnetism"; Serial 313, Special publication 117, Dept. of Commerce, U.S. Coast and Geodetic Survey.
"Directions for Magnetic Measurements"; Serial 166, Department of Commerce, U.S. Coast and Geodetic Survey.

Eve, A. S., and Keys, D. A.: "Applied Geophysics", Chap. II, Cambridge University Press, 1929.

ELECTRICAL AND ELECTROMAGNETIC METHODS OF PROSPECTING

Electrical methods of prospecting depend on the differences of electrical properties that are associated with certain minerals, and with certain rocks and covering materials that compose the earth's crust. The position of bodies of such minerals may be indicated, and information that helps to solve such problems as the thickness of drift cover and the existence of faults or other geological structures may be obtained, if the differences in electrical properties exist over an extended area and are sufficiently great to admit being readily measured.

The electrical methods may be divided into three main classes which respectively depend on:

(I) The measurement of the distribution of self potential and the properties of the resulting natural currents.

(II) The measurement of the properties of a direct current which is passed through the region that is under investigation by the application of a direct difference in potential from a battery or other generator.

(III) (*a*) The measurement of the properties of an alternating current which is passed through the region that is under investigation; (*b*) the determination of inductive effects of an alternating current passed through an adjacent insulated, closed wire loop by the application of an alternating difference in potential from a suitable generator.

(I) Self-Potential Method

This method depends on the occurrence of a set of conditions that are much like those associated with the simple galvanic cell. For example, an ore-body containing sulphide of iron or copper and which is embedded in suitable surrounding materials may form a battery in which the upper part commonly forms a negative pole and the lower part a positive pole and there are continuous natural currents of electricity, as indicated in Figure 1.

Surfaces that cut the current lines at right angles will be surfaces of equipotential and the intersections of these surfaces with the surface of the earth will be lines of equipotential. The positions of the equipotential lines depend on: (*a*) the positions of the resultant poles associated with the underground body, and (*b*) the conductivity of the surrounding materials. By means of exploring electrodes connected with simple instruments, the lines of equipotential on the surface of the ground may be located and the difference in potential between adjacent equipotential lines may be measured. The interpretation of these results is not in general simple and direct especially where conditions (*a*) and (*b*) are complex. Where simple uniform conditions exist the interpretation is correspondingly simple and in the hands of competent investigators should lead to the location of the underground body.

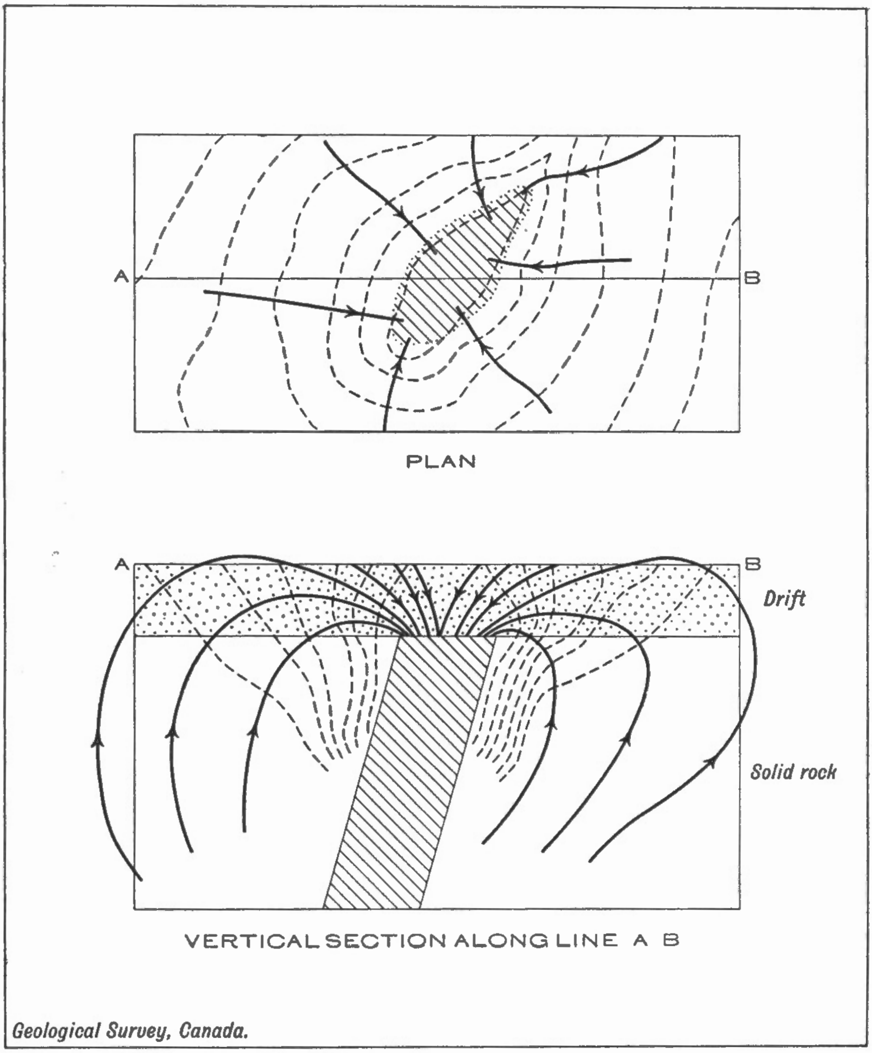

Figure 1. Plan and vertical section of a body of mineral sulphides illustrating positions of lines of currents (shown by solid lines) and traces of equipotential surfaces (shown by pecked lines) at 50 millivolt intervals.

(II) Direct Current Method

In this method instead of making use of information obtained from the self potentials and natural currents in the region, measurements are made of a direct current which is passed through the region under investigation. Electrodes are driven into the surface of the earth and are connected to a direct current generator or battery. By way of these lead-in electrodes, impressed direct currents pass through the region. The impressed potential difference is in general considerably greater than the self potentials associated with underground bodies. If the self potentials or potentials due to polarization set up by the direct current are negligibly small or if they can be eliminated, e.g., by compensation, or if they can be taken into consideration accurately in the final computations, then a portrayal of the current lines and the equipotential curves on the surface of the ground may be made in a manner quite similar to that which has been described in the self-potential method.

Since with this method the generator and the character and disposition of the electrodes as well as the measuring instruments are under control, the scope of the investigation is considerably wider than is possible by the self-potential method. It can be arranged that the potentials and currents will be distributed to the best advantage in determining the existing conditions of conductivity, and that they will be of such magnitude that they may be measured with a reasonable degree of accuracy. There are, for example, several ways of arranging both the lead-in electrodes and the exploring electrodes, and for each arrangement suitable mathematical formulæ must be derived in which the results of measurement may be incorporated in order to permit of interpretation. There is an extensive range of possibilities in these arrangements and their accompanying formulæ, especially since the formulæ even for simple cases can only be approximate. These formulæ are the very essence of the methods made use of by the exploring companies and are, therefore, private in character. It is to be expected, however, that the methods and formulæ made use of by the different companies will differ considerably.

TABLE I

Material	**Specific resistance in ohms per cm. cube**
Calcite	$5{\cdot}5 \times 10^{14}$
Chalcopyrite	$0{\cdot}2$
Diabase	2×10^{8}
Granite	approx. 10^{10}
Hornblende	approx. 10^{9}
Magnetite	$0{\cdot}5$
Porphyry	$1{\cdot}5 \times 10^{9}$
Pyrite	$0{\cdot}05$ to $0{\cdot}5$
Sphalerite	$1{\cdot}5 \times 10^{8}$
Wet blue clay	10^{3}
Humus	10^{4}

There is a wide range in the condition of conductivity that may exist (*See* Table I). In a general way a series of terrestrial conductors ranging from very low to very high specific conductivities shows a rough classification into rocks, soils, and minerals with extremely large differences between the classes, and large differences within each class. Basic rocks are usually more conductive than acid rocks. Differences exist in the conductivities of humus, sand, and clay varying especially with the conditions of moisture or occluded solutions of mineral salts. Minerals themselves differ largely, ranging from very good conductors such as pyrite, chalcopyrite, and pyrrhotite, to poor conductors such as sphalerite and stibnite, and to extremely poor conductors such as oils and solid salt. Since the distribution of these substances is usually very complex, it is apparent that any exploratory method can determine only an average specific conductivity which will depend on the extent and character of the region in which the measurements are made. It is not surprising, therefore, that at times there will be a pronounced divergence in the conclusions reached as a result of investigations, for no method is adequately applicable to all sets of conditions. If, however, the mineral body is a good conductor and is massive and if the surrounding substances are of a fairly uniform low conductivity, the conclusions reached even for a mineral body at considerable depth, provided it is sufficiently extensive, should not greatly diverge.

There are two types of lead-in electrodes which are commonly used in the impressed direct current method: (1) the point electrodes (*See* Figure 2); and (2) The parallel wire electrodes (*See* Figure 3). These, together with the accompanying exploring electrodes, are fully described in the recent publication of the United States Bureau of Mines[1] and in the published proceedings of the American Institute of Mining Engineers.[2] The point electrode arrangement is an obvious modification of the parallel wire electrode set-up.

(1) POINT ELECTRODES

The generator is connected to the ground at two points. Since the current strength depends largely on the size of the electrodes and the conductivity of the ground adjacent to the electrodes, resort is made to a group of contacts that replaces each single contact electrode. However, the contacts of each group are placed sufficiently close to form an approximate point electrode. The group of contacts is indispensable when the lead-in electrodes are far apart, or where the conductivity of the ground is very low, or where the potential difference set up by the generator is low.

Two very useful modifications are as follows:

(*a*) One lead-in electrode is placed a great distance from the other and using one of these points as a single electrode, measurements are made in its vicinity.

(*b*) One electrode is a single electrode as in (*a*), but instead of one other at a great distance a number are placed symmetrically about the first and at some distance from it. In (*b*) the currents through the distant electrodes are equalized and measurements are made in the vicinity of the central electrode.

A current is thus made to pass through the region under investigation. The distribution of the current will depend on the conductivity of the bodies of the region. In the presence of highly conductive bodies surrounded by material of much lower conductivity, the lines of flow of current will be much distorted. They appear to crowd into the conductor. From a study of this distortion of the lines of flow the positions of the good conductors are located.

In practice it is not distribution of the current but the drop of potential, on the surface of the ground, along the path of the current, that is

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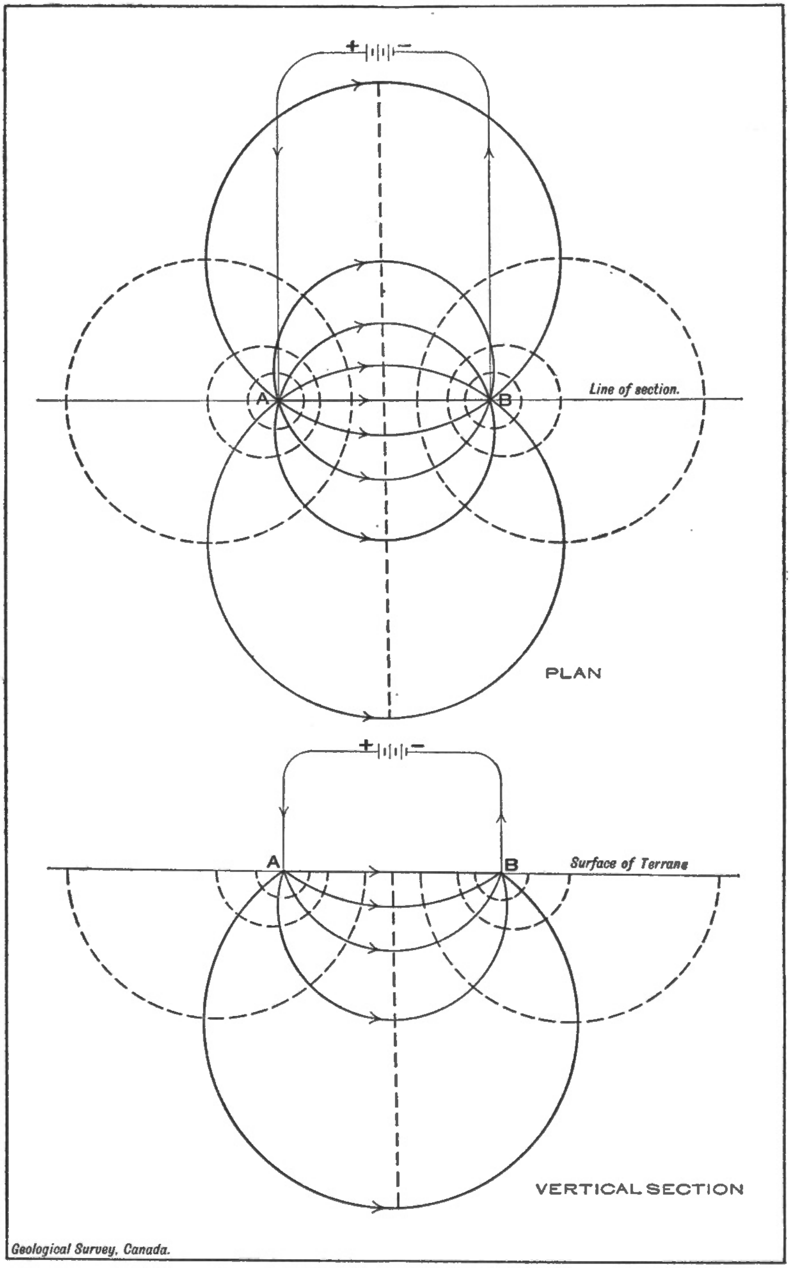
[1] Eve, A. S., and Keys, D. A.: "Geophysical Prospecting: Some Electrical Methods"; U.S. Bureau of Mines, Tech. Paper 434 (1928).

[2] "Geophysical Prospecting 1929"; Am. Inst. Min. Eng.

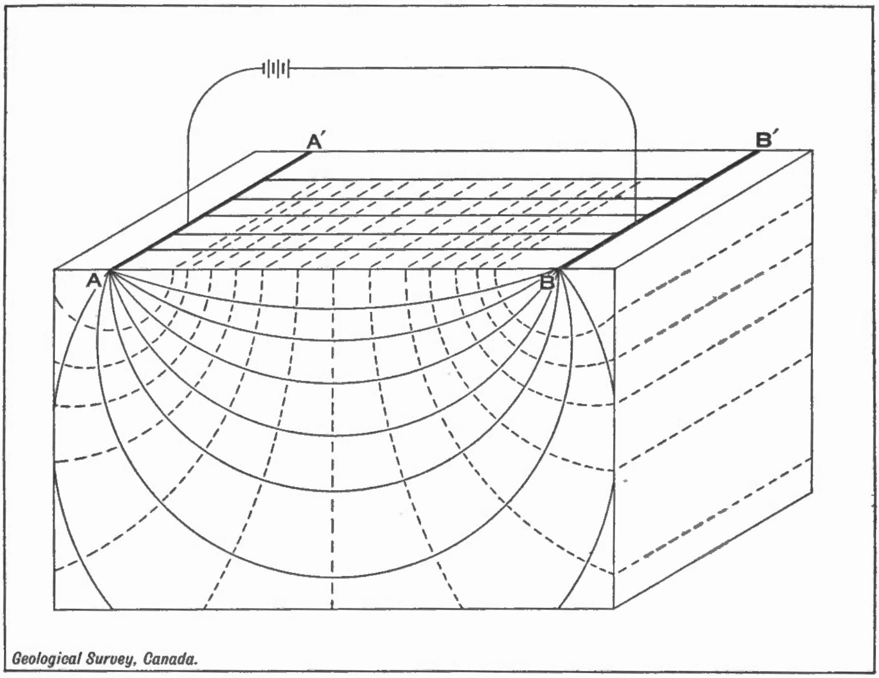


Geological Survey, Canada.

Figure 2. Positions, in a homogeneous conducting media, of lines of currents (shown by solid lines) and traces of equipotential surfaces (shown in pecked lines) between two point lead-in electrodes (A and B).

determined. This potential gradient may be measured with a voltmeter or a potentiometer. An equal drop of potential will take place in a longer distance in a good conductor than in a poor conductor and the distances are proportional to the conductivity. Lines drawn at right angles to the current paths are equipotential lines and these are the lines that are usually traced. They appear to crowd away from the good conductors.

This feature is, therefore, used in the location of the conducting bodies. Usually in this method it is found convenient to make measurements along the line joining the lead-in electrodes. In some instances the distance between the exploring electrodes is kept constant and the drop in potential is measured over equal portions of the line between the lead-in electrodes. Over a conducting body the drop in potential is smaller than over a non-conducting body. From the potential gradient and the strength of the lead-in current average resistivities may be calculated and regions of pronounced differences in conductivities may be located in simple cases. This point electrode method is very flexible indeed and several modifications have been used.



Geological Survey, Canada.

Figure 3. Positions, in a homogeneous conducting media, of lines of currents (shown by solid lines) and traces of equipotential surfaces (shown by pecked lines) between grounded parallel-wire lead-in electrodes (A-A′ and B-B′).

(2) PARALLEL WIRE ELECTRODES

In general principles the use of parallel wire electrodes is quite similar to that of the point electrodes. The current that flows through the region under investigation does not pass between two single electrodes but between two parallel wires which are grounded at many points along their length. The length of the wires should at least be very little less than their distance apart. If they are uniformly well grounded and if material of uniform conductivity lies between them the lines of current flow on the surface of the ground will be parallel to each other and will be perpendicular to the wires except near their ends, and the accompanying equipotential lines will be parallel to the wires, and may be spaced to indicate equal drops in potential as in Figure 3. If the parallel wire electrodes are grounded deeply and uniformly throughout their length the equipotential lines in the central part in Figure 3 should be more nearly equally spaced. If a good conductor is present in the region the equipotential lines will crowd away from it.

The methods of measuring the potentials or of tracing the equipotential lines are similar to those used with the point electrodes, although the modifications that have been developed and applied are probably not yet so numerous. It is noteworthy that Eve and Keys[1] consider that the parallel wire electrodes are similar and more reliable than the point electrodes.

(III) Alternating Current Methods

In several methods an alternating current generator, e.g., a transformer or induction coil, replaces the battery or direct current generator and use is made of suitable recording or measuring instruments. Certain difficulties associated with the direct current methods are eliminated, e.g., polarization and the effects of self potential. And, further, the scope of the investigation is greatly extended. High voltages may be readily used and amplifiers may be associated with the recording apparatus. Entirely new methods based on the electromagnetic properties of alternating currents of a wide range of frequency have been devised. New difficulties have arisen, however, due to the inductive effects associated with alternating currents and in general greater skill and care are required in order to arrive at dependable conclusions.

(1) RESISTIVITY AND EQUIPOTENTIAL METHODS

As with the direct current method both point and parallel wire electrodes may be used in the delineation of the directions of conductivity and the lines of equipotential (*See* Figures 2 and 3). Lines of current flow and equipotential lines may be traced and current strength and potential drops may be measured, but the recording instruments must be adapted to the new method. Unless the current is rectified for purposes of measurement, then alternating current ammeters and voltmeters must be used and in the direct determination of equipotential lines the galvanometer is replaced by the telephone receiver. The modifications of the methods that have been developed for use with alternating currents and the necessary formulæ that have been proposed are as numerous as with the direct current methods and many of these are regarded as private property by the exploring companies.

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[1] Eve, A. S., and Keys, D. A.: "Applied Geophysics in the Search for Ore and Oil"; Camb. Univ. Press 1929, p. 32.

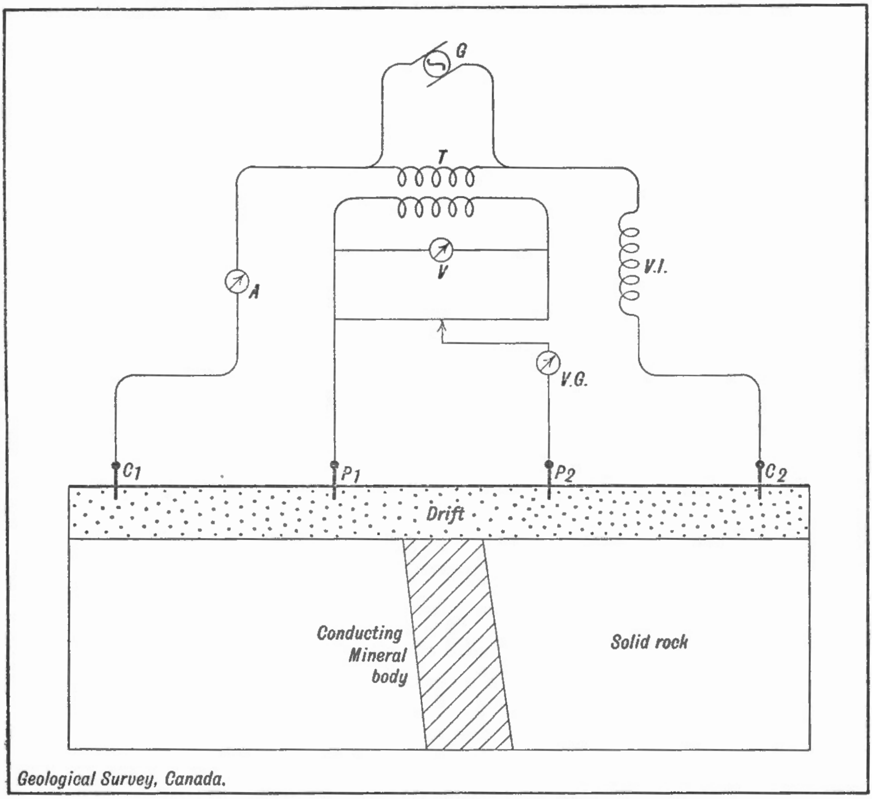

Figure 4. Diagram after Wenner, showing arrangement for measuring four-terminal earth resistance by potentiometer-voltmeter-ammeter method. G=alternating current generator; T=transformer; A=ammeter; V=voltmeter; V.I.=variable inductance; V.G.=vibration galvanometer; C_1, C_2=lead-in terminals; P_1P_2=exploring terminals.

An interesting example of the methods has been published by Wenner[1]. In this method the exploring electrodes of the potential measuring circuit are collinear with the lead-in current electrodes and are intermediately placed so as to divide the line joining all the electrodes into equal parts as in Figure 4.

In conjunction with this arrangement Wenner developed a formula,

$$\rho = 2\pi \text{ a } \frac{V}{i} = 2\pi \text{ a R} \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where ρ=average resistivity or specific resistance of a section of ground of unlimited depth and bounded on the sides by hemispherical shells of radius a cms. and centres c_1 and c_2. In practice the effective depth was found to be approximately equal to a cms. by Rooney (Terrestrial Magnetism and Atmospheric Electricity, September-December 1927).

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[1] Wenner: Bull. U.S. Bureau of Standards, vol. 12 (Sci. paper No. 258, pp. 449–478 (1916)).

V=potential difference between P_1 and P_2 in volts.
i=total current in amperes.
a=$\frac{1}{3}$ $(C_1-C_2)=P_1-P_2$ (distance in cms.). In practice this distance is limited by the range of the generating and measuring instruments.

R=Resistance=$\frac{V}{i}$.

$\pi=3\cdot1416$

It was found by Rooney that the presence of a highly conductive body embedded in a region of uniformly poor conductivity within the depth of a cms. could be readily detected by a definite change in the average resistivity.

Several modifications of the apparatus, notably the development of an instrument (designated the "Megger") to eliminate polarization difficulties and to obtain R directly, and also modifications in the method of application have been made to facilitate its use practically and to increase the accuracy of measurement. A considerable body of good results has been obtained by Rooney, Rooney and Gish[1], and by F. W. Lee[2]. It is to be noted that by this method the "strike" or direction of the axis of conductivity as well as the depth of the conductor may be determined.

A test described in the following short paragraph from Lee's paper is of very great significance. In this test he claims to have succeeded in solving the problem of obtaining definite indications of a conductor even when it was overlain by a second conductor some distance above it.

> "A very interesting test was the use of a megger upon a proving ground in which the ore-body dipped north. The line of stakes taken on the east and west line showed increased conductivity at about 25 feet depth, then the average resistivity increased again to 130,000 ohms, until at 80 feet depth another sharp drop of resistivity occurred. Ore may, therefore, be anticipated at two strata separated by about 50 feet of granite rock. Furthermore, the direction of the strike is east and west with a dip north or south. In this instance the dip was known to be south from old drill-hole records for the vicinity."

It is evident from Lee's conclusions regarding improvements that may be made in the method that skill and care are required in order to obtain dependable results. As in other cases the formula associated with this method had been developed for use in the simple condition where an extensive conductor is embedded in a uniform poorly conducting material. Investigations in regions where the conditions of conductivity are more complex should lead to interesting modifications and to further good results.

Methods similar to those that have been described have been discussed in detail and applied very successfully under fairly complex conditions of conductivity by A. S. Eve and D. A. Keyes.[3] The articles by these investigators not only give the principles underlying the various methods, the details of procedure, and the results obtained, but also indicate clearly the difficulties which they found to be associated with the application of each method and the interpretation of the information obtained. Attention is also directed to the necessity for further investigations under other conditions.

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[1] Am. Inst. Min. Eng., Tech. Pub. No. 82, 1928.
[2] U.S. Bureau of Mines, Tech. Paper 440, 1928.
[3] U.S. Bureau of Mines, Tech. Paper 420, 1927, and 434, 1928.
Eve, A. S., and Keys, D. A.: "Applied Geophysics in the Search for Ore and Oil"; Camb. Univ. Press, 1929, pp. 32–35.

(2) INDUCTIVE ELECTROMAGNETIC METHODS

These methods are based on the principles underlying (a) the magnetic field associated with an electric current in a primary conductor, and (b) the induced potential differences and currents that are set up in adjacent secondary conductors by the changing magnetic fields that are associated with an alternating current in the primary conductor.

When a current is flowing through a conductor, e.g. a wire, lines of magnetic force link themselves about it in rings. If a magnetic needle is brought near such a conductor, it takes up a position along the magnetic lines of force and in fact these lines of force have the same properties as those found associated with an ordinary magnet, but owing to their association with a current of electricity they are known as electromagnetic lines of force.

If a good electrical conductor, e.g. a wire, is moved across a magnetic field, an electromotive force or potential difference, and consequently a current, is produced in the moving conductor. The direction of this induced or secondary current is in a definite direction with respect to the magnetic lines of force and the direction of motion of the conductor. The strength of the secondary or induced current is directly proportional to the number of lines of force of the primary field which are cut in unit time and is also proportional to the conductivity of the secondary conductor. This secondary or induced current will also have associated with it a magnetic field proportional to the strength of the secondary current.

If the current in the primary conductor is alternating, the magnetic field associated with it will also be changing in intensity and alternating in direction. In this case the secondary conductor need not be moved for there will be induced in it an alternating current due to the changing primary magnetic field and of the same frequency of alternations in general as that existing in the alternations of the primary current. This secondary alternating current will, of course, also have its own magnetic field associated with it. In any region, therefore, where there is a primary conductor carrying an alternating current and one or more secondary conductors the direction and intensity of the magnetic field will be the resultant of the fields that are associated with all of the conductors. This interaction of each of the changing magnetic fields and the conductors is known as mutual induction.

In general, for purposes of investigation, the instantaneous resultant field may be divided into two components, and where the existing conditions are not too complex the direction and magnitude of the portions of these components that are due to the primary and secondary fields may be determined separately, or if it is desirable either portion may be eliminated from the investigation.

It is apparent that the problem of organizing and interpreting the information obtained from an investigation of the effects of mutual induction, may be quite difficult unless the conductors are few in number and simply and symmetrically situated. Moreover, there is also an interaction between each conductor and the changing magnetic field associated with its own current and, consequently, a "back" or opposing electromotive force is induced in each conductor. This interaction is known as self induction and must be incorporated in the measured results of the investigation. Another important factor, that of the distributed capacity of the conductors, depends on the size, shape, and distribution of the conductors, and the intervening media and its effects must be carefully evaluated.

It has been pointed out that it is the effect of the instantaneous resultant magnetic field that is registered on the testing instruments. Now it is a well-known accompaniment of the property of mutual induction that the currents in the secondary conductors and, therefore, the magnetic fields associated with them, are out of phase with the current and magnetic fields associated with the primary conductor, that is at the instant when the magnetic field associated with the secondary conductors is a maximum the magnetic field associated with the primary conductor is a minimum. These magnetic fields are also at right angles to each other. This out of phase condition and perpendicularity of the magnetic fields associated with the primary and secondary conductors combine to produce what is called an elliptical field. Moreover, the properties of self induction and capacity which in general are different in magnitude for every secondary conductor have the effect of putting the current in each secondary conductor out of phase with the potential difference applied to the conductor. All of these factors combine to produce a wide range of phase differences of the magnetic fields associated with a network of conductors. Further, alternating currents from ordinary generators are not usually of a single frequency. Several harmonics accompany the fundamental.

When telephone circuits and amplifying sets are used in the testing apparatus a further set of harmonics is introduced. The mutual inductions, self inductions, and even the capacities vary with the frequency and contribute to the complexity of the conditions that are the result of the changing magnetic fields. The use of inductive methods introduces, therefore, unique factors which require full consideration.

The general procedure made use of in some of the inductive methods may be indicated briefly. These methods depend on certain types of generators and of arrangements of primary conductors and on suitable single or double exploring coils with auxiliary apparatus such as amplifiers, phase compensators, and measuring or indicating instruments. There are two distinct classes:

A. Those that make use of primary alternating currents of low frequency, that is, lower than 5,000 cycles a second and usually lower than 1,000 cycles a second.

B. Those that make use of alternating currents of high frequency, in general above 5,000 cycles a second and usually from 25,000 to 150,000 cycles a second. The higher frequencies of this class are those commonly used in radio transmission.

A. Low Frequency Primary Alternating Current Method

The generator may be an ordinary rotary dynamo type of alternating current generator with interrupter and slip ring attachment, and driven by hand or by a gasoline motor or it may be a battery and transformer or induction coil with suitable interrupter device which will maintain a speed of alternation that is as constant as possible. In either case it is difficult, but not impossible, to suppress some of the harmonics that inevitably arise when the generator is attached to a network of circuits that contain complex combinations of resistance, inductance, and capacitance, and this network linked up with amplifiers that form a part of the receiving or testing apparatus. The presence of harmonics is a condition commonly found in other fields of scientific and commercial endeavour such as radio broadcasting, movietone exhibitions, telephonic communication, and power transmission where it has been more successfully dealt with than in electrogeophysical work.

Current may be supplied from the generator to the region under investigation, through grounded electrodes of the single point or parallel wire types which have already been described. Or the generator may be attached to an insulated primary conductor in the form of a large triangular or rectangular, or square or circular, loop which should enclose an area of at least 20 acres. The receiving or testing apparatus is usually a single coil with instruments for indicating the strength of the magnetic fields or double coils for registering the comparative field strength at two points. In either case amplifiers may be used, together with such devices as phase compensators or electrical filters, either to simplify some of the complex conditions that have been portrayed or to make use of them in obtaining the necessary experimental results.

The measurable properties of the electromagnetic fields which exist about conductors when inductive electromagnetic methods are used are the following:

(1) The horizontal and the vertical components of the intensity of the resultant of the primary and secondary fields.
(2) The total strength of the resultant magnetic field.
(3) The "strike" and the "angle of dip" and consequently the direction of the resultant field.
(4) At least in simple cases, the phase difference between the primary and secondary magnetic fields which are associated with the fundamental frequencies of the alternating currents in the primary and secondary conductors.

(1) Horizontal and Vertical Components of the Intensity of the Resultant Field

Both the horizontal and the vertical components of the field are measured in much the same way and usually only one of these components is actually measured. In practice the components are measured by using a detector coil—usually a rectangular or circular coil of 2 or 3 feet diameter. This is connected with a microammeter to measure the current or with a microvoltmeter to measure the electromotive force that is induced in this coil by the alternating magnetic field that threads the coil. Readings are taken at regular intervals all over the area which is to be prospected and which is subjected to the magnetic field associated with the primary current.

If, for example, the vertical component is to be measured, and if the primary current is supplied through a rectangular loop, the following is the practice. The broadcasting loop is placed close to the surface of the ground. The region to be investigated is enclosed by the loop or is adjacent to one of the longer sides of the loop. The electromagnetic field produced by the current supplied to the loop threads the loop at right angles to its plane and is, therefore, perpendicular to the earth's surface. The detector coil is placed horizontally at any given place within the region under investigation. If secondary conductors are present in the region they will produce a disturbed field and the lines of force will in general cut this horizontal detector coil at an angle to the vertical. The vertical component of the resultant field due to the primary and secondary conductors will thread the detector coil and will induce a current in the detector coil and this current is proportional to the vertical component of the resultant field. A microammeter in series with this coil will record the strength of the current. The strength of the primary field and of its vertical component is determined as is shown in the chapter on the fundamental mathematical formulæ. Then the vertical component of the field which is due to the disturbing conductor may be calculated. In an analogous way the horizontal component may be determined.

(2) Total Strength of the Resultant Field

If the detector coil is placed normal to the direction of the lines of force, the greatest possible number of lines of force thread this loop and the total strength of the field may be measured by measuring the current that is induced in the loop.

(3) Direction of the Resultant Field

If the plane of the detecting coil is placed in the plane of the resultant field, no lines of force will cut it and, therefore, a zero reading will be obtained. If a telephone receiver is used in this circuit, no sound will be given out by it. The plane of the detecting coil is at right angles to this direction when the maximum effect of the resultant field is obtained. The plane of the detecting coil by its direction and inclination will show the direction and dip of the resultant field. It may be recalled that this resultant field is composed of the fields that are associated with the current in the primary conductor and the currents in the secondary conductors. In the case where the broadcasting loop is of a simple form and is placed in a horizontal position the direction and magnitude of the primary field may be calculated or determined experimentally and from this may be deduced the component of the resultant secondary field which is resolved along the direction of the resultant of the combined primary and secondary field. Consequently the general direction of the resultant electrical axis of the secondary conductors may be obtained if measurements are made at suitable points in the area under investigation.

(4) Phase Difference between Primary and Secondary Field

The procedure described in 1, 2, and 3 may be applied with confidence only in very simple conditions and then only when another important factor is taken into account. An alternating electromagnetic wave is similar to an ordinary sound wave and both are analogous to an ordinary wave on the surface of water. These waves have a crest and a trough and in a section shown diagrammatically in elevation a complete wave length comprises a crest and a trough. The waves in two such sections which are parallel to each other are said to be "in phase" if their crests and their troughs coincide at the same instant. If this state of coincidence does not exist they are said to be "out of phase". If these sections represent waves of the same wave length and these waves are being propagated in the same direction with the same velocity, the waves will be constantly in phase. If at their origins they are out of phase, or if the directions and distances or the velocities of their propagation are different, they will, in general, be out of phase, though a combination of their initial conditions, their directions and velocities, and the distances of propagation from their sources may give a unique position of " in phase " condition.

In general, then, the resultant secondary fields about a group of mineral bodies are not in phase with the primary field. This is due to the factors of mutual inductance, self inductance, and capacitance. This is further complicated by the presence of harmonics which originate in the generator or testing apparatus, especially when amplifiers are used, and by the lack of constancy of the generators and amplifiers. Methods of direct measurement such as are outlined in sections 1, 2, and 3 are, therefore, usually rather inadequate and the results obtained, although serving as a general indication of the existence of secondary conductors, may be misleading if used to locate definitely the position of the secondary conductors. Moreover, the interpretation of the indicated experimental results is always very difficult.

Efforts have been made by various investigators to cope with these difficulties, notably, during this investigation, by the Swedish American Prospecting Corporation. Ingenious methods have been devised to eliminate or to make use of those factors that are characteristic of inductive methods. These investigators make use of phase compensators and of two separate coils, instead of the single detecting coil, which may be placed at different points in the area under investigation, and which are connected in series and may, therefore, be balanced electrically. The original methods of Sundberg, Lundberg, and Eklund[1] have been somewhat modified by the Swedish American Prospecting Corporation, the details of which are not published, but the operation of this method under their auspices will be considered later in this report. A phase compensator was also devised by Bieler and Watson and applied in 1927 during investigations in Quebec.

Eve and Keys[2] discuss at length the condition of elliptical polarization of the resultant magnetic field due to the " out of phase " condition of the component fields.

B. High Frequency Primary Alternating Current Methods

This is the method that has been used largely by the Radiore Company and is described in detail by J. J. Jakosky[3] in a paper presented at the

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[1] *See* Bibliography, p. 26.

[2] Eve, A. S., and Keys, D. A.: "Applied Geophysics in the Search for Ore and Oil"; Camb. Univ. Press, 1929, p. 54.

[3] Jakosky, J. J.: "Principles of Inductive Geophysical Processes, Geophysical Prospecting"; Am. Inst. Min. Eng., 1929, pp. 138–179, or Tech. Pub. No. 134, 1928.

meeting of the American Institute of Mining Engineers at Boston in August, 1928, and in previous papers by the same author.

The primary loop is of small dimensions as compared with those of the primary loop made use of for low frequency currents (usually a few square feet in area). Both primary loop and detector coil are insulated from the ground as efficiently as possible. To provide for good insulation presents a difficulty, especially in moist climates, for with high frequency currents instantaneous very high values of the potentials commonly occur and act as " break down " potentials. Two other difficulties of considerable importance are associated with this method. (*a*) Secondary conductors of comparatively low conductivity, especially if near the surface of the ground or above it, are excited and the magnetic fields associated with them are of a magnitude comparable with the fields that are associated with good conductors at greater depth. Surface contours have an increasingly important bearing and are difficult to take into account. The phase relationship that exists between the primary and secondary fields becomes complex indeed and the difficulty of interpretation of experimental results is increased correspondingly. (*b*) If the high frequencies are obtained by spark gaps or vacuum tube oscillators in the primary circuit, the broadcast field made use of is not in general that which originates uniformly from the primary coil as a whole, but that portion of the field that is more intensive in character and is " radiated " from the oscillator. Although it is true that the higher the frequency of the primary magnetic field the greater is the potential difference induced in the secondary conductors, the dissipation of energy during the passage of the radiation through the upper portions of the ground becomes of increased importance with high frequencies. Absorption increases rapidly with the conductivity of the upper portions and with the frequency of the radiation and consequently penetration is greatly diminished. If the covering ground over an extensive area is a good conductor it may act as a shield to the extent that the secondary magnetic fields associated with deeper conductors will have no noticeable effect on the detecting instruments placed at the surface of the ground. Narrow portions of the ground cover, of some length, such as swampy ravines, may be of sufficiently high conductivity that the magnetic fields associated with the currents induced by them form a considerable part of the resultant secondary magnetic field and thus the indications may be very misleading.

Methods that make use of high frequency primary currents have, therefore, not only to contend with difficulties similar to those associated with low frequency primary currents, but they must, as well, take into account factors of considerable importance which, though they were also associated with low frequency currents, were in that case possibly of negligible magnitude. These new factors must either be eliminated or made use of to advantage in the process of making measurements.

It is evident, then, that in all inductive methods the problem of the application of the methods and the interpretation of the results of experiment become very perplexing indeed and the task of the investigator appears to be stupendous, if not hopeless, at least in all regions except those where very simple conditions of conductivity exist.

The factors associated with the inductive electromagnetic method are so numerous and their effects so involved that it is impossible to present briefly and clearly, all the conditions associated with a typical problem, the information that must be obtained experimentally, and the methods of interpreting the experimental results. This has been done carefully though not exhaustively for certain simple hypothetical and actual problems, by Sundberg, Lundberg, and Eklund, A. S. Eve and D. A. Keys, Etienne S. Bieler, Hans Lundberg, J. J. Jakosky, and others (*See* appended Bibliography).

It is unnecessary, therefore, to discuss inductive methods any further. It may be noted, however, that methods have been devised to eliminate or make use of the factors that are involved and a degree of success has been attained under simple conditions at least, that inspires confidence that dependable results will be obtained under more complex conditions. It must be noted again that due to commercial exigencies some of these methods are of a private character.

The development of the mathematical formulæ which are associated with these methods and the conditions under which they are applicable do not lend themselves to exposition that is simple or easily understood, at least to those who have had limited experience in this field. A critical study might well be made that would be of special interest to those actively engaged in geoelectrical or kindred investigations, but it does not appear to be desirable to incorporate such a study in this report. However, a brief reference to some of the fundamental formulæ that are associated with the various methods of exploration and an indication of their applicability and their significance is given in an appendix to this chapter. It is made apparent there that exceedingly great care and discrimination must be exercised in the development of the formulæ that are associated with any method of investigation. Attention has already been called to the non-existence of a simple standard set of conditions such as may be found in many engineering problems. Instead, a wide range of very complex conditions is prevalent. The formulæ that must be developed to take account of measurements in such complex conditions must necessarily be extensive and complex and approximate in character.

It is evident, therefore, that all investigations must be in part at least in the nature of a research. Moreover, it is probable that this element of research in investigations will persist indefinitely with, however, a rapidly increasing degree of success with the discovery of the existence of similar sets of conditions in several areas.

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Appendix

FUNDAMENTAL MATHEMATICAL FORMULÆ

There are fundamental differential equations which are associated with the instrumental methods of producing an electrical or a magnetic disturbance, and with the propagation of these disturbances through space or through conducting media and the detection and measurement of these disturbances. From these equations must be deduced analytical expressions comprehensive of the existing conditions and in which the instrumental factors and the experimental measurements may be incorporated in order that the results of the investigation may be interpreted.

The following cases may serve to illustrate the character and the significance of some of the formulæ:

(1) The propagation of a potential (V) through an extensive medium such as the earth.
(2) The production of an alternating current of low frequency in a primary conductor insulated from the ground, and the inductive effects on secondary conductors in the neighbourhood.

(3) The inductive effects of an alternating current of low frequency where the ground is used as the primary conductor.

(4) The propagation of electromagnetic radiation through space and through media that are (*a*) non-conductors of electrical current, (*b*) conductors of electrical current.

(1) The propagation of a potential (V) through an extensive medium such as the earth may be represented by the differential equation

$$\frac{d^2V}{dx^2} + \frac{d^2V}{dy^2} + \frac{d^2V}{dz^2} = K\frac{dV}{dt} \quad \ldots\ldots\ldots\ldots \quad (1)$$

where x, y, z, and t are the space and time co-ordinates, and K is a constant of the medium. When a steady state exists this takes the form

$$\frac{d^2V}{dx^2} + \frac{d^2V}{dy^2} + \frac{d^2V}{dz^2} = 0 \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Now in order to make use of the measured results by any method of experimental investigation it is necessary to obtain the analytical expression involving V, x, y, z, which is a solution of this differential equation.

For the simple case of an extensive conducting medium this expression may be obtained readily and an example (by Wenner) has been given on page 17, and it may be noted that in this simple case the expression made use of was obtained by a simple and direct method without resort to the differential equation. This is often possible where the conditions of the problem are not too complex.

The expression deduced may be used without modification to determine the position of a good conductor embedded in an extensive, poorly conducting medium if the good conductor is of simple geometrical form and if the experimental procedure is suitable. If the good conductor is an extensive layer having great depth and underlying an extensive horizontal or tilted poorly conducting thin layer, or if the converse conductive condition exists, the expression to be used may be readily obtained and the depth of the thin, overlying layer may be determined approximately if the experimental information is adequate. If the underlying layer having great depth is comparatively narrow, the strike of this body may also be obtained. These cases are discussed by Warren Weaver.[1] The problems of several horizontal layers and of an embedded highly conducting sphere are also discussed in this article. In the investigation of a field problem where even these simple conditions may exist it is emphasized in the article that the problem must be approached with caution and that it is imperatively necessary to obtain as much experimental evidence as possible.

For the case of a homogeneous, extensive, very poor conductor underlying a homogeneous extensive good conducting layer the applicable formulative solution may be obtained fairly readily and coupled with experimental accuracy fairly precise prediction is possible. A simple, interesting, and highly successful application of this is described by Irving B. Crosby and E. G. Leonardon.[2] In this publication, as in that of Weaver, the formulæ used are evidently considered to be of a private character and are not presented.

For more complex conditions the solutions of the differential equations which depend on the initial states of electrical potential and on the boundary

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[1] Am. Inst. Min. Eng., Tech. Pub. No. 121, Feb., 1928.

[2] "Electrical Prospecting Applied to Foundation Problems"; Am. Inst. Min. Eng., Tech. Pub. No. 131, Sept., 1928.

conditions are correspondingly involved. For the case of disseminated conductors embedded in a non-conducting medium or for the converse conditions the formulæ which may be used in the simple cases are not applicable without modification and their use may introduce considerable error in the interpretation of the measured results that are incorporated in them.

Solutions of the differential equation for hypothetical cases where complex conditions exist are only approximate and have been obtained in a comparatively limited number of cases only. Some of these approximate solutions have been made with the aid of certain functions such as Bessels Functions or Fourier's Series. They must be applied with exceedingly great care in geophysical work where approximate discontinuities may be numerous and complex in character. In view of the recent intensive development in the application of geophysical methods to determine terrestrial conditions it is to be hoped that many more solutions of the differential equations for problems based on hypothetical conditions will be placed on record.

The development of the formula which is applicable in the method of Wenner, viz. $\rho=2\,\pi a\,R$ (*See* page 17) for the simple conditions where a homogeneous, extensive, good conductor overlies a homogeneous, extensive, very poor conductor, may serve as an illustration.

As another illustration, suppose the lead-in electrodes, C_1 and C_2, are at a distance apart such that attention may be given to the point C_1 alone. In this case differential equation (2) page 27 is applicable, viz.,

$$\frac{d^2V}{dx^2}+\frac{d^2V}{dy^2}+\frac{d^2V}{dz^2}=0$$

If the electrode C_1 is small then there is a point source of potential applied at the centre of the plane face of a hemisphere of a homogeneous conducting material. The solution for a homogeneous sphere may be taken tentatively, viz.:

$$V=-\frac{A}{r}+B=(V_a-V_b)\frac{ab}{b-a}\,\frac{1}{r}+\frac{V_b b-V_a a}{b-a}\quad\ldots\ldots(3)$$

where a and b are the distances from C_1 to two adjacent equipotential surfaces and V_a and V_b are the potentials at these surfaces and may be measured on the surface of the ground.

The current i between two equipotential surfaces is given by

$$i=-\frac{1}{\rho}\,\frac{dv}{dr}\,2\pi\,r^2=\frac{1}{\rho}\,2\pi\,(V_a-V_b)\frac{ab}{b-a}\quad\ldots\ldots\ldots\ldots(4)$$

where ρ is the specific resistance or resistivity.

Now $\frac{V_a-V_b}{i}=R$ the resistance of the conductor lying between the hemispherical equipotential shells a and b

$$\therefore\ \rho=2\pi R\,\frac{ab}{b-a}\quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

If b—a is taken as 1 cm. then V_a-V_b is the potential gradient and $\frac{V_a-V_{a+1}}{i}=R$

$$\therefore\ \rho=2\pi\ R\ a\ (a+1)\doteqdot 2\pi R\ a^2\ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

which owing to the change in the method of measurement replaces the Wenner formula. To obtain the depth of the good conductor it is necessary to find the value of a at which there is a fairly abrupt change in ρ.

This formula for ρ is inadequate, but is, possibly, applicable where the distribution of the potential at the plane face of the hemisphere is not greatly different from that which is supposed to exist here. Further, known depths may be used to obtain values of ρ which in turn may be used to obtain unknown values of the depths at nearby points.

Since the effective distribution of potential at the surface of the ground is to be found in the immediate neighbourhood of the lead-in electrode, it is of advantage to treat the problem as one of conduction through a cylinder, of radius $\bar{a}$, of homogeneous conducting material with the point of application of the potential at the centre of the upper face. In this case the differential equation for the propagation of potential is

$$\frac{d^2V}{dr^2} + \frac{1}{r}\frac{dV}{dr} + \frac{d^2V}{dz^2} + \frac{1}{r^2}\frac{d^2V}{d\phi^2} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

and since for this case $\frac{d^2V}{d\phi^2} = 0$ the equation becomes

$$\frac{d^2V}{dr^2} + \frac{1}{r}\frac{dv}{dr} + \frac{d^2V}{dz^2} = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

where r= radial distance from the axis of the cylinder, z=depth, and the boundary conditions are

$V = f(r)$ when $z = o$
$V = o$ when $r = \bar{a} \doteq \infty$ and $z = o$
$V = o$ when $z = \infty$

f (r) may be obtained experimentally at the surface where $z = o$, $\bar{a}$ is in practice only a short distance measured from the lead-in electrode and may be obtained from the plotted curve of $V = f(r)$ at the surface. The solution of the equation under the above conditions is given by

$$V = \frac{2}{\bar{a}^2} \sum_{m=1}^{m=\infty} e^{-\mu_m z} \, Jo\,(\mu_m r) \, \frac{\int_0^{\bar{a} \doteq \infty} \lambda f(\lambda) \; Jo\,(\mu_m \lambda)\, d\lambda}{\{J_o\,(\mu_m \bar{a})\}^2} \quad \ldots\ldots\ldots (9)$$

where $J_o\,(\mu_m r)$ is Bessel's function of the order zero, μ_1, μ_2, μ_3, etc., are the roots of $J_o(\mu\bar{a}) = o$. λ is a parameter substituted for the parameter r in order to evaluate the coefficients in the series. Here the current

$$i \doteq \frac{1}{\rho}\frac{dV}{ds}\, 2\pi s^2$$

where s is the distance from the lead-in electrode to the surface of equipotential and is a function of r and z,

and $\frac{dV}{ds}$ may be obtained from equation 9 above. For the case of a non-homogeneous conducting medium where the distribution of potential is a function of r, z, and ϕ the problem is usually much more complex and in many cases it is highly necessary to obtain a varied range of experimental results and it is probable that this would assist in the development of a useful but more or less empirical formula. Even in the case where one medium overlies another medium of considerably different but not uniform conductivity formula 9 for V must be varied accordingly.

(2) If alternating currents of low frequency, viz., less than 1,000 cycles a second, are made use of in an insulated primary conductor, then the action on the secondary conductors is of the same character as that found in the simple transformer and the formulæ associated with transformer action are generally well known. For application to geophysical conditions the distances from the primary conductor to the secondary conductors and the distances from the primary conductor and the secondary conductors to the detector coil must be taken into consideration. In this case the usual procedure is to obtain first the formula for the current and the intensity of the magnetic field which is associated with the primary conductor, viz.

$$i = \frac{E}{\sqrt{R^2+X^2}} \sin\left(\omega t - \tan^{-1}\frac{X}{R}\right) \ldots\ldots\ldots\ldots\ldots (10)$$

where

$X = L\omega - \frac{I}{C\omega}$

R = resistance in the primary circuit

i = current in the primary circuit

E sin w t the impressed electromotive force

$\omega = 2\pi \times$ the frequency

L = self inductance of the primary circuit

C = capacity of the primary circuit

and the intensity of the magnetic field depends on the form of the primary circuit. For example, for a long straight primary circuit

$H = \frac{2i}{d}$ where d = the distance from the primary circuit

i = the current in primary circuit in electromagnetic units

H = intensity of the magnetic field

Then the formulæ for the electromotive force and the current and the intensity of the magnetic field, which are associated with the secondary conductors, may be obtained. These will, of course, vary with the form and size and specific conductivity of the secondary conductors and the interaction on each other of the magnetic fields associated with them. Finally the expression for the direction and magnitude of the resultant magnetic field at any point may be obtained.

Simple hypothetical cases are discussed by Sundberg, Lundberg, and Eklund (*See* Bibliography, page 26), by J. J. Jakosky (*See* Bibliography, page 26), and without presentation of formulæ by Dr. Max Mason,[1] and by A. S. Eve and D. A. Keys (*See* Bibliography, page 26).

For simple conditions this method may be readily applied if such difficulties as the existence of harmonics and phase dispersions are successfully met. Absorption and the presence of secondary surface fields do not enter to the same extent as with the high frequency currents. Where

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[1] Proc. Am. Inst. Min. Eng., New York, Oct. 27, 1927.

complex conditions exist the problem of developing suitable formulæ or of simplifying the measurements becomes difficult, but appears to be more easily dealt with when the frequency of alternations in the primary is low.

(3) It is unnecessary to discuss the formulæ for the case where the primary conductor is not completely insulated from the ground. They are modifications of the formulæ discussed in the case of the insulated primary conductor. The expressions for the current and for the intensities of the magnetic fields associated with them are more involved. They must be comprehensive of the conditions that the primary current is distributed through an extensive region which includes superficial and embedded conductors and that the primary magnetic fields as well as the induced secondary magnetic fields are associated with these conductors. The form and distribution of the primary currents and primary magnetic fields are not under the control of the experimenter as in the case of the insulated primary and consequently it can not be provided that the expressions for these primary currents and fields will be simple and definite.

(4) In the case of the propagation of an electromagnetic radiation, e.g. a wireless wave disturbance through an isotropic non-conducting medium, the differential equation for the propagation of the magnetic intensity (H) is

$$\frac{k\mu}{c^2}\frac{\delta^2 H}{\delta t^2} = \frac{\delta^2 H}{\delta x^2} + \frac{\delta^2 H}{\delta y^2} + \frac{\delta^2 H}{\delta z^2} \ldots\ldots\ldots\ldots (11)$$

where k=the dielectric constant, μ=the permeability, k and μ each equal unity for free space, c=the velocity of propagation of the radiation in free space. Where the medium is conducting the differential equation which represents the propagation of the magnetic intensity better though not adequately is

$$\frac{k\mu}{c^2}\frac{\delta^2 H}{\delta t^2} + \frac{4\pi\mu\gamma}{c^2}\frac{\delta H}{\delta t} = \frac{\delta^2 H}{\delta x^2} + \frac{\delta^2 H}{\delta y^2} + \frac{\delta^2 H}{\delta z^2} \ldots (12)$$

where γ is the specific conductivity of the medium. For the propagation of the complementary electric intensity (E) the corresponding differential equations are respectively

$$\frac{k\mu}{c^2}\frac{\delta^2 E}{\delta t^2} = \frac{\delta^2 E}{\delta x^2} + \frac{\delta^2 E}{\delta y^2} + \frac{\delta^2 E}{\delta z^2}$$

and

$$\frac{k\mu}{c^2}\frac{\delta^2 E}{\delta t^2} + \frac{4\pi\mu\gamma}{c^2} = \frac{\delta E}{\delta t}\left(\frac{\delta^2 E}{\delta x^2} + \frac{\delta^2 E}{\delta y^2} + \frac{\delta^2 E}{\delta z^2}\right) - \frac{4\pi}{k}\left(\frac{\delta\sigma}{\delta x} + \frac{\delta\sigma}{\delta y} + \frac{\delta\sigma}{\delta z}\right) \ldots (13)$$

where σ is the density of the "intrinsic charge" in the conductor.

Where conductors exist the secondary radiation is also propagated and must be considered in conjunction with the primary radiation and the problem for solution is correspondingly complex.

Again in this case solutions are only approximate, even for fairly simple conditions, and must also be applied with care. Moreover, the attenuation of the amplitude of the electric and magnetic displacement depends exponentially on a function of the product of the conductivity and the frequency of radiation. From the expression for the amplitude the intensity which is proportional to the energy ($\frac{1}{2}$ mv^2) may be obtained. The expression for the intensity also involves the frequency. Consequently the penetration of the radiation of high frequency is greatly diminished.

CHAPTER III

GEOLOGICAL CONDITIONS AT THE SITE OF THE INVESTIGATION

By J. B. Mawdsley

Abana Mines, Limited, controls 600 acres in the north part of Desmeloizes township, Quebec, comprising lots 44 and 45 and the south halves of lots 38 to 43, inclusive, in range X, and the north halves of lots 46 and 47 in range IX. A shaft has been sunk and most of the work done on the south half of lot 44. The mine is 11½ miles north of the village of Dupuy on the Canadian National railway. From Dupuy there is a good automobile road for 2½ miles, beyond which for 9 miles to the property is a road good in winter but only fair in summer.

The property was first visited by the writer in October, 1925[1]. Up to the end of September, 1928, a shaft had been sunk 315 feet, about 1,800 feet of drifting and crosscutting had been completed on the 300-foot level, and stations had been cut at the 100 and 200-foot levels. Two thousand feet of diamond drilling had been done from the 300-foot level. Considerable trenching, chiefly on lots 44 and 45, had been performed and a surface plant and various buildings built.

The shaft is on the southeastern slope of a broad ridge. Northwestward from the shaft, the ground rises 90 feet in a distance of 700 feet, and over a section 200 feet wide and extending for 600 feet west from the shaft bedrock outcrops are numerous and the surface is broken by rocky projections 10 to 15 feet high and shallow gullies 15 feet or less deep. Eastward from the shaft the surface falls 40 feet in a distance of 700 feet, bedrock does not outcrop, and the area is traversed by steep-sided gullies as much as 30 feet deep.

GENERAL GEOLOGY

Except for the mineralized rock disclosed by trenching a few yards southeasterly of the shaft, rock outcrops are confined to the steeper area west and north of the shaft (*See* Plan No. 1). The drift over this rocky section is thin, averaging 2 to 5 feet in depth, and consists of unassorted morainal material containing boulders up to 2 feet in diameter. The area east and southeast of the shaft has a drift cover that eastward increases in thickness to over 200 feet at a point about 450 feet east of the shaft where underground mine workings broke through the rock surface and entered the drift. Farther eastward, beyond this point, the thickness probably decreases, for in trenches 1,000 feet east-southeast of the shaft, bedrock was reached in places at depths of 4 to 10 feet (*See* Figure 5). The drift cover east of the shaft is fine sand with some clay. In small excavations, the sandy material was seen to be bedded and, therefore, had been deposited by water.

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[1] Geol. Surv., Canada, Sum. Rept. 1925, pt. C, pp. 78-81.

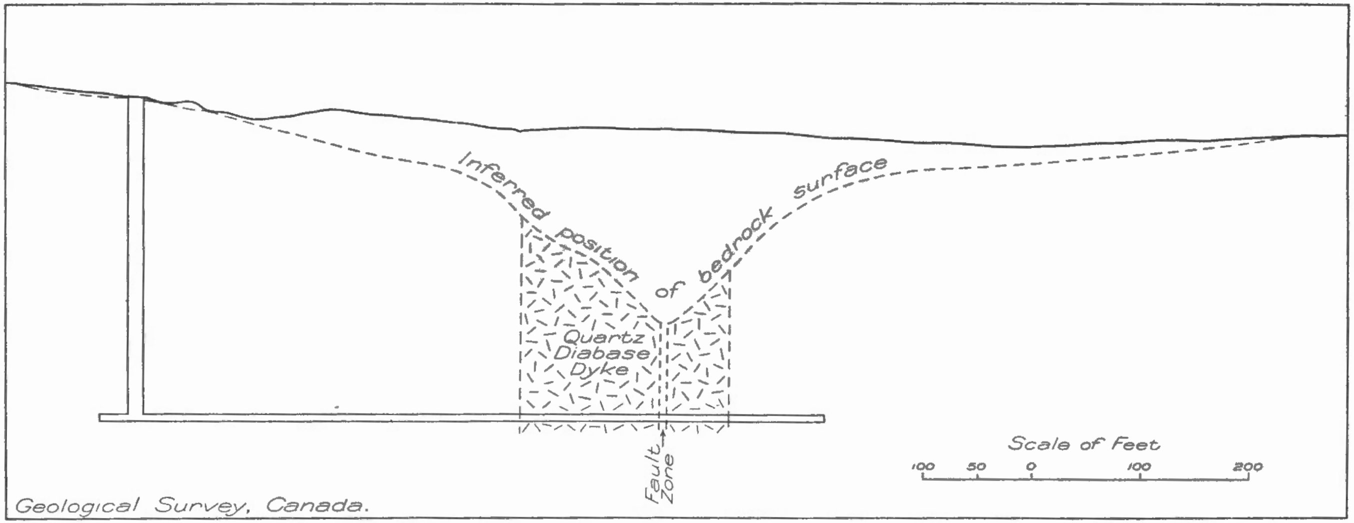

Figure 5. East-west vertical section through shaft and main drift at 300-foot level, Abana mine, Desmeloizes township, Quebec, to show inferred position of solid rock surface.

The rocks exposed at the surface (*See* Plan No. 1), in the underground workings and by diamond drilling, are Keewatin volcanics and related sediments, feldspar porphyry dykes and areas replaced by materials of the porphyry, a quartz-albite granite dyke, and a porphyritic quartz diabase dyke. Ore consisting of sulphide replacements in, apparently, sheared and shattered rhyolite flows, forms two bodies separated by a 200-foot wide, porphyritic quartz diabase dyke which strikes north and is vertical.

The volcanics are chiefly flows of fine-grained rhyolite and porphyrite rhyolite, although more basic varieties are found to the north of the ore-bodies. The flows strike 115 degrees and probably dip 80 to 85 degrees to the north. Their attitude was not determined on the property, but from evidence gathered elsewhere they are believed to face to the south. The sediments recognized are mostly tuffs of andesitic composition difficult to differentiate from sheared flows. Five hundred feet north of the shaft trenching disclosed small thicknesses of slate and impure quartzites.

All the outcropping volcanics have been sheared and the sediments farther to the north have been sheared to paper thin lamellæ. The planes of shear strike 110 to 126 degrees and dip 80 to 85 degrees to the north.

The volcanics are not more markedly altered near the ore-bodies than at a distance from them. Three types of alteration were noticed: sericitization; silicification and carbonatization; and chloritization. The secondary minerals of all three types of alteration are much alike and may indicate that the various alteration phases are closely related in origin.

Sericitization is the most extensive and is most marked in the strongly sheared rocks and these are very light coloured, have a silky lustre on cleavage faces, and much of them holds green chlorite individuals 1 or 2 millimetres long. The rocks are very fine grained, having a grain of 0·01-0·03 millimetres. The mineral content varies considerably. Quartz predominates and wisp-like flakes of sericite usually occur throughout. The large, phenocryst-like individuals of chlorite have ragged ends and are of clinochlore in many cases replaced in part by quartz and calcite. Calcite is commonly present in considerable quantities. Rutile and iron ore are in some cases present. Sulphides are absent from most of these rocks, but are found near the ore-bodies. This type of alteration (sericitization) is probably the commonest near the ore-bodies.

The above type of altered rock grades imperceptibly into one in which the chlorite content is high. In these rocks the chlorite does not occur in phenocryst-like individuals, but in radiated and fine granular masses. Quartz, sericite, and calcite occur in varying but subordinate proportions.

Silicified and carbonatized rocks are well displayed underground in the crosscut extending north from the shaft and are found elsewhere. The schistose volcanics and sediments are replaced, in a varying degree, along the planes of schistosity, by elongated, lens-like bodies, 0·5 to 5 mm. broad, of fine-grained quartz and carbonate. These lenticular bodies are commonly composed of 50 per cent quartz and 50 per cent calcite in grains of 0·03 millimetres diameter; a few flakes of chlorite are also present. The lenticular bodies are sharply bounded against the enclosing schist which for the most part is a sericite schist in many cases composed of about 80 per cent sericite, 10 per cent quartz, and 10 per cent chlorite. A few cubes of pyrite are present in many cases.

Feldspar porphyry cuts and replaces the volcanics at various points on the property. Ten narrow dykes, from ½ to 2 feet wide, cut volcanic agglomerate in an outcrop back of the staff house, 1,050 feet west of the shaft. The dykes strike 115 degrees and dip vertically. One dyke cuts the shearing at an angle. The volcanics at this place are also partly replaced by materials from the porphyry, as is also the case in an outcrop 200 feet west of the shaft. A diamond drill hole drilled southward from the 300-foot level a few feet east of the diabase dyke, intersected a 200-foot section containing five porphyry dykes, 1 foot to 6 feet wide, some others a few inches wide, and about 150 feet of fairly basic volcanics partly replaced by materials from the porphyry. In an outcrop 1,700 feet from the shaft along a course bearing 147 degrees, at a place 200 feet west of lot line 45/46, and 600 feet north of range line IX/X, greenstone is partly replaced by porphyry and there is exposed a width of 70 feet of porphyry containing shreds of greenstone. Part of the sheared andesitic volcanics of this outcrop are replaced by quartz and carbonate.

The feldspar porphyry dykes have sharply defined edges, but do not possess chilled margins. The rock is pink-coloured. Phenocrysts form about 45 per cent of its volume and are of plagioclase feldspar and quartz. They lie in a groundmass the grains of which are about 0·03 millimetre in diameter and are quartz, feldspar, and sericite with some carbonate. The composition of the rock is about quartz 40 per cent, plagioclase 40 per cent, sericite 10 per cent, and calcite 10 per cent. The quartz phenocrysts are euhedral or rounded grains many of which have crenulated margins and show undulatory extinction. The feldspar phenocrysts are very numerous and many of them are partly altered to carbonate and sericite. The feldspar in one specimen was determined to be basic albite and in another to be acid andesine. The sericite in the groundmass occurs in small, ragged, narrow flakes. Calcite occurs in irregular grains both in the feldspar and groundmass.

The volcanics where replaced by materials from the feldspar porphyry grade in short distances into typical feldspar porphyry and into typical volcanics. These relations are most prominent in the case of the more greenish, chlorite-rich volcanics. The volcanic rocks where most altered by addition of materials from the porphyry have a porphyritic appearance. The phenocryst-like forms are irregular-shaped plagioclase crystals containing inclusions of sericite and calcite and, in many cases, irregular quartz grains. The rest of the rock consists of varying proportions of chlorite, sericite, calcite, and minute grains of, probably, quartz and feldspar. The chlorite in many cases forms a considerable proportion of the rock and occurs in irregular patches and in imperfectly radiating aggregates.

A quartz-albite granite dyke outcrops west of the shaft and has been found in two places underground, east of the shaft. It strikes 140 degrees, dips 80 degrees to the north, and varies in width from 25 to 45 feet. At the easternmost outcrop, 100 feet west of the shaft, it cuts volcanics replaced by materials from feldspar porphyry and, therefore, is younger than the feldspar porphyry. The dyke cuts the shearing planes in the volcanics at a slight angle. Although in places slightly sheared it has not suffered as much shearing as the volcanics. Its intrusive nature is clearly shown in the outcrop just west of the shaft where its sinuous contacts and the presence of an apophysis extending into the volcanics are clearly exposed.

The dyke rock is rusty weathering and dark coloured, the colour varying with the content of ferromagnesian minerals. Its grain varies from about 0·2 to 2 millimetres. A specimen from the 300-foot level is composed of 40 per cent feldspar, 10 per cent quartz, 20 per cent chlorite, and 30 per cent carbonate. In thin sections the feldspar, which has a euhedral tendency, has a very dusty appearance owing to alteration products. It apparently is albite. The quartz occurs occasionally as large grains, but is mainly in small grains. Micrographic intergrowths of this mineral occur. The chlorite is the variety penninite and occurs in shred-like flakes containing numerous inclusions. Irregular plates and grains of a ferruginous carbonate are common. Small amounts of sericite, leucoxene, and pyrite are also present.

The porphyritic quartz diabase dyke does not outcrop in the immediate vicinity of the mine. It strikes nearly due north and where cut by the mine workings is about 200 feet broad. The rock varies somewhat in appearance, but generally is dark with a greenish cast, coarse grained in its central parts, and fine at the margins. The phenocrysts are irregular-shaped, greenish feldspar aggregates which form from 5 to 15 per cent of the rock and have a diameter of as much as 1 inch. They occur not only in the central part of the dyke but also in its chilled margins.

Under the microscope the phenocrysts are seen to be composed of more than one individual. The individual grains generally have idiomorphic outlines, but which in places are modified as, apparently, the final growth of the feldspar was contemporaneous with the growth of the minerals of the groundmass. The small plagioclase crystals of the groundmass are, in places, idiomorphic where parts of them are involved in the margin of one of the larger crystals forming the phenocrysts. The augite is interstitial, but in places the boundary between it and the phenocryst is sinuous as if the growth of the augite was in part contemporaneous with the growth of the margins of the large feldspars. Most of the feldspar phenocrysts are clouded in patches as a result of alteration. The unaltered parts are labradorite (An_{55}), as are also the feldspars of the groundmass. The groundmass has a diabasic texture. The laths of labradorite average 50 per cent of the groundmass. Their diameters vary from 0·2 to 0·4 millimetre and their lengths from 1 to 2·5 millimetres. Most of them show a little alteration in patches and resemble that seen in the phenocrysts. Sericite and chlorite are present in other parts of these crystals. Interstitial to this feldspar is a pale, non-pleochroic augite forming 40 to 45 per cent of the groundmass. This mineral is not much altered, but in places a little, strongly pleochroic green hornblende has developed from it. Aggregates of strongly pleochroic brown biotite, chlorite, and magnetite are present and may be largely secondary after augite. Leucoxene grains lie around some of the augite individuals. Some of the grains of leucoxene have diameters of 1 millimetre, are embayed, hold inclusions, and probably were among the earliest minerals to crystallize. It forms from 1 to 2 per cent of the rock volume. Quartz and micropegmatite form from 3 to 10 per cent of the rock volume. The feldspar of the micropegmatite in one case was determined to be andesine (An_{36}), but usually it is much altered. In one case it is completely altered to chlorite. The accessory minerals are small needles of apatite, which are more abundant in the micropegmatite, a little pyrite usually in irregular grains, as well as the previously described magnetite.

The margins of the dyke, as seen underground, have been chilled against both the volcanics and the ore-bodies. The line of contact of the dyke with the country rock is smoothly crenulated on a very minute scale. The chilling of the dyke at its contact with the ore is clearly shown on the 300-foot level along the west side of the dyke. The edge of the dyke here bends inwardly around the end of the ore-body and is chilled for a width of 5 centimetres, whereas against the adjacent rhyolite the chilled edge is only 0·5 millimetre wide. Small offshoots of the dyke cut the ore, are extremely fine grained, and are much lighter in colour than the main dyke; they seem to have cooled extremely rapidly. At one point, a tongue of pyrite 8 inches wide extends into the dyke for a distance of 3 feet. It is bordered by a relatively narrow, chilled margin of the diabase. The narrowness of this part of the chilled margin is, probably, a result of the small volume of the ore projection whose chilling effect would, therefore, be small. Fine veinlets of pyrite traverse parts of the diabase dyke near the ore-body and are believed to represent pyrite obtained by the dyke from the ore-body. Undoubtedly, in the writer's opinion, the dyke is younger than and cuts the ore deposit.

MINERALIZATION OBSERVED ON THE PROPERTY IN 1925

At the time the property was first visited, in the middle of October, 1925, no underground work had been performed, but considerable trenching had been done and a section of a mineralized area had been uncovered. The information about the property as it existed in 1925 was published in the form of a short report.[1] It seems worth while to repeat here the parts of this report referring directly to the mineralization.

> The mineralized showings on the property are on the south slope of a low ridge which in part is bare rock . . . To the south of this ridge the country rapidly declines into a drift-covered stretch with few outcrops.
>
> At the time of the visit the company had completed a series of trenches on the south slope of the ridge. . . . . These trenches, 20 to 40 feet apart, exposed an area 250 feet in length in a northwest and southeast direction, and having a width of approximately 60 feet . . . . . Southeast by east of the main trenched area, at a distance of about 800 feet, are two trenches which penetrate the heavy overburden on what was believed by the operators to be an extension of the mineralized zone, and expose bedrock.
>
> The mineralized area is exposed in the main series of trenches and at the time of visiting the property was exposed over a length of more than 200 feet and a width of from a few feet at the northwest to about 60 feet at the southeast. The mineralized area is composed of much altered rocks . . . . now strongly carbonated and sheared, and in places silicified. The shearing is vertical and has a

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[1] James, W. F., and Mawdsley, J. B.: "Certain Mineral Deposits in Desmeloizes and Trécesson Townships, Quebec"; Sum. Rept. 1925, pt. C, pp. 78-80.

strike of 140 degrees. Within this area are four mineralized zones striking from 130 degrees to 140 degrees, dipping vertically, and separated from one another by areas of barren or slightly mineralized rock.

One zone lies at the northeast corner of the general mineralized zone. It contains two bands of solid chalcopyrite and pyrite, 1 to 2 feet wide, respectively, and separated by 3 feet of disseminated pyrite and chalcopyrite. Some quartz stringers are associated with the sulphides. This zone narrows considerably northwesterly along the strike. In a trench, 60 feet away, a little disseminated pyrite and chalcopyrite are all that is visible and in a trench at 80 feet along the strike no mineralization has been encountered.

The second and most important mineral zone is about 20 feet southwest of the first and is exposed northwesterly in various trenches for 140 feet and 80 feet farther northwest a mineralized mass is found which probably is a continuation of the same zone. The zone over the distance of 140 feet swells and pinches from a width of 4 to 10 feet. Within it are bands of nearly solid sulphides. The best cross-section shows a band 1½ feet wide of sphalerite with a little pyrite intermixed. On one side is a band of nearly equal width formed of 50 per cent chalcopyrite and 50 per cent glassy quartz, and on the other side is a 2-inch band of solid pyrite. In the southeasternmost trench a 6-inch band of disseminated sphalerite is also present. The rest of the 8 or 10 feet making up the zone is formed of bands of silicified and sheared quartz porphyry and greenstone containing a small amount of disseminated pyrite. Along the strike of this mineral zone the mineralization in places is represented by disseminated sphalerite, chalcopyrite, and pyrite developed over a width of 4 to 5 feet. A little galena was seen in a couple of places.

A third mineral zone occurs in the southeasternmost trench, southwest of the second-mentioned zone. This third zone is of minor importance and is visible only in the most southeasterly trench, where it is represented by 1 foot of solid pyrite. In the same trench, 12 feet farther southwest, is the northeastern edge of the fourth mineral zone, there exposed over a width of 8 feet. Its continuation is revealed in cross trenches to the northwest over a distance of 160 feet. It narrows progressively in this direction to where it is not more than 2 feet wide. The gossan top of this mineralized band had not been removed when the property was examined. Very probably the chief mineralization is pyrite.

The two trenches, 800 feet to the southeast of the main strippings, are 50 feet apart and in both is visible a sheared zone which strikes 10 degrees south of east in the northwestern trench and 27 degrees south of east in the most southeasterly trench. In the northwesternmost trench the mineralization consists of a band 4 feet in width, composed of 50 per cent of pyrite and of contiguous bands 4 and 8 feet wide of disseminated pyrite. In the southeasternmost trench, 50 feet away, the mineralization consists of a little pyrite and a few quartz stringers. The country rock is a chlorite schist.

. . . . The showings in the main strippings become progressively more interesting as the low ground is approached. Whether mineralization increases below the heavy drift of the low ground is a matter of pure conjecture. It is not certain that the mineralization in the trenches 800 feet southeast of the main strippings is related to the mineralization found in the main showings. If further work is deemed advisable, the position for it is in the low ground adjacent to and southeast of the main showings."

The conclusions drawn from the evidence available in 1925 and as set forth in the preceding paragraph are guardedly expressed, as must be the case in a report published by the Geological Survey. Designedly they contained no opinion as to whether further work on the property was or was not warranted. If the writers of the report had been engaged by the mining company to advise them as to what further work if any should be undertaken and if a full report had been made, this report would have directly stated various deductions not mentioned in the published report, but which, nevertheless, may be deduced from the stated facts. Amongst other things it would be emphasized that the mineralization as visible in the trenches varies, from place to place, both in the relative and absolute amounts of the various sulphides and that lacking any evidence to the contrary, this variation would hold in depth as well as along the strike. It would be stated that though at the surface the mineralization decreased and finally died away in a westerly direction, it might be that at some depth the mineralization extended farther westward. It would be pointed out that since at the surface the amount of the sulphides increases in an easterly direction and that since in that direction the rock surface was descending, therefore, it was probable that the amount of sulphides increases not only easterly along the strike but downwards along the dip. It would be indicated that since the value of the deposit depends not only on its dimensions both along the strike and dip, but also on the variations in mineral composition both along the strike and dip, therefore, underground explorations either by sinking and drifting, or by drilling, or by both methods, are required. Furthermore, the possibility of the mineralization visible in the two eastern trenches, 800 feet southeast of the main showing, not being a direct continuation of the main mineralization would be emphasized and it would be pointed out that the exploration of the mineralization to the east should be conducted as a separate operation.

Since the 1925 report was written, the mining company has sunk a vertical shaft near the western end of the mineralized area revealed by trenches and stripping. The mineralization encountered along the shaft indicated that the ore zones dipped northward. At a depth of 300 feet a crosscut was run northward to cut the ore and from this crosscut a drift was run along the foot-wall side of the ore-body. Various drifts, crosscuts, etc., have established that the ore occurs in two bodies, each striking easterly but separated from one another by a diabase dyke 200 feet broad and striking north. This dyke does not outcrop on the property. Its presence was not suspected, for it lies below the drift-covered area situated between the western, main showing of mineralization, and the two long trenches 800 feet to the east.

The two ore-bodies disclosed by the underground workings were originally one body which was divided in two by the intrusive dyke. The only outcrops of the ore lie within a few yards of the shaft. The remainder of the ore-bodies are deeply buried beneath drift and were visible only in the shaft and the underground workings at the 300-foot level. The ore-bodies lie in rhyolite porphyry. Their major axes strike parallel with the shearing of these rocks or at 112 degrees. The shaft is sunk on an outcrop of ore situated very close to the western end of the western ore-body (*See* Plan No. 1). Work on the 300-foot level shows this western body to be 400 feet long. On the 300-foot level its greatest width is about 55 feet, one-third way from the east end, which is blunt. The west part forks into two bodies at a point about 170 feet east of the end, the southern fork has an average width of 18 feet, and the northern fork of 6 feet. They are separated by, on an average, 12 feet of unmineralized country rock. From the evidence gained at the surface, in the shaft, and on the 300-foot level it is evident that this western ore-body dips about 80 degrees to the north. A little mineralization seen on the surface a short distance west of the shaft and on the strike of the ore-body is evidently close to the west end of the body and its position relative to the end of the body on the 300-foot level indicates that the rake of the western end of the ore zone is, probably, vertical.

The small exposures of ore at the surface near the shaft and the disposition of the mineralized areas in the shaft and the crosscut from the shaft, at the 300-foot level, make it appear that at the surface the western end of the ore-body consists of four bands which downwards join and divide, and finally unite to form the southern fork of the ore-body at its west end on the 300-foot level (*See* Figure 6).

On the 300-foot level the western ore-body has been explored by a drift, in ore along the foot-wall, and by five crosscuts at intervals of about 100 feet. This development shows the body to be mineralized with pyrite, sphalerite, galena, and chalcopyrite, occurring in varying proportions. The distribution of the sulphides is irregular, one kind giving place either gradually or rapidly to another kind. Small slips and faults help to complicate the relationships.

Along the foot-wall a continuous zone, rich in zinc, extends for 230 feet from the west end of the south branch of the ore-body. Its boundaries follow irregular courses and the width varies from 3 to 12 feet. It averages about 70 per cent sphalerite and 25 per cent pyrite with small shreds of the wall-rock and small quantities of quartz, calcite, chalcopyrite, and, in places, a little galena. To the east of the end of this band, from the third crosscut to the end of the body, the ore along the foot-wall consists of 10 to 50 per cent pyrite disseminated in rhyolite, with occasional patches high in pyrite or sphalerite.

The ore along the hanging-wall of the western ore-body is, in the three westernmost crosscuts, rich in chalcopyrite. This chalcopyrite-rich band in the two westernmost crosscuts forms the north branch of the ore-body. The width of this zone in the three crosscuts from west to east is 1 foot, 11 feet, and 10 feet, respectively. The average chalcopyrite content is about 35 per cent, the rest of the mineralization being pyrite with, in places, minor quantities of sphalerite and shreds of the country rock. In the two crosscuts to the east the position of the chalcopyrite-rich band is taken by rhyolite rich in pyrite; the pyrite content across 15 feet in the western of the two crosscuts averaging about 40 per cent, and across a few feet in the eastern crosscut averaging 20 per cent.

In the westernmost crosscut, the south fork of the ore-body is the sphalerite-rich band along the foot-wall and the north fork is the chalcopyrite-rich band along the hanging-wall; the two bands are separated by 12 feet of unmineralized rock. In the next crosscut to the east the sphalerite-rich band is succeeded by a 15-foot band containing, on an average, about 40 per cent pyrite, 20 per cent chalcopyrite, and 5 per cent sphalerite. This is followed by 10 feet of unmineralized rock, beyond which is the chalcopyrite-rich band, 11 feet wide, forming the northern fork of the ore-body.

In the next crosscut to the east (the third) the narrow, sphalerite-rich band along the foot-wall is followed northward by a band 30 feet wide, irregularly mineralized with pyrite which forms not more than 5 per cent of the whole. The 30-foot band is succeeded by a 10-foot band contain-

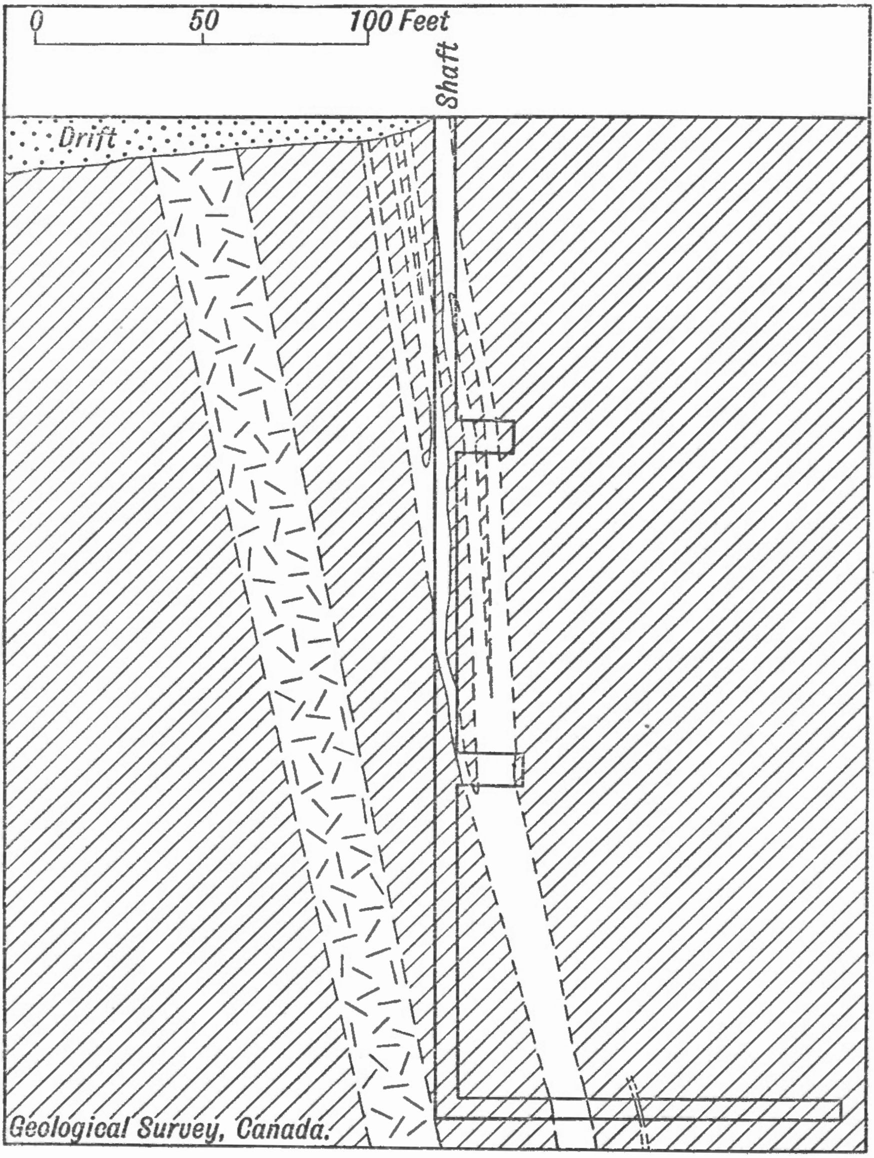

Figure 6. Vertical section through shaft and crosscut from shaft at 300-foot level, Abana mine, Desmeloizes township, Quebec.

ing about 60 per cent pyrite and 3 per cent sphalerite. It is followed by the chalcopyrite-rich band, 10 feet wide, lying along the hanging-wall.

In the two easternmost crosscuts, the central parts of the ore-body hold 80 per cent or more of pyrite across widths of 25 feet. As already mentioned, the ore along the foot-wall in these two crosscuts consists of rhyolite carrying 10 to 50 per cent pyrite with occasional patches high in pyrite and sphalerite; along the hanging-wall, the ore consists of rhyolite holding about 40 per cent pyrite across 15 feet in the western of the two crosscuts, and about 20 per cent in the eastern crosscut.

The mineralization in the shaft and at the 100- and 200-foot stations does not seem to vary in any regular fashion. At higher levels chalcopyrite and galena are more abundant relative to sphalerite and pyrite, but owing to the patchy distribution of these minerals and the small widths exposed, it is thought these variations have no real significance.

The western ore-body is separated from the eastern by the north-striking diabase dyke which on the 300-foot level is 200 feet wide. The eastern ore-body has the same strike as the western, but lies farther north. When studied by the writer it had been partly explored by a drift along the foot-wall and by two crosscuts at, respectively, 110 feet and 190 feet east of the east side of the diabase dyke. Since then drifting and crosscutting have shown the body to be longer than the western body and to end somewhere near the east boundary of lot 44. At the time of examination, the eastern of the two crosscuts had not yet reached the hanging-wall. In the western crosscut, the ore-body is 28 feet wide and carries about 50 to 60 per cent pyrite and within a central section 8 feet wide, 15 per cent sphalerite. In the eastern crosscut, which at the time it was examined had not yet reached the hanging-wall, the exposed width was 34 feet. The ore-body in this crosscut is solid pyrite and sphalerite grading from about 15 per cent sphalerite at the foot-wall to about 60 per cent sphalerite with a little chalcopyrite at a point 22 feet north of the foot-wall. For the next 6 feet to the north the sphalerite content is 10 per cent. In the face of the crosscut an 8-inch stringer of chalcopyrite containing a little quartz was seen. Westward beyond the western crosscut, a little sulphide mineralization, mostly pyrite, is visible in the drift run to the dyke. Quite a few slips and minor faults striking and dipping in various directions are visible in this drift. It seems probable that faulting has displaced the west end of the ore-body and, probably, crosscutting near the dyke would disclose a body of sulphides equalling in width that found in the two crosscuts.

Ore Minerals

Specimens of the sphalerite-rich sections of the ore consist of bands alternately rich in pyrite and sphalerite and roughly paralleling the strike and dip of the ore-bodies. The bands vary in width from a very small fraction of an inch to 3 inches. They lack definite boundaries, the bands grade either rapidly or gradually into adjoining bands and change in composition along their strike. The grain varies much, although commonly, it is from 0·5 to 2 millimetres, but the pyrite grains for the most part are of smaller average sizes. Most, but not all, of the pyrite grains have idiomorphic outlines. The sphalerite usually occurs as a mosaic of allotriomorphic grains which after etching with HCL and HNO_3 show a lamellar twinning with, in many instances, small, irregular grains of chalcopyrite along the twinning planes. Pyrite grains with idiomorphic outlines are scattered through some sphalerite individuals. Irregular grains of quartz and calcite are common throughout the sphalerite. Small quantities of irregular specks of galena are present in some sphalerite grains and in many such cases tend to be associated with the quartz and calcite grains.

In one specimen grains of what is believed to be enargite were found. They contained blebs of chalcopyrite and associated with galena, occur in the sphalerite. The colour of the mineral in reflected light is yellow-grey. Its hardness is about the same as that of sphalerite. To the following six re-agents it gave the following reactions: HNO_3, positive, slight brown tarnish which rubs clean; HCL, $FeCL_3$, NaOH, all negative; with KCN tarnishes iridescent. Because of its appearance and its reaction with the re-agents, the mineral is believed to be enargite rather than pyrrhotite which it slightly resembles.

The order of crystallization of the sulphides, all of which are believed to have formed at one period of mineralization, is: first, pyrite; second, sphalerite, chalcopyrite, and enargite; and, largely third, galena. The periods of crystallization of the three groups appear to have overlapped.

A specimen of ore 95 per cent chalcopyrite shows the following mineral content and relationships: small, cubical pyrite in chalcopyrite and sphalerite; sphalerite in grain of 1 to 2 millimetres containing bleb-like specks of chalcopyrite throughout which are scattered irregular to rounded grains of pyrrhotite. A dark grey gangue mineral which is not a carbonate, but probably is a silicate, is present in small quantities associated with the sphalerite. Irregular veinlets of chalcopyrite cut the pyrrhotite and pyrite. In various parts of the mine chalcopyrite was seen associated with glassy white quartz and occurred cutting the country rock. It was also found disseminated with the other sulphides in schistose phases of the country rock.

Fragments of coarse, ferruginous carbonate veined by the sulphides are present in some specimens of sphalerite-rich ore. Fine-grained quartz and carbonate display the same relationship with the sulphides. In one specimen, fine-grained, disseminated sphalerite replaces such fragments. Galena is common near the margins of these fragments or deeply penetrates them.

Origin of Ore-bodies

The feldspar porphyry is older than the quartz-albite granite dyke which lies south of the ore-bodies. Both rocks were intruded apparently after the main period of shearing of the volcanics. The volcanics forming the country rock of the ore-bodies are rhyolite and possibly some fine, tuffaceous sediments. In places the rhyolite in and adjacent to the ore-bodies has been brecciated rather than sheared. The localization of this brecciation may have been due to the buttressing effect of the quartz-albite granite dyke during a later period of shearing. That later shearing, at least on a small scale, did take place, is shown by the slight shearing of the margins of the quartz-albite granite dyke and of areas of the volcanics replaced by materials from the feldspar porphyry dyke. It may be that the localization of the solutions which produced the ore-bodies was due to the existence of a brecciated zone produced as stated above.

The sulphides were introduced before the 200-foot quartz diabase dyke was intruded. The intrusion of the dyke divided in two what originally was a single sulphide body. The dyke as seen on the 300-foot level is traversed by a vertical fault which lies 80 feet west of the east edge of the dyke and strikes north 17 degrees east at a slight angle to the course followed by the dyke. The fault zone is 8 feet wide and filled with brecciated diabase and gouge-like material. This fault displaced the eastern ore-body northward with respect to the western ore-body. Conclusive proof of the displacement suffered by the two parts of the originally simple sulphide body is furnished by the relative positions of the two parts of the quartz-albite granite dyke which are to be seen in the same relative position to the ore-bodies on the two sides of the quartz diabase dyke and which have suffered a similar horizontal displacement. The amount of vertical displacement is unknown.

The sulphide deposit can not be related in origin to the diabase dyke, it probably is related to the feldspar porphyry. Rocks similar to the feldspar porphyry occur as marginal phases of granitic masses occurring within the district and in the vicinity of these intrusive granitic masses sulphide deposits occur. Nevertheless the Abana sulphide body may be related to the quartz-albite granite dyke which resembles a dyke in the vicinity of the Windsor mine ore-body some miles southeast.

CHAPTER IV

ELECTRICAL AND MAGNETIC CONDITIONS AT THE SITE OF THE INVESTIGATION

By L. Gilchrist

There were conditions at the place of investigation that would have an important bearing on the procedure if an electrical or electromagnetic exploration were contemplated. Some of these conditions could be readily recognized by a simple preliminary examination, whereas others were revealed as the mining operations proceeded.

(I) CONDITIONS RECOGNIZABLE BY A PRELIMINARY EXAMINATION

(1) At rock outcrops there were traces of magnetite and at places in the adjoining regions the effect on a magnetic needle was pronounced. On this account a magnetic survey of the region was made and the results are given in Chapter V.

(2) The ore outcrop did not noticeably affect a magnetic needle.

(3) The overburden consisted of a surface layer of humus about one foot thick underlain by a wet, sandy clay layer and that again by a deep layer of sand. The clay subsoil did not provide good drainage and stagnant water lay in pools under the humus. In the ravines and watercourses there was an abundance of wet clay and humus. The experience of Bieler and Watson[1] shows that these materials may be an important factor in the distribution of conductivity in regions where they exist extensively and their consideration should not be neglected in the application of electrical methods of exploration or in the interpretation of the results.

Measurements were made of the resistivities or specific resistances which are the inverse of the conductivities of these materials and the results, though meagre, give sufficient evidence of the necessity of obtaining this information. They are given in Table II. The values given are those of the resistivities of the materials in place.

(4) The schisted condition of the rock of the outcrops suggested the necessity of measuring the resistivities of the mineralized and unmineralized parts in place and in different directions. No preliminary measurements were made of these resistivities, but it appeared probable that they would be different along and at right angles to the direction of schistosity. In this connexion it may be noted that a simple approximate method of obtaining these results is described by J. G. Koenigsberger.[2]

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[1] Can. Min. and Met. Bull., May, 1928.

[2] Proc. Am. Inst. Min. Eng., Boston Meeting, August, 1928.

(II) CONDITIONS REVEALED DURING MINING OPERATIONS ON THE 300-FOOT LEVEL

(1) There was a wide variation in the conductivity of samples of the materials of the ore-bodies. There were two ore-bodies, a western and an eastern, separated by a dyke about 200 feet wide. Measurements were made of the resistivities of samples from different portions of the ore-bodies in the 300-foot level (*See* Table II). In that part of the western body near the shaft, the materials of the ore-body were much more conducting than the materials of the overburden. In the eastern body the average conductivity of the samples was very low, much lower than that of the overburden and not greatly different from that of the dyke. This condition of conductivity was evidently associated with the proportion and distribution of materials in the ore-body, of widely varying conductivity, e.g., chalcopyrite, pyrite, sphalerite. The results of the measurements of samples are very meagre indeed nor are they as satisfying as results that are obtained from measurements of the resistivity of the materials in place. They accord, however, with the results of the electrical explorations given in Chapter VI.

(2) A banded and a broken or discontinuous condition existed in both ore-bodies and in some places this discontinuous condition approximated dissemination. Considerable difference was found in the resistivities measured along and at right angles to the banding.

(3) The dyke was found to be magnetic due to the presence of disseminated magnetite. Its conductivity, although low, was much higher than that of the surrounding rock and not sufficiently different from the low conductivities of parts of the ore-bodies adjacent to the dyke, to permit of easy delineation by electrical exploring methods.

(4) The overburden varied in depth from zero at the western extremity of the western ore-body, to probably 100 feet to 200 feet above the dyke, and to probably 75 feet above the eastern ore-body.

TABLE II

Resistivity of Materials of the Abana Mine Property

Many of the specimens were banded. The resistivities in different directions are given for several specimens.

Locality	Material	Resistivity in ohms per centimetre cube
1 Surface	(*a*) Running water from ravine 1,000 feet northeast of No. 1 shaft	$2\cdot5\times10^4$
	(*b*) Water in pools under humus	$2\ \ \times10^4$
	(*c*) Lower part of humus	$2\cdot8\times10^4$
	(*d*) Sand and clay below humus	$2\cdot1\times10^5$
2 Diabase dyke (300-foot level)	Three measurements, along directions at right angles to one another	$4\cdot5\times10^8$ $6\cdot1\times10^8$ $3\cdot6\times10^9$
3 Ore-body 300-foot level, main drift near shaft	(*a*) Sphalerite with 10% pyrite Three measurements at right angles	495 590 $1\cdot4\times10^6$
	(*b*) Rhyolite with 15% pyrite in stringers Three measurements at right angles	200 3500 140
4 Ore-body, 300-foot level, main drift about 100 feet east of shaft	(*a*) Chalcopyrite with small amount of silicate	0·21
	(*b*) Second specimen	0·31
5 Ore-body, 300-foot level, north cross-cut about 200 feet east of shaft	(*a*) Pyrite with small amount of silicate	54
	(*b*) Sphalerite with about 15% pyrite	715
	(*c*) Volcanic rock with about 10% chalcopyrite and 10% pyrite	466
	(*d*) Chalcopyrite with small amount of pyrrhotite and silicate	0·08
6 Ore-body, 300-foot level, north cross-cut about 275 feet east of shaft	(*a*) Pyrite with a small amount of silicate	3·7
	(*b*) Volcanic rock with chalcopyrite and sphalerite; the sulphides = 20% of specimen	170
	(*c*) Pyrite Three measurements at right angles	54 34 5·3
7 Ore-body, from between shaft and dyke	(*a*) Chalcopyrite	0·179
	(*b*) Sphalerite and rock	2625·9
	(*c*) Sphalerite and pyrite	10·19
	(*d*) Sphalerite and rock with a little pyrite	1604·7
8 Ore-body, main drift east of and close to dyke	(*a*) Pyrite and small amount of silicate	7
	(*b*) Volcanic rock with 20% sphalerite and pyrite	$1\cdot5\times10^8$
	(*c*) Volcanic rock with 20% sphalerite, 25% pyrite, and a little chalcopyrite	$1\cdot6\times10^4$
9 Ore-body, main drift a short distance east of dyke	Sphalerite with 15% pyrite Measurements at right angles to banding	$4\cdot6\times10^7$ $4\cdot7\times10^7$ $9\cdot3\times10^7$

CHAPTER V

MAGNETIC SURVEY OF ABANA PROPERTY

By L. Gilchrist

Two magnetic explorations were made.

(*a*) The first exploration was carried out without the aid of the exploring companies. It was made with a Miner's Dip Compass or 3-inch Dip Needle with fixed counterpoise, made by W. and L. Gurley, Troy, N.Y., with which readings of the inclination or dip could be made to within 1 degree. The maximum reading was 20 degrees. From the readings at various points magnetic contours were plotted and are shown on Plan No. 2.

(*b*) The second exploration was made by the Swedish American Prospecting Company with a Schmidt balance or variometer. This instrument was very much more sensitive than the dip needle. It gave variations in the intensity of the magnetic field in gammas (1 gamma$=\frac{1}{10^5}$ gauss). One gauss is a force of one dyne on a unit magnetic pole. Unit magnetic pole is defined on page 5. Readings could be made to 10 gamma. The maximum reading was about 800 gamma. The sensitivity of this instrument will be comprehended better if it is noted that the intensity of the earth's field at Ottawa is normally about 0·6 gauss.

The exploration was very brief, was made only in the neighbourhood of the dyke, and was of the nature of a demonstration of the use of the instrument. The points at which measurements were made were along a line crossing the dyke. The results obtained are also shown on Plan No. 2.

The following conclusions may be made from the results of the magnetic survey:

(1) The variations in the dip as given by the dip needle, indicate the presence of local magnetic material and of a pronounced magnetic condition associated with the diabase dyke. The distribution of the magnetic field associated with the local bodies was determined, but not the intensity of the field. Magnetite occurs in the dyke and probably had much to do with increasing the conductivity of the material of the dyke. The information obtained was not sufficient, however, to make it possible to correlate the intensity and distribution of the magnetic property of the bodies with their conductivity.

(2) The results obtained with the Schmidt balance, or variometer, gave more definite and accurate information on the distribution and magnitude of the intensity of the magnetic field associated with the local bodies. Since the property of magnetism associated with quantities of

magnetite is sometimes very weak, an indication of the presence of weakly magnetic magnetite would be obtainable only by a highly sensitive instrument. Since the magnetite is conductive it would have an important bearing on the distribution of conductivity in the region.

(3) From the results obtained with the dip needle it is evident that much useful information may be readily obtained in suitable localities even with an instrument that is only fairly sensitive, in the hands of an operator with but little training or experience but with a fair degree of skill.

CHAPTER VI

ELECTRICAL AND ELECTROMAGNETIC SURVEYS OF ABANA PROPERTY

By L. Gilchrist

(I) An exploration by a field party of the Radiore Company of Canada, Limited, consisting of Messrs. Carl Klinkenberg, Keith Beisel, and James Howard. This party made use of high frequency inductive methods with primary loop and detector coil insulated from the earth.

(II) An exploration by a field party of the Schlumberger Electrical Prospecting Methods, consisting of Messrs. J. J. Breusse and S. Millet. This party made use of the following methods:

(1) Self potential and natural current method.
(2) Resistivity method in which applied direct currents were used.

(III) An exploration by a field party of the Swedish American Prospecting Company of Canada, Limited, consisting of Messrs. Helmer Hedstrom and H. Burton. This party made use of the following methods:

(1) An equipotential method in which applied alternating current of low frequency was used with parallel electrodes.
(2) An electromagnetic inductive method in which a primary current of low frequency was applied to point electrodes.
(3) A method of phase compensation as a demonstration, but not for measurements.
(4) A method with a Schmidt variometer for the determination of magnetic conditions.

METHOD OF PROCEDURE

In all cases the field parties were asked to proceed in their usual way as if they were under contract with a mining company.

No information regarding underground conditions was given to the field parties.

No information was given of the geological or other physical conditions at the surface. These conditions are presented in Chapters III and IV and it is apparent that a knowledge of much of the surface conditions was readily obtainable without assistance by experienced observers.

Every possible assistance was given to the field parties in order to enable them to carry out their explorations.

In all cases the field parties were finally asked to make any explorations or demonstrations which might appear to them as useful in presenting their methods.

During the explorations readings were made at intervals by the authors of this report, hereafter referred to as the observers, as well as by the members of the field parties. Additional work suggested by the observers for the purposes of gaining further information was carried out by the field parties.

A complete record was kept by the observers of the details of all work and of all observations or measurements made by the members of the field parties or by the observers.

The Schlumberger Company and the Swedish American Company submitted detailed statements of their work and their interpretations of the results, together with illustrative maps.

These detailed statements are presented with certain modifications for clearness and evaluation, viz.,

(*a*) Matter which has been presented in other parts of the report or which appeared to be of minor importance was deleted from the detailed statements.
(*b*) The actual geological conditions of the mine were added to the maps submitted by these companies.

The Radiore Company submitted accounts of their detailed work on the depth of the electrical axis of the conductor but not of the preliminary work by which the electrical axis was located. This company submitted detailed reports of other work as an example of their usual custom and also an outline of their usual method of procedure. This outline is presented in a slightly modified form in the following section.

EXPLORATIONS CARRIED OUT BY THE FIELD PARTY OF THE RADIORE COMPANY OF CANADA, LIMITED

Method and Apparatus Used

The party used a high frequency method ranging from 90 to 130 kilocycles a second throughout the exploration. The method is briefly described on pages 23-25, and is given in detail in several publications by members of the staff of the company and by others (*See* references, page 26).

The apparatus consists of a square, primary broadcasting loop, 6 feet to the side, and a detector coil with telephone receiver and amplifier attached. The latter coil is used to indicate the " strike " or horizontal direction and the " dip " or angle with the vertical plane of a resultant electromagnetic field due to the primary field and a secondary field due to a secondary conductor. The loop and detector coil are set up with their planes in the same vertical plane. The detector coil is now rotated on a vertical axis until the maximum effect of the resultant magnetic field on the coil is obtained. The plane of the detector coil is at right angles to direction of the horizontal component of the resultant magnetic field and is known as the " strike ". The detector coil is now rotated until its plane is again coincident with that of the broadcasting loop. The coil is now rotated about a horizontal axis until the minimum effect of the resultant magnetic field on the coil is obtained. The direction of the resultant magnetic field is then approximately in the plane of the coil. The angle which the plane of the coil makes with the vertical plane is the angle of " dip " which the resultant magnetic field makes with the horizontal plane. This is in accord with the account furnished by the company (*See* below) in which the plane of the detector coil is made to coincide with the plane of the loop before the " dip " is determined. However, it would perhaps be well to determine also the " dip " in the plane of the " strike ". The procedure is probably sufficiently accurate in the preliminary work of locating the resultant electrical axis of the secondary conductors, and in the detailed work near the electrical axis of the secondary conductors if the broadcasting loop is placed in a vertical plane containing the electrical axis the procedure is satisfactory, for the " strike " is now approximately in this vertical plane. The " strikes ", together with pronounced convergence of dips, indicate the approximate vertical plane in which is located the resultant electrical axis of the secondary conductors. With the primary loop set up over the axis, the convergence of dips which are obtained with the detector coil set up on opposite sides of the axis more accurately indicates the position of the axis of the secondary conductors.

Procedure Followed by Radiore Company of Canada, Limited

The following account was furnished by the company.

Usually, lines are cut or staked on the ground before we begin our survey. In most cases, these lines form 200-foot squares or grids and they are picketed or numbered in two directions, which enables us to map located indications approximately as we progress with the survey. In addition, the lines are of assistance in moving our transmitting set about in heavy bush.

The transmitter or broadcasting loop is set up with its plane vertical in a portion of one of these squares, in some cases on the cross lines, and readings are then made with the receiving or detecting coils at intervals on two or more circles about the transmitter. The plane of the detecting coil coincides with the plane of the broadcasting loop. The radii of these two circles are roughly 200 and 400 feet, respectively, and approximately twenty-five readings are made on each circle. If converging dips are encountered, a flag is set near the vertical dip read between these converging dips. If a flag is set on both circles, they may indicate the general direction of the conductor.

The transmitter or broadcasting loop is then set up on one of these flagged points and the indication traced if possible. Converging dips may not be encountered, in which case it is necessary to move the transmitter again, usually to one of the other four corners of the square. From this new position, readings are made about the transmitter and, of course, these observations will overlap the original circles. Very often, the same ground is covered four times, but with the transmitter in four different positions.

This circling method of reading around the transmitter is not a fixed rule and other systems of traversing the ground are often used. Sometimes dips are observed that only dip in one direction and it is very often found that the indicated axis lies outside and nearly tangent to the circle.

The strength of the secondary field associated with this conductor is not great under such conditions because of the distances the transmitter is from the conductor, which reduces its power of energization. This conductor may be running almost at right angles to the direction in which the energizing loop is trained.

It should be borne in mind that the detector coil is always pointed toward the loop and the loop toward the detector coil. The electrical strike is disregarded except as an aid in ascertaining the direction of the conductor, when the transmitter is not set up directly above its axis.

Of the various problems encountered in making a Radiore survey, that presented by closely adjacent conductors offers, probably, the greatest trouble. We sometimes, in such cases, energize more than one conductor at a time and thus set up more than one powerful secondary field. If such closely adjacent conductors are of equal length, depth, and electrical strength, it is difficult to separate them. If that is the situation, we are endeavouring to locate a mineralized area within a "mining limit" and it is not necessary to locate the individual conductors. But if the closely adjacent conductors are of unequal lengths, it does not require much effort to trace each of them roughly. By placing the transmitter over a projecting end of the longer conductor, it is then quite easy to trace this conductor independently. In most instances, this move allows work on a single secondary field to be done with adjacent conductors on either side that are not being energized.

These adjacent conductors are very easy to determine under some conditions such as sulphide deposits in a schisted formation, where one or more convergencies on two or more conductors are often observed from the same transmitter set-up (prior to setting the transmitting loop over one axis). Usually each indication can be traced independently and without interference from the others by placing the transmitter over one of the converging points. If the sulphide deposits are very unequal in size, the stronger conductor will sometimes present an obstacle in tracing the weaker. Here is another clear example of why operators are given a thorough schooling in comparative electrical reaction over known mineralized deposits and also artificial conductors.

Disseminated sulphide zones of considerable width presented a very difficult problem until recently, when conclusive proof was obtained that a wide shifting of the electrical axis will be experienced at times when the transmitter is moved to another position along the same indication or close by. This proof came from the drill core of more than thirty drill holes and several crosscut tunnels driven through various located conductors.

This wide shifting of the axis occurring above a broad, disseminated sulphide zone is explained as follows:

A converging point is located and marked while the transmitter is over a certain portion of this zone: the receiving coils and transmitter may be in line and directly above a more heavily mineralized sulphide portion of this zone, but when the transmitter is moved to another position, over or near this zone, it may not be directly above or in line with the massive portion and very often it will not be above much mineralization. It is possible that another band of disseminated sulphide in the same zone will be energized and that this band will not connect or line up with any of the points flagged from the first set-up. The points from this second loop set-up may be to either side of the original converging point.

Some of the lesser obstacles which have to be overcome in field work are artificial conductors, wave-front distortion, and extremely slightly converging dips obtained at times, such as in swampy depressions. The converging dips obtained from weak electromagnetic fields created in such poor conductors are always very indefinite, and they are never accepted as a conductor.

If a network of mineralized deposits is encountered and their electrical axes cross at various angles, the survey must be conducted by a process of elimination. First, by moving the transmitter back and forth along what is assumed to be the location of a conductor and to other possible test positions. If some of the conductors are stronger than others, these can be eliminated and the weaker ones traced (by using different loop set-ups).

The following is the method of obtaining the depth of an electrical axis (*See* Figure 7). The observed dips at measured distances on both sides of the vertical dip are plotted and the lines of dip are continued to their intersections with the line of vertical dip. Vertical lines are drawn downwards from the points at which readings were made on the surface; horizontal lines are drawn through the points of intersection of the dip lines with the vertical dip line. The intersections of the horizontal and vertical lines locate the points A, B, C, E, F, and G. A smooth curve drawn through these points locates the point D at the depth of the electrical axis.

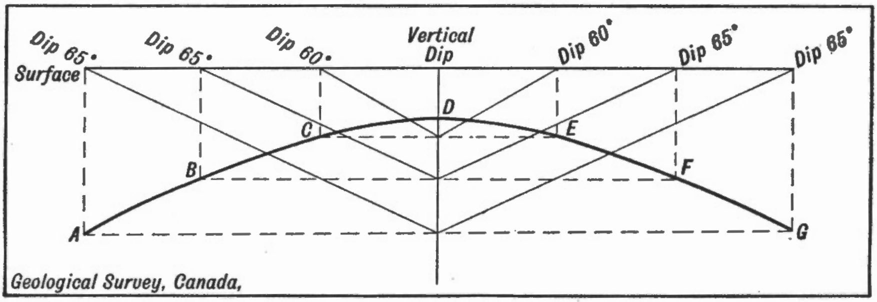

Figure 7. Determination of depth of an electrical axis by method of Radiore Company of Canada, Limited.

Conductors are classified electrically by the following characteristics: the strength of the electromagnetic field as indicated by the sharpness of the minimums and signal intensity at distance: the nearness which the detector coil can be carried to the transmitter and dips to the conductor can still be observed: the distance the conductor can be energized with the transmitter to either side of its axis; and other characteristics of lesser importance.

In classifying conductors, the depth of the electrical axis has to be considered at all times; shallow conductors having greater dip gradients and also greater signal strength.

EXPLORATIONS AS CARRIED OUT

The following statements and the accompanying illustrations have been prepared by the authors of this report.

(1) *Demonstration on Wires and Pipes*

On Monday and Tuesday, June 18 and 19, 1928, at Rouyn, demonstration was made of the method of determining the position of surface metal conductors such as telephone wires and of submerged metal pipes in Osisko lake. The demonstration on the submerged metal pipes gave the following results:

(*a*) The distance at which the presence of a pipe was indicated varied with the length of the pipe.

(*b*) For a pipe 60 feet long, 2 inches in diameter, and submerged 5 feet in the water, the indications at short distances from the pipe were strong, but at a distance of about 50 feet from the end of the pipe in a line at right angles to the pipe, the indication was much fainter and at about 150 feet was not detectable. Intermediate readings were not taken.

(2) *Demonstration on Abana Property*

(*a*) The party and equipment, after the demonstration at Rouyn, were transferred to the Abana mine and proceeded with the exploration. The investigation on the Abana property was carried out from June 20 to June 29 inclusive. The results of the preliminary work are shown on Plan No. 3. Eight set-ups (Nos. 1 to 8 on Plan No. 3) of the broadcasting loop were made in order to determine the position of the trace on the surface of the ground of the intersection of the vertical plane containing the axis of an indicated buried conductor. Set-up No. 9 was approximately vertically over the axis and set-up No. 10 was more accurately placed over this axis. With these set-ups of the broadcasting loops, the detector coil was used to determine seven points vertically above the axis. The position of these points, numbered 1 to 7, are shown on Plans Nos. 3 and 4; points Nos. 1 to 5 were more definitely indicated than Nos. 6 and 7. Details of the observations made from set-ups Nos. 8 and 9 are given on Plan No. 4.

Broadcasting loop set-up No. 11 was made on the axis at point 6, in order to explore for a continuation of the axis eastward. The results of this set-up and of others, for example No. 15 and No. 16, although giving dips did not show convergence of dips and, therefore, no conclusions were made as to location of a buried conductor east of axis point No. 7. The results of these set-ups are shown on Plan No. 5. The dips, however, are evidence of the existence of secondary conductors probably of complex character and distribution.

(*b*) Detailed exploration was made at axis points 1, 3, and 5 in order to determine the depth of the axis of the conductor according to the method described above (*See* Figure 7). At these points, lines were located at right angles to the vertical trace of the axis and on these lines points were established on both sides of the axis at distances of 5, 10, and 15 feet respectively. With the detector loop the convergent dips were carefully determined. From these readings the depths of the axis of the secondary conductor were determined. This gave depths of 40 feet at point 1, 205 feet at point 3, and 450 feet at point 5.

(*c*) At the suggestion of the authors of this report, experiments were carried out to determine if the radiation from the broadcasting loop would penetrate to the 300-foot level. Two sets of experiments were carried out:

(i) The broadcasting loop was set up on the surface at the points A and B (*See* Plan No. 3) and the detector coil was placed at the end of the crosscut on the 300-foot level, 300 feet directly below the point A. The nearest trackage to the detector coil was in the main drift about 45 feet distant. For both positions of the broadcasting loop the signal received with the detector coil was sufficiently strong to make possible the approximate determination of the strike and dip of the electromagnetic field.

The detector coil was then brought to the surface and at a point near the shaft the signals were readily obtained. The position of telephone wires and other surface conductors near the broadcasting loop and the shaft gave rise to the suggestion that the signal was transmitted by these conductors. On this account another set of experiments was carried out.

(ii) The broadcasting loop was set up at the points C, D, and E (*See* Plan No. 3), some distance from telephone wires and other conductors. The detector coil was placed near the shaft. The signal received was weak and from the point E was so weak as to be considered undetectable by some of the observers.

The detector coil was then taken to the same point as in the previous experiments in the crosscut on the 300-foot level directly below set-up point A. The signal from stations C, D, E was received, but in all cases was very weak and, especially from E, was barely detectable.

The detector coil was again brought to the surface and placed near the shaft. The signal received from E was detectable, but much like that received at the underground station.

The experiments were not sufficiently extensive to determine conclusively whether the signal was transmitted through the shaft or through the ground. The intensity of the signals received at the underground station was so weak, however, as to make it highly improbable that a conductor at a depth of 300 feet would become a secondary conductor sufficiently energized to be detectable at the surface.

CONCLUSIONS

The following observations on the procedure followed and results presented by the Radiore party appear to be warranted.

(1) A careful study of the surface geology and an appreciation of the geological structures and conditions that are observable on the surface would have rendered unnecessary much of the preliminary search for the hidden conductor and would have helped in the latter part of this exploration.

(2) The determined positions in plan and in depth of the points along the electrical axis of the buried conductor are misleading and not electrically significant, for the measured data obtained are inadequate either for the delineation of a complex set of conductors in plan or in depth. Necessarily the method of interpretation is also inadequate. The position of point 1, for which the depth is given as 40 feet, agrees in plan approximately with the inferred position of the top of the ore-body, but lies approximately 35 feet below it. Points 3 and 5, for which the depths are given as 205 feet and 450 feet respectively, are considerably south and outside the inferred position of the ore-body at these depths. The axis as mapped from point 1 to point 4 closely corresponds to the inferred position of the medial line of the top of the ore-body below the drift. The depth determinations obtained by the method used, locate the axis outside of the ore-body and, therefore, it is obvious that this method of obtaining the depth of the electrical axis, as carried out, did not achieve its objective. The probable reasons for the position of points 5 to 7 on the indicated axis diverging from the position of the known ore-body, are discussed in some of the following paragraphs.

(3) The results obtained east of the dyke are difficult of interpretation. The following observations may, however, be made: (*a*) the area over which dips in one direction were obtained, was extensive; (*b*) the results, as given in Table II, of resistivity measurements on ore, dykes, and overburden in this locality, indicate a complex distribution of minor conductors.

(4) The high frequency of the radiations which were broadcast contributed to the production of high potentials in the indicated minor conductors such as surface soil, clay, and diabase dyke. This would be especially the case near the surface in the locality east of the dyke. An intensification of the secondary radiation from these conductors probably took place together with a corresponding diminution in the radiation from the deeply embedded conducting ore-body. This was probably the case at all points except point 1 on the mapped axis of conductivity, and was probably especially so for points 6 and 7 and in the area east of the dyke.

(5) The axis of conductivity was evidently the resultant axis of all the conductors present. At point 1 on the axis of conductivity, the ore-body conductor dominated, but at points 2, 3, 4, 5, 6, 7, and in the area east of the dyke the other minor conductors became, in the order in which the positions are named, more and more effective in proportion to the effect of the ore-body. As these inferred minor conductors were spread over a considerable area the resultant axis quickly diverged from the position of the known ore-body. It is claimed by the company in their statement on page 53 that these minor conductors could be easily delineated. In the actual work this was not done, nor are the methods as applied capable of delineating them. Further, the methods as described on page 53 cannot be considered adequate.

(6) It may be suggested that a repetition of this survey, using a very low frequency primary current, should in conjunction with the results

already obtained, improve greatly the accuracy of interpretation of the distribution of conductors, especially those that exist near the dyke and eastward. A group of such surveys made with different frequencies systematically graded should prove of greater assistance still.

(7) The results of the tests in which the detector was taken underground strongly suggest that a conductor 300 feet deep could not become a secondary conductor sufficiently energized to be detectable at the surface. This indicates that the detection of conductors at depths as great as 300 feet could, probably, not be attained by this method as it was used in this case and in the conditions of conductivity which existed at the place of investigation.

EXPLORATIONS CARRIED OUT BY THE FIELD PARTY OF THE SCHLUMBERGER ELECTRICAL PROSPECTING METHODS

The work by this company was completed July 22, 1928, having required sixteen actual working days in the field. Of these, eight were rainy, which interfered with the work to a certain extent. The following report (to the middle of page 61), with two maps, was submitted by this company. This report and the illustrations have been modified in accordance with the statement on page 51.

Introduction

After a preliminary visual reconnaissance of the surface, it was decided to make a methodical and detailed study of an area 800 by 1,400 feet. To this was later added a second area, 800 by 400 feet. It should be emphasized that this survey was a detailed one and hence required much more time than would a reconnaissance over the same area.

The regions mentioned are located so as to include the shaft and the two ore-bodies of the Abana Mines. It should be clearly stated here, that our observer and his assistant were entirely ignorant of the situation at the Abana Mines, and made no observation of conditions underground.

Two separate techniques of exploration were employed; one is known as the self-potential or spontaneous polarization method, and was used for a preliminary investigation; the second involves a study of the electrical resistivities of the ground and was used to check and supplement the first. These methods are developed in different technical publications, all well known, and will not be discussed here. (*See* " Exploration for Ore by Potential Methods " by E. G. Leonardon and Sherwin F. Kelly, Canadian Mining and Metallurgical Bulletin, No. 129, pp. 157-178, January, 1928.)

Exploration by Self-Potential or Spontaneous Polarization Method

The study of the currents spontaneously generated by minerals possessing metallic conductivity (sulphides, arsenides, etc.) provides the basis for a first technique of exploration. The differences of potentials occurring at the surface of the ground are measured along straight lines. Using the distances along these lines as abscissæ the corresponding potential values are plotted as ordinates, thus producing a profile of potentials. When this profile is flat, or only slightly wavy, no electrical activity is noted. Areas of current generation are indicated by pronounced depressions of negative potentials in the profiles where they cross such areas. Eleven of these profiles were traced in a northeast direction in the neighbourhood of the shaft, as shown on Plan No. 6.

These profiles indicate the existence of two zones of electrical activity. The first extends in a southeast direction from profile P 1 to profile P 4. This zone is the stronger of the two, the potential reaching a maximum negative of 230 millivolts on profile P 3.

These profiles may be considered in the nature of a preliminary study which has been somewhat further extended by tracing equipotential curves. Each such curve joins all points at the surface of the ground that are at a given electrical potential, and may be pictured as a " contour line " of the mountain of electrical activity which is centred in the mineralization. These curves, then, give a general idea of the outline of the conductive zone. Accordingly, a curve of the potential of 100 millivolts (with respect to the potential of the surrounding unmineralized area which is taken as zero) was traced, and inside of it two smaller ones at 200 millivolts were also traced. The form of the 100 millivolts equipotential curve suggests an elongated mineralized mass striking approximately north 55 degrees west. The two 200 millivolts equipotential curves outline the top of the mountain of electrical activity, hence the places where the mineralized body probably comes nearest the surface.

Particularly worth noting is the flattened form of the 100 millivolts curve on its eastern side and the sharp drop of potentials there indicated by the closeness of the eastern 200 millivolts curve. This would indicate either an abrupt termination or an almost vertical rake of the mineralized mass at this place. On the contrary, at the western end the drop of potential is slower, and either the mineralization fades out gradually or plunges gently beneath the barren overburden or rock.

The second area, crossing profiles P 9, P 10, and P 11, is weaker, the maximum negative potential being only about 80 millivolts, but is comparatively wide (200 feet at least). No equipotential curve was traced on this area, in view of the fact that the tracing of such a curve, with the small differences of potential encountered and their slow variations in a given distance, would have required much care and time. The fact that the negative peak is weak and broad suggests the hypothesis that the mineralization is here comparatively deeply buried. It is by no means an acute peak such as would indicate a mineralization which comes within a few feet of the surface. Such an area, if so far unexplored, should decidedly be tested, not by trenches but by drilling.

Exploration by Resistivity Method

Following this work by spontaneous polarization, further investigation was carried out by means of resistivity studies. This had a twofold advantage; in the first place, it provided a valuable and necessary check on the conclusions drawn from the first results, verifying and confirming them; in the second place, it yielded additional information which supplements and completes that already obtained.

By means of passing an electric current through the ground and taking appropriate measurements at the surface, it is possible to determine the average resistivities of the underlying formations. As in the case of spontaneous polarization profiles, the lines along which readings are made are plotted on the accompanying plan. Using the distances along these as abscissæ, the resistivities are plotted as ordinates. Low points in the curves represent places of low resistance where formations more conductive than the average can be expected.

The results are shown on Plan No. 6. The profiles P I to P VI, and P VIII and P IX show a marked decrease in resistivity along the same zones previously outlined by the self-potential method.

Two different field techniques were used in measuring the resistivity. Profile P III was obtained with one technique and the others with another. As a matter of fact, there is an entire series of the former type. These have been suppressed in order to avoid complicating the map, as they only confirm the ones given and do not yield any important additional information. This is especially marked on P III which indicates a resistivity of 600 ohms near the shaft. The resistivity of massive sulphides is incomparably less than this, but a dissemination of the sulphide minerals in gangue or country rock naturally raises the resistance. An increasing thickness or overburden also has the effect of raising the apparent resistance, since the covering material plays a larger rôle in the measurements.

The drops of resistivities on the different profiles, combined with results of the spontaneous polarization reconnaissance permits tracing a tentative form for the mineralized bodies which are shown on Plan No. 6 as conductive zones. On profile P VII a drop of resistivity will be noted, which we do not join with the similar drops on P VIII and P IX on account of its eccentric position and of the fact that no self-potential evidence is found at that point. Probably such a drop is due to a disturbance which is not in connexion with mineralization, such as a local spot of conductive overburden, contact between two sorts of rock, etc. This is an example of the utility of checking by a second independent method of investigation, the indications which are given by a first one.

On P I and P II it will be noted that the resistance at the northeast end is much lower than at the northwest. This is especially marked on P I. At the same time this general zone of low resistivities does not correspond with any pronounced self-potential electrical activity (*See* Plan No. 6), which leads to the idea that here there may exist a contact between two formations of differing resistivities. Another hypothesis would be one of a fissure filled with more conductive material than the wall-rocks. The possible trend of this contact is indicated on Plan No. 6 by the line A-A. The same appearance still persists on P III, a fact that would indicate that the supposed contact may be in relation with the occurrence of the conductive mineralization. Although these differences of resistivities may be explained in other ways, the hypothesis of a mineral-bearing contact is nevertheless worth noting.

From the results of the measurement on resistivities approximate values of the depths of the conductor may be determined. This has been done for the point marked S on resistivity profile P IV and the depth of the conductor at this point is about 40 feet.

Conclusions

In conclusion, both the self-potential and resistivity data lead to the same deductions. It will be noted that the phenomena observed with the two methods are considerably weaker for the east body than for the west one, which leads to the conclusion that the eastern conductive mineralization lies under a thicker overburden than does the western. Also it should be borne in mind that the electrical methods apply to conductive minerals only and consequently exclude pure sphalerite from the discussion.

A brief summary of work done and results obtained follows:

(1) A study of both self-potential and resistivity methods was carried out over a portion of the Abana property.

(2) Two zones, conductively mineralized, were put in evidence, one to the east and one to the west, both striking in a southeasterly direction. These are outlined on Plan No. 7. That to the east seems to lie under deeper overburden than the other.

(3) The possibility is pointed out that the western mineralized body may lie at the contact between two formations. The electrical study of its western portion supports this hypothesis to a certain extent.

(4) None of the conclusions applies to pure sphalerite, which is electrically non-conductive and, therefore, acts, in that respect, like gangue or country rock, with all electrical methods.

MEASUREMENT OF SELF POTENTIALS AND RESISTIVITIES ON 300-FOOT LEVEL, ABANA MINE

At the suggestion of the authors of this report, measurements of self potentials and of resistivities were made underground on the 300-foot level, Abana mine. The electrical contacts in the mine workings were made without the members of the Schlumberger Prospecting Methods party going underground. The exploration was in the nature of an experiment. It was rather hastily done and the results are meagre.

(1) Measurements of Self Potentials

Potential differences were obtained between stations in mineralized and unmineralized portions of the workings. The stations are indicated on Figure 8.

Contact points	Potential difference in millivolts
Station 16—Station 17	− 50
" 14— " 15	+275
" 13— " 14	+ 45
" 12— " 13	− 65
" 10— " 12	−160
" 10— " 9	+170
" 9— " 6	+230
" 6— " 5	+165
" 5— " 4	−115
" 4— " 3	− 12
" 3— " 2	+ 25

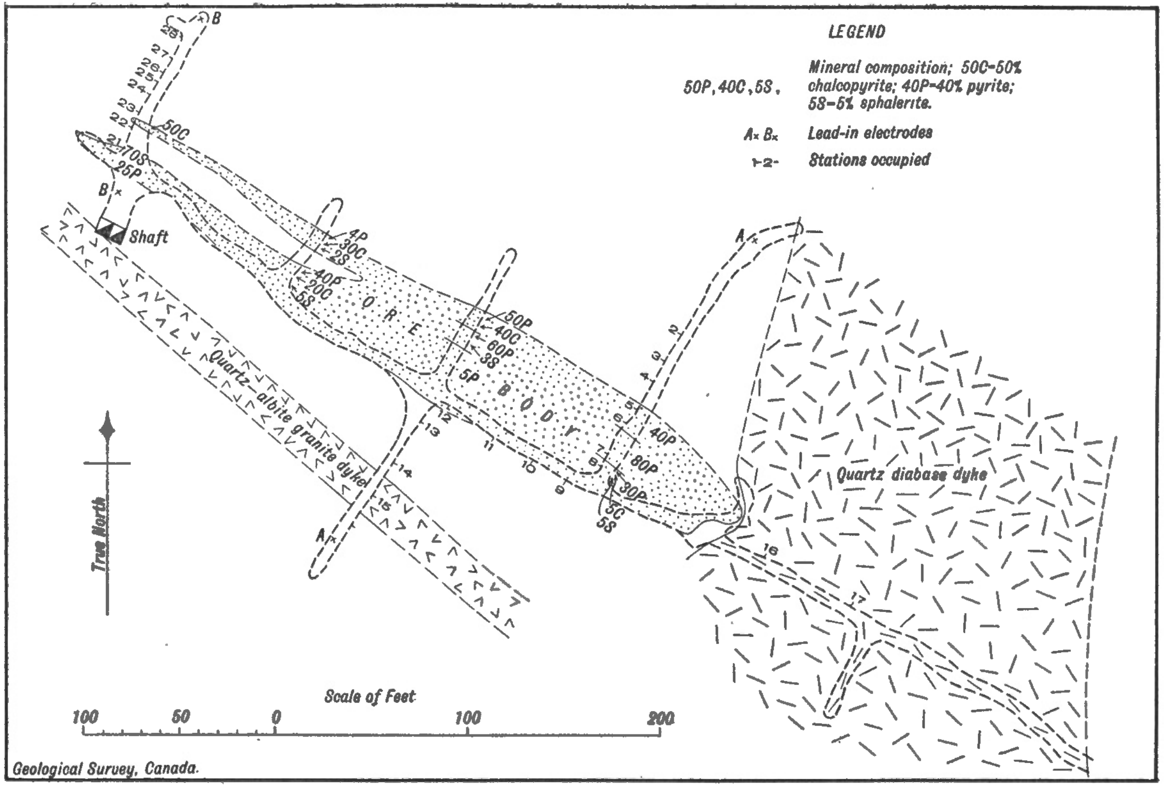

Figure 8. Abana mine, Desmeloizes township, Quebec; 300-foot level, showing stations occupied to measure self potentials and resistivities underground.

These differences of potential are sufficiently great to provide for the largest potential differences recorded at the surface, viz., 200 millivolts as shown on Plan No. 6, and also for a difference of potential of 275 millivolts which was found to exist between the ore-body at the outcrop and a point not sufficiently distant to give the maximum potential difference.

It is of interest to compare these potential differences with the maximum potential differences from a distant point which are set up by the following minerals, almost all of which were present in the region of exploration. The values of the maximum potential differences given in the existing literature are, roughly: pyrite, 700 millivolts; magnetite, 700 millivolts; pyrrhotite, 500 millivolts; chalcopyrite, 500 millivolts; and sphalerite (probably associated with other sulphides), 300 millivolts.

From a consideration of the values of the maximum potential differences, it is suggested that more extensive experiments might well give results that would indicate the distribution of materials.

(2) Measurements of Resistivities Associated With Applied Direct Currents

A direct potential difference of 100 volts was applied at two points by means of lead-in electrodes. Two exploring electrodes which were connected to a potentiometer were used to measure the potential difference between intermediate points. Two sets of measurements were made. The stations are indicated in Figure 8.

SET I

Lead-in Electrodes at Points AA

Exploring contact stations	Potential difference in millivolts	Current in milliampere
2— 3	430	1·25
3— 4	82	1·25
4— 5	43	1·25
5— 6	0	1·25
6— 7	0	1·25
7— 8	0·6	1·25
8— 9	3	1·25
9—10	2·5	1·25
10—11	4·5	1·25
11—12	2	1·25
12—13	1	1·25
13—14	1	1·25
14—15	4·5	1·25

SET II

Lead-in Electrodes at BB

Exploring contact stations	Potential difference in millivolts	Current in milliampere
21—22	49	1·1
22—23	14	(Some
23—24	395	uncertainty
24—25	205	in
25—26	310	current
26—27	750	readings)

The results are too meagre, and in Set II, too uncertain to warrant a determination of the resistivities. However, the distribution of potential corresponds to the distribution of resistivities and is in rough accord with the distribution of conducting minerals on the 300-foot level, notably in Set I from Station 5 to Station 15 and in Set II at Stations 21 to 23.

Conclusions

(1) The party in the arrangement of their lay-outs did not at first avail themselves fully of a preliminary study of the geological conditions that existed in the region. The members of the party were not given information on these conditions, but, as has already been pointed out, much of it was obtainable by means of a rapid preliminary examination; for example, the schisted condition of the rock outcrop, the location of the ore-body outcrop, and the direction of the strike. Even in the actual lay-outs used full advantage was not taken of these conditions.

(2) The location of the conductor in the western zone corresponds quite well with the position of the ore-body in this region between the shaft and the dyke. The extension of the conductor to the west of the shaft has not yet been shown to correspond to a pronounced mineralized region. No underground exploration had been done in this part of the mineralized zone.

(3) In the case of the eastern ore zone no indication was obtained corresponding to the part of the ore-body near the dyke. It is made evident in the report that the indications obtained were not pronounced and the result is ascribed to depth of overburden and to the possible existence of pure sphalerite. It is suggested that the measurements on conductivities of materials in the eastern zone given in Chapter IV account for the weak indication. It may be pointed out that the overburden is, presumably, quite shallow and that mineralization is practically absent at the eastern extremity of the indication in the eastern zone.

(4) The self potentials in the eastern zone were low. It was found by experiment that the electrodes used in this region when placed in contact showed such a potential difference as to diminish the values of the readings in this region considerably, and it is suggested from this experience that this condition should always be checked at intervals in order to ensure accuracy.

(5) The depth of 40 feet given for the conductor at the point S on profile IV, Plan No. 7, in the western zone, checks closely with the inferred thickness of the overburden of this point. Considering the known dip of the ore-body and the inferred thickness of overburden, the point S must be close to the northern boundary of the ore zone at the subdrift rock surface.

(6) The outline in plan of the position of the conducting body which is given in Plan No. 6 is an approximation somewhat roughly determined from the measurements made. Much more extensive measurements in detail would be necessary to justify a definite outline. It may perhaps be set forth by the exploring company that the definiteness of outline is based on wide general experience or on available geological information obtainable from a preliminary examination of the surface conditions. Although the intelligent use of these factors is not only justified but indeed highly desirable the degree of definiteness in the conclusions is difficult to appraise since they are not set forth in detail. The actual results of the measurements do not of themselves give sufficient information on which to determine a definite outline.

EXPLORATIONS CARRIED OUT BY THE FIELD PARTY OF THE SWEDISH AMERICAN PROSPECTING COMPANY OF CANADA, LIMITED

The following report (to the middle of page 70), together with a map, was submitted by this company. The report and illustrations (Plans Nos. 8 and 9) have been modified in accordance with the statement on page 51.

Introduction

TOPOGRAPHY

The one shaft of the mine is sunk on the eastern side of a gently sloping hill, which is covered by a thin layer of soil, except for small, bare patches where the rocks outcrop. East of the shaft, the eastern slope is very slight and the overburden, consisting mostly of sand, is apparently thick, though deeply cut in places by watercourses.

GEOLOGY

No information as to what was known of the geology on the property was given to us before the survey. However, a brief excursion over the surface of the property disclosed the following:

The rocks in the hill west of the shaft have a common, very marked, strike and dip (bedding), the strike being north 60 degrees west and the dip vertical or slightly to the north. Macroscopically, they look like volcanics, such as quartz-porphyry, rhyolite, andesite, and various kinds of greenstones.

On the property there are further fairly large glacial boulders of granite, indicating proximity to a granite area north of the property.

Close to the shaft, on its western side, there is evidence of a shearing along the line of strike, and about 100 feet east of the shaft there is, partly uncovered in a gulch, an outcrop of mineralization, apparently following the strike of the country rock.

Samples from the ore dump at the shaft show heavy mineralization of pyrite, sphalerite, chalcopyrite, bornite, and galena. One of the mine dumps contains a large mass of diabase.

THE ELECTRICAL SURVEY

General

The equipment arrived at Abana mine late in the afternoon of September 14. The reconnaissance work started on September 15 and was completed on the 18th. The 19th was used for putting together of apparatus, for demonstrations, and some transit surveys. On the 20th and 21st detail investigation was carried out over the indications found during the reconnaissance survey. As it was found that the next available train from Dupuy was on the 24th, before leaving the mine a demonstration of apparatus, methods, and theoretical principles, and some additional surveying work was carried out on the 22nd and 23rd.

Methods Employed

The fact of the presence of a large percentage of sphalerite (which is a non-conductor) in many of the ore samples from the mine dump was a contributing reason for choosing the equipotential method for the geoelectrical reconnaissance survey, as this method in this company's practice has previously proved more sensitive for the detection of poor conductors at moderate depths than electromagnetic methods.

The tracing of equipotential lines for investigation of electrical fields on the surface of conductors has been used by physicists for at least the last ninety years. This method has further been described fully in several papers on electrical prospecting for ore, and it may, therefore, be assumed that this method is fairly well known (*See* Chapter II).

By the equipotential method one is able quickly to find any distortion from the normal of an alternating electrical field applied over the ground to be prospected.

Indications of conductors found in the course of such a reconnaissance survey are, as a rule, specially investigated by detail work, for which the company have several electrical methods. In the course of an ordinary survey the principle is to apply, for reconnaissance, as well as for detail work, the method that is likely to give the best economical result under the special conditions at each property. (That is, maximum amount of information for minimum cost.) It might, for instance, well happen that under certain conditions the best method to employ for detail work would be trenching across the reconnaissance indications.

The method chosen for the detail work in this case, the *two-frame process*, is an electromagnetic method, comprising a complete investigation (direction, dip, amplitude) of the alternating electromagnetic field from various transmitting set-ups.

The set-ups used for the detail work at Abana mine were long, straight cables, grounded at both ends. An alternating current of moderate frequency sent through such a cable sets up an alternating electromagnetic field of cylindrical shape with the axis along the cable. Through electromagnetic induction from this field, as well as by concentration of the return current between the grounding points of the cable, secondary currents are caused to flow in any conductors in the ground, which are more or less parallel to the cable. The electromagnetic field from these secondary currents distorts the normal electromagnetic field from such a set-up, along profiles perpendicular to the cable, and investigations of the distorted field are usually made along these profiles, and by subtracting the effects of the known normal field at each point one is able to single out the secondary electromagnetic fields, and consequently to determine the location and depth of the axis of the secondary currents.

If a homogeneous conductor in the ground has any appreciable width, the secondary currents will concentrate along the side of the conductor that is nearest to the set-up. By using one set-up on each side of the strike of such a conductor, one is, therefore, able to determine its width with fair accuracy (greater the more pronounced the secondary field, and vice versa). If the conductor is not homogeneous, but has, within its mass, bands of much higher conductivity than its edges, then this method may not give the whole width of the conductor, but even in this case it gives a minimum width, the knowledge of which will be useful in many cases.

In addition to the two methods just described, which are very simple and allow very good speed at a survey, *compensator survey* of the electromagnetic field from a long grounded cable was demonstrated, though it was not employed for the actual survey.

By the use of a compensator, one can measure *amplitude and phase* of any component of the alternating electromagnetic field from a primary grounded cable or closed loop; one can also measure amplitude and phase of potential difference along profiles in an alternating electric field, applied between electrodes as described above.

The information about the *phase dispersion* in electrical and electromagnetical fields, that a compensator survey gives in addition to what equipotential and two-frame survey can give, will in many cases prove useful, and in other cases indispensable. In this case, however, it was found from the first test of the two-frame method for detail work, that the phase dispersion of our electromagnetic fields evidently was too small to be worth considering in the ordinary course of a survey. It may be noted, also, that the harmonics accompanying the fundamental wave made the method difficult of application.

THE RECONNAISSANCE SURVEY

The area chosen for the geoelectrical reconnaissance survey (equipotential method) extended at right angles to the strike 500 feet on each side of the shaft, and along the strike 600 feet west and 1,000 feet east of the shaft.

For the survey of this area two linear electrodes of about 1,700 feet in length were put out at right angles to the anticipated strike of the mineralization, and at a distance from each other of about 1,900 feet, the site of the mineralization outcrop mentioned above being roughly the centre of the rectangle thus enclosed.

About half a day was required to make up and try out this layout, and the remainder of the first day was used for demonstrations of the method. During the three following days the area of 38 acres, mentioned above, was covered by the reconnaissance work. This is only about half the normal speed of reconnaissance surveys by the parties of this company which, however, is explained by the delay caused by strong reactions from pipe-lines in the western part of the area, and by the necessity of putting equipotential lines close together over the indications obtained.

Result of the Reconnaissance Survey

The equipotential lines traced during the geoelectrical reconnaissance were surveyed with transit, and are plotted on Plan No. 8 accompanying this report.

Apart from disturbances that can be explained by the broken topography, and by the visible pipe-lines on the property, they disclose the following indications:

(1) One, which below is called the western indication, extending in the direction of the strike of the country rock, from a point some 30 feet northwest of the shaft to a point some 360 feet southeast of the shaft, as shown on the map. This indication is strong in its western part and gets weaker eastward, the depth to the current concentration apparently increasing eastward.

(2) One, which below is called the eastern indication, off set some 120 feet northeastward from the line of strike of the western indication, and extending, as shown on Plan No. 8, from a point some 500 feet east-southeast of the shaft, along the strike of the country rock out to the eastern boundary of the area which was surveyed. The depth to this current concentration apparently decreases eastward.

In the ordinary course of a survey the easternmost electrode would have been shifted northeastward and the reconnaissance continued in the same direction, for the purpose of locating possible extensions of the "eastern indication", and also in order to be able better to investigate the suspicious looking northeastern corner of the first layout.

(3) One, strictly local disturbance, was located about 130 feet southwest of the shaft, or some 50 feet northwest of the blacksmith shop, as shown on Plan No. 8. This indication, which is on a level part of the mine dumps, was interpreted as probably being caused by a piece of pipe or something similar, buried under the dump and dipping steeply east-northeast. Later information from the superintendent of the mine stated this to be the site of an inclined drill hole, which had some iron pipe casing left in its upper part.

(4) An area some 320 feet south of the ore-body outcrop was marked by dull minima (change in phase of the electrical field) and by some

abnormal curvature of the equipotential lines. This area was gone over with a few equipotential lines after the survey, with a second layout consisting of the same eastern electrode as in the first layout, but with another position of the western electrode. From what this incomplete second survey discloses, one may venture the assumption that part of the disturbance in this area probably is caused by a mineralized fault, striking roughly northwards in a direction towards the blacksmith shop. This area was not subjected to any complete or detailed survey. However, from the result of the geoelectrical investigation this area would at least be considered suspicious, and in the ordinary course of a survey it should have been more closely investigated.

THE DETAIL SURVEY

The two reconnaissance indications, mentioned above under (1) and (2), were investigated in detail by the two-frame electromagnetic method described above.

For this purpose two different set-ups were used, each one consisting of a long, straight cable, laid out to the north and to the south, respectively, of our indications as shown on Plan No. 8, and grounded at both ends.

The detail survey, which took two days, was carried out along nine profiles, four across the western indication, and five across the eastern indication, as shown on Plan No. 9. Over and on both sides of the concentrations of secondary current, the electromagnetic field was investigated at intervals of 15 feet.

Result of the Detail Survey

Over the western indication the electromagnetic detail survey gave the picture shown on Plan No. 9.

The conducting body that gave the reconnaissance indication, appears, from the result of the detail work, to have a total thickness of some 60 to 65 feet, and to extend some 350 feet southeast of the shaft. It further appears, as shown on the plan, to be banded, its southernmost band of some 15 feet thickness having less conductivity than the other bands and being separated from them by a band of still less conductivity.

The depth to the axis of current concentration in this body appears to be some 60 feet at the westernmost profile and some 100 feet at the eastern end.

The eastern indication turned out, by the detail survey, to correspond to a much poorer conductor than most parts of the western indication. This was not evident from the reconnaissance survey, which, however, is fully explained by the fact (well known from theory as well as from practice) that the electrical field investigated by equipotential survey, is distorted nearly as much by a conducting body of fair conductivity as by a similar body of very good conductivity.

On account of the weak secondary fields obtained by the detail survey over the eastern indication, the data given by this detail work must be expected to have much lower accuracy than the corresponding data for the western indication (as was pointed out above under " Methods employed ").

The result of the detail work over the eastern indication is shown on Plan No. 9. The conducting body appears to be banded, the best conducting part of it has a maximum thickness of some 80 feet, starts at a distance of some 650 feet east-southeast of the shaft, and continues southeastward to the boundary of the area surveyed. The depth to the current concentration in the best conducting part of the eastern body appears to be less than 40 feet.

Recommendations for Exploratory Work

The underground workings near the shaft should be extended on the 100-foot level at least 350 feet southeast of the shaft, and crosscuts should be driven to cross the entire width of the conducting body shown on our map as corresponding to the western indication.

A prospecting shaft should be sunk to a depth of 40 feet at a point 80 feet magnetic south of the entrance to the Pool Hall. From this shaft a crosscut should be driven 80 feet in a direction west 60 degrees south and at least 80 feet in the opposite direction. If commercial ore is found during this work, it should be followed up by drifting eastward and westward along the strike of the conducting body, shown on our map as corresponding to the western indication.

The disturbance mentioned above as (4) under " Result of the reconnaissance survey ", should be investigated by geoelectrical methods, and electrical prospecting should be applied for an extended survey northeastward from our eastern indication.

Conclusions

The following observations on the procedure and results which were presented by the Swedish American Prospecting Company of Canada appear to be warranted.

(1) A rapid but intensive preliminary examination of the surface conditions was made by the members of the party and the layout of the rectangular area for exploration was made in accordance with this study, the long side of the rectangle running north 60 degrees west, closely corresponding to the strike of the mineralization in the outcrop near the shaft.

(2) The position of the indicated conducting body given in the region west of the dyke corresponds very closely to the probable position of the ore-body at the depths of the axis of conductivity which are given by the company, viz., 60 feet in depth at the most westerly profile and 100 feet in depth adjacent to the west side of the dyke. These depths would place the axis of the conductor 20 to 25 feet below the probable position of the subdrift rock surface.

(3) The evidence obtained of a conductor in the westerly portion of the western zone was very definite. In the region adjacent to the dyke it was not so definite, especially with the electromagnetic inductive method.

(4) The banded western conductor as mapped corresponds approximately with the structure of the ore-body.

(5) In the eastern ore zone the position of the indicated conducting body corresponds roughly with the probable position of the ore-body in this region. The depth of the axis of conductivity is given as less than 40 feet. The evidence on which this conclusion is based is associated with a considerable margin of uncertainty. The evidence of the existence of a conductor which was given by the equipotential method was quite definite. The applied current was alternating and although it was of low frequency the low conductivity of much of the ore-body in this region and the presence of other adjacent conductive material as shown in Chapter VI probably account for the rather indefinite delineation of the location of the conductor.

(6) Attention is called to an area of " dull minima " 320 feet south of the ore-body outcrop and a recommendation is made for further geo-electrical investigation in this region. It is also of interest to note the form of the Schlumberger 100 millivolt equipotential curve in this region. Some diamond drilling has since been done in this locality, but did not disclose mineralization.

(7) It was impossible to make any underground electrical explorations at the time the Swedish American Company's party were in the region. It is highly desirable that tests should be made of the penetrability of low frequency alternating currents both when applied to the ground through point or parallel wire electrodes, and the penetrability of the electromagnetic inductive effect due to a large insulated loop with sources of alternating current such as were used by this party.

(8) The actual method of operation of the reconnaissance or equipotential survey and of the detail or electromagnetic survey are omitted from this report. The equipotential results are presented in equipotential lines in Plan No. 8. No calculations are entailed in the method and the significance of the lines is fairly evident.

In the detail survey none of the actual measurements are given nor are the methods of interpretation or degree of approximation presented. A brief outline of inductive methods in which low frequency currents are used is given in Chapter II, page 21, and the actual methods are given in more detail, though not fully, in a paper by Lundberg.[1] It is perhaps well to point out that it was necessary to determine the following elements:

(*a*) The " strike " of the plane containing the axis of the resultant magnetic field at arranged points along each profile.

(*b*) The dip from the vertical plane of the resultant magnetic field.

(*c*) The relative change in the vertical and horizontal components of the resultant field from point to point along the profile, and a reference of this change to the change that would exist if only the magnetic field due to the primary cable existed.

It is apparent that a margin of error exists in all these measurements, especially when the relative changes due to weak secondary fields are small. For example, telephone receivers were used to indicate balanced or zero

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[1] Am. Inst. Min. Eng., Tech. 98, New York meeting, 1928.

fields by minimal sound conditions, and in some of the measurements considerable lack of definition existed in the minima due to the presence of elliptical magnetic fields possibly from the presence of harmonics.

Further, in both surveys parallel wire electrodes were used. A considerable source of error may arise if these electrodes are not uniformly earthed throughout their length. To provide for this, short stakes attached at frequent intervals along the wire electrodes were driven into the ground. This precaution might ordinarily be expected to provide for fairly uniform earthing, but in this instance there was considerable difference in the resistivity of the surface layers of the ground at different points. Subsequent measurements by the observers gave stake resistances for short stakes ranging from 200 ohms to much more than 3,000 ohms, and special precautions might well have been taken to ensure uniformity of earthing. There was some evidence in the course of exploration of a disturbing effect such as might be expected from this cause, especially in the region east of the dyke.

The exploring company considered that this source of error can be met readily by extending the distance between the parallel electrodes. It would appear preferable to avoid introducing this source of error which may be done fairly readily and expeditiously rather than providing somewhat uncertain means of eliminating the disturbing effects subsequently.

Another possible source of disturbance was thought to be due to the position of the insulated cable which joined the parallel wire electrodes. It was considered of sufficient importance to check the results by transferring the insulated cable from the southern to the northern ends of the wire electrodes and repeating the measurements.

The interpretation of the results as depicted in plan must be considered, therefore, as approximately rather than definitely outlining the location of the conducting body. In particular, although the existence and general location of the bands of highest conductivity are indicated by the results of experimental measurement, the definiteness of outline, especially of these bands, which is presented, must, however, be considered to be based on the general experience and knowledge of the interpreters.

CHAPTER VII

CONCLUSIONS AND SUGGESTIONS

By L. Gilchrist and J. B. Mawdsley

As previously pointed out, the work upon which this report is based was of a limited nature. The report is in no sense a comparative study of the relative merits of the various geophysical exploration companies that so generously took part in the field work. The report is merely an attempt to help all who are interested to understand better this special phase of prospecting practice.

The field work by the parties of the three exploration companies concerned in this investigation, was carried out according to their usual custom when under a commercial contract, and the authors of this report assisted in these surveys. The parties of the exploration companies were always asked to make any measurements or demonstrations which they might consider to be of advantage in presenting their methods and in these respects no limitations were placed on the field parties.

It is emphasized in a section of this report that only mineral deposits which are distinctly magnetic or electrically conductive, can be located by these methods of exploration in their present state of development. The principles upon which the magnetic and electrical methods of prospecting are founded are the basis of magnetic and electrical theory. In the application of these principles to the peculiar requirements of prospecting many difficulties have been encountered; many have been overcome, but many yet remain to be solved. Mathematical formulæ are an integral part of these branches of physics and are, therefore, of very great importance in the carrying out of the geophysical surveys and in interpreting the results obtained. Considerable work of a fundamental nature yet remains to be done and it is obvious that continued research both by the various companies and by others will eventually improve apparatus and field technique and provide accurately applicable formulæ.

To carry out the geophysical surveys in the most efficient manner and to assure that the best results will be obtained, demand a knowledge as complete as possible, of the magnetic and electrical conditions present. This necessitates a careful study of the geology of the area and of the magnetic and electrical characteristics of the geological material present. Much of this information might, in many cases, be obtained from previous geological and geophysical work on the particular area, or from experience in similar areas.

It must be quite evident that both in the field and in the laboratories connected with these field parties there must be men highly trained along geological, geophysical (e.g., magnetic and electrical), and mining lines. All these men must be capable, and they and their assistants must be thoroughly reliable, to assure that the results of their labours are dependable and useful.

The geological investigation and the magnetic and electrical surveys carried out over the Abana mineral deposit show that the physical conditions existing there are complex and that, despite this complexity, the magnetic and electrical methods of exploration when used intelligently are feasible and productive of valuable results.

MAGNETIC METHODS

Magnetic methods have, in the past, repeatedly been of value in locating magnetic minerals occurring near or not far below the surface. The magnetic surveys carried out on the Abana with the ordinary dip needle and sensitive Schmidt balance gave definite indications of the presence of the magnetite-bearing dyke that intersects the Abana ore zone. The much greater sensitiveness of the Schmidt balance as compared with the dip needle was clearly shown and indicated that with it surveys could be carried out where the magnetic anomalies are much smaller than on this property. The dip needle survey indicated that the dip needle, although less sensitive, was an instrument whose sensitiveness was probably within the requirements of the case and that its use even for such comparatively weak magnetic anomalies as existed on this property would give results of value.

A magnetic survey would indicate the presence of a mineral which besides being magnetic might also be conductive and might have an appreciable effect on an electrical or electromagnetic survey.

The magnetic surveys clearly indicated that under the magnetic conditions existing at the Abana mine, the interpretation of the results is difficult without considerable geological assistance. The general direction and extent of the dyke could be readily indicated by magnetic surveys.

The information obtained by the magnetic surveys on the Abana gave no direct information regarding the ore-bodies, as these are non-magnetic.

ELECTRICAL AND ELECTROMAGNETIC METHODS OF EXPLORATION

Electrical and electromagnetic methods of exploration, although used for a much shorter time than the magnetic, have been of great value in locating hidden conductive mineral bodies.

The volcanics in which the Abana ore-bodies are found are electrically non-conductors having an average resistance of probably considerably greater than 10^{10} ohms per centimetre cube. Although containing a little of the magnetic mineral, magnetite, the diabase dyke that cuts the ore zone is also a very poor conductor having an average resistance of about 10^9 ohms per centimetre cube. Of the two developed ore-bodies lying, respectively, west and east of the diabase dyke, the western body was found to be the best conductor. It contains less of the non-conducting mineral sphalerite and more of the conducting minerals, pyrite and chalcopyrite, than the eastern body where sphalerite is present in large proportions. The average resistivities of, respectively, the western and the eastern ore-bodies are less than 4,000 and greater than 1,000,000 ohms per centimetre cube. The detection of the western body was also helped by the fact that the drift cover over that body is comparatively thin, varying from 0 feet to a maximum of 70 feet, whereas the drift cover over the eastern body is much greater, probably 75 feet or more, at its western end, but decreasing rapidly to the east. It is known that the western ore-body reaches the rock surface below the drift. This is believed to be true, also, of the eastern body, but it is possible that the top of the eastern ore-body does not reach the rock surface.

All three electrical methods used succeeded in obtaining strong indications of the existence of an electrical conductor in the region of the ore-body west of the dyke. All three field parties indicated its sub drift axis in plan and two delimited its width closely. (Swedish American and Schlumberger.)

The ore-body east of the dyke gave much smaller reactions to all the various methods used. The indications obtained by the high frequency method (Radiore) were so slight that no conclusions were based on them. The self-potential method (Schlumberger) and the resistivity method (applied direct current) (Schlumberger) gave weak indications of a conductor in the region of this ore-body. The resistivity method (applied alternating current) (Swedish American) gave somewhat stronger indications of the existence of a conductor in this region. Both of the two last-mentioned surveys only roughly agreed in the location of the indications and these in turn roughly agreed with the actual location of this ore-body.

Depth measurements on the ore-body west of the dyke were given by all three companies. The report of the Schlumberger and Swedish American companies places the top of the ore-body close to the geologically inferred position of the bedrock surface. The Radiore high frequency method gave what they term the electrical axis of the body and this was represented as being, generally, deep. Judging from the location of this axis and the disposition of the ore-body as known, it seems that in this case the depth determinations could hardly be considered as particularly significant or precise. The east end of this mapped axis extends a considerable distance beyond the east end of the western ore-body.

The work carried out on the Abana by the various companies indicates that the western body was relatively easy to locate by the methods used, whereas the eastern ore-body was near the limit of detection by nearly all the methods. The dimensions of the two bodies both in length and width are now known to be approximately the same, the eastern ore-body being somewhat larger. The conductivity of the western body is much the better, the depth of the top of this body is less than that of much of the eastern body and there are indications of weak conductors within the drift cover over the eastern ore-body. All these factors play a part, but probably the relative conductivity played the greater part in determining which of the two ore-bodies could be detected more easily.

The results of this investigation indicate that if the mineral bodies of the Abana lay at greater depths, but yet at shallow mining depths, say 300 or 500 feet, their detection and especially the detection of the eastern ore-body would be very difficult, if not impossible, except by more highly developed applications of the methods adopted.

None of the methods as used could give any idea of the relative assay values of the bodies indicated nor was any attempt to do so contemplated by the companies. The methods merely differentiated between good and poor electrical conductors. For instance, by the methods as used there was no way by which the drift-covered, poor conducting, but valuable, sphalerite-rich eastern ore-body could be differentiated from a body of equal conductivity composed of pyrite disseminated through volcanic rock.

As the various methods were tested only under a single set of conditions, those existing at the Abana, a comparison of their respective merits is not warranted. It is by no means uncertain, in fact it is quite probable, that under other conditions the methods used would have shown different relative values. It is very evident that a prospecting company using more than one field method and using them discriminatingly and combined with comprehensive study of the conditions, will be in a much more favourable position than a company relying on only a single process, for they will be better able to cope with the different conditions of different areas.

The employment of only one method is likely to give results whose interpretation may be quite misleading. When inductive methods are used, especially those that make use of high frequency primary currents, the information obtainable is very useful in a preliminary way, but the investigation should be repeated using primary currents of much lower frequency. Moreover, confidence in the interpretation of the results may be further increased by the employment of at least another auxiliary method that is non-inductive in character.

That a knowledge and appreciation of the geological conditions greatly speeded up the field work and improved the results was well brought out by the work of the various parties. For instance, the great advantage of knowing the probable strike of the conductive zones before the electrical layouts were made is obvious. If the parties had been given all available geological information disclosed by the mining operations, there is no doubt the results would have been more detailed and more valuable.

The present knowledge of the results of the various investigations in the region suggests a consideration of an advantageous method of procedure, assuming that there had been no previous explorations except that exploration which resulted in finding the outcrop of ore. Suppose all the geological and geophysical methods to have been made available before any underground mining operations had commenced, it is instructive to consider what might be the proper course to follow in exploring the Abana property both before and during mining development. The following course of procedure would have been advantageous. It is presented only as a suggestion; several modifications are possible.

(1) Obtain a knowledge of the geological conditions such as is presented in Chapter III.

(2) At the ore outcrop determine the magnitude of the self-potential difference from a distant point.

(3) Determine the magnetic conditions of the area with a dip needle or magnetometer.

(4) Proceed with an electrical or electromagnetic exploration in the western zone. The knowledge obtained by (1) to (3) would, evidently, be of considerable assistance in choosing methods. It would be also evident that one method would be insufficient.

(5) A drilling or trenching campaign, or the location of a shaft, or the subsequent drifting and other mining operations should be based on the knowledge that had been gained through the above preliminary works.

(6) Further electrical or electromagnetic exploration should now proceed in conjunction with mining operations. Underground as well as surface explorations would hardly fail to be of increased value if carried out under expert supervision. For example, much of the drifting and diamond drilling, especially after the dyke had been reached on the 300-foot level, would not have been done and the eastern ore zone could have been entered much more directly.

CHOICE OF ELECTRICAL PROSPECTING METHODS

As already stated, geophysical methods of exploration merely differentiate between geological formations of different physical properties. Therefore, an engineer considering the use of geophysical methods of exploration for the solution of an engineering or mining problem will always require a knowledge of the geological conditions present. The physical properties of the overburden, solid rock, mineral bodies, etc., will have to be determined or inferred by analogy with similar materials elsewhere, preferably in similar geological relationships. If the mineral body proves to be, or is inferred to be, a good electrical conductor as compared with adjacent geological material and if the mineral body is known or believed to be sufficient in quantity and not too deep to be detected from the surface, he might consider the possibility of using surface electrical or electromagnetic methods of exploration. He will then need a discriminating knowledge of these methods. He will have to weigh the cost of such methods and the results to be expected from them (the indication of the presence or absence of conducting bodies) against the cost of other methods of exploration and the results they promise. If he decides on the use of electrical or electromagnetic methods the choice of which method to use is admittedly a difficult problem. At this point and during the course of an investigation the exploration companies can at present go far to meet the trained engineer by being as open as possible regarding the technique used and the nature of the results that can be obtained by the methods used by them.

Properly trained persons capable of evaluating the various factors of a prospecting problem and qualified to guide the necessary geophysical exploration work are needed. The interest already displayed by various organizations and institutions promises that this need will eventually be met.

PART II

GEOPHYSICAL INVESTIGATIONS AT THE MAMMOTH CAVES, KENTUCKY, AND IN SUDBURY BASIN DISTRICT, ONTARIO

CHAPTER I

INTRODUCTION

In 1928 the Geological Survey, Canada, invited Geophysical Exploration Companies to employ their various methods on one and the same proving ground (the Abana mine) in order to form a just estimate of their possibilities. A report on this work by Dr. L. Gilchrist, Professor of Physics, University of Toronto, and J. B. Mawdsley, of the Geological Survey, forms Part I of the present volume.

In June and July, 1929, investigations were made by the Geological Survey, Canada, in co-operation with the United States Bureau of Mines which had conducted research work on applied geophysics in Colorado during the summer of 1927, and at Mineville, N.Y., and elsewhere, during the summer of 1928.

It is noteworthy that the art of geophysical prospecting is in Canada linked with the Geological Survey, and in the United States of America, with the Bureau of Mines. There is much to be said on both sides, as to whether applied geophysics is to be the handmaid of geology or of mining, but the matter need not be discussed here.

Co-operation between the two bodies was cordial and successful, and each party was given complete independence as to publication, and all results and information were available to those concerned.

The members of the parties in the field were: U.S. Bureau of Mines—Dr. F. W. Lee, Dr. J. H. Swartz, geologist, Mr. J. W. Joyce, Mr. E. V. Potter, assistants; Geological Survey, Canada—Dr. A. S. Eve, Dr. L. Gilchrist, Dr. D. A. Keys, Dr. J. B. Mawdsley, geologist; Mr. H. G. I. Watson, assistant.

The work was carried out: (1) At Mammoth cave, Kentucky, in order to obtain measurements underground, in a region free from conductors, of electromagnetic currents and waves produced on the surface of the earth.

(2) At the Abana mine, northern Quebec, in continuation of the work on the proving ground carried out in 1928.

(3) In Kentucky on the natural asphalt sands, in order to test the electrical resistance methods for the measurement of depth and thickness of deposits with a resistivity greater than the strata in which they are embedded. This is the direct converse of the search for good conductors in the earth.

(4) In Sudbury district at the Falconbridge mine, where magnetic methods and electrical methods could be checked against the results of a well-drilled and definitely located nickel-copper deposit. At this place the problem was direct and simple and the results were definite.

(5) At the Errington mine, Treadwell-Yukon Company, where copper-zinc-lead deposits occur within Sudbury basin. This area offers the most profoundly difficult problem yet faced by the geophysical prospector. The graphitic veins mimic the conducting ore-bodies, carbon distributed through the slates and tuff render the whole area at least as conducting as the "quartz-carbonate" containing the ores, and pyrite veins and crystals cause self potentials as prominent as that of the ore; moreover the whole region is covered with about 100 feet of glacial drift. Magnetic variations are readily measured and plotted, but they bear no relation to the valuable ores. Here we met for the first time an area of a type, happily rare, where we had to confess that, in the present state of our knowledge, geophysical methods were of small avail, and where the diamond drill under the direction of geologist and mining engineer was the sole guide to further discovery.

CHAPTER II

GEOLOGICAL ACCOUNTS

GEOLOGY OF THE MAMMOTH CAVE REGION

By J. H. Swartz

Geologically, Edmondson county, Kentucky, is noted for two things: its caves and its rock asphalt. The caves, of which Mammoth cave is the most famous, are confined to the eastern part of the county where a thick series of Mississippian (Lower Carboniferous) limestones lies at or near the surface of the ground. The asphalt is restricted to the western part of the county where the surface rocks are sandstones and conglomerates of Pennsylvanian (Upper Carboniferous) age.

Structurally the region is a simple one. The rocks are nearly, but not quite, horizontal, showing a slight monoclinal dip of from 30 to 50 feet to the mile in a northwesterly direction. Superimposed on this are a few small anticlines and synclines. Five faults with displacements of from 50 to 150 feet have been recognized in the county.

The rocks exposed in the area are given in the following stratigraphic column:

	Bed feet
PENNSYLVANIAN	
(1) *Pottsville formation.* Sandstone, conglomerate, rock asphalt, shale, a little coal..	600
(Marked unconformity)	
MISSISSIPPIAN	
(2) *Leitchfield formation.* Blue and grey shales, with some interbedded sandstone and limestone..	0–125
(3) *Glen Dean limestone.* Grey, more or less crystalline limestone, rarely oölitic, with thin shale partings..	30–70
(4) *Hardinsburg sandstone.* Brown, rather thin-bedded sandstone, often crossbedded..	30–40
(5) *Golconda limestone.* Grey, more or less crystalline limestone with thin shale partings; at base a thin shale series..	20–40
(6) *Cypress sandstone.* Soft, sparkling, brownish sandstone..	40–110
(Slight unconformity)	
(7) *Renault-Paint Creek* (=*Gasper*) *limestone.* Light grey, dense to crystalline, commonly oölitic limestone..	80–200
(Probable unconformity)	
(8) *Ste. Genevieve limestone.* Light to bluish grey, dense to crystalline, commonly oölitic, usually cherty limestone..	180
(Limestones 7 and 8 are sometimes united by authors to form the so-called "Mammoth Cave limestone.")	
(9) *St. Louis limestone.* Light to dark grey, cherty, usually finely crystalline limestone. In some cases petroliferous near base..	300

The numerous caves of the region lie beneath wide, mesa-like ridges which have been carved out of a long, narrow plateau. The plateau is capped by the Cypress sandstone, to whose erosion-resisting qualities it owes its existence. Beneath the Cypress is found the thick series of limestones noted above, which manifests its presence not only by the caves but also by the numerous sink-holes and underground rivers and the almost complete absence of surface streams. It is to this limestone that the caves owe their presence. Nearly insoluble in pure water, limestone is easily dissolved by water-containing carbon dioxide, a common constituent of all surface waters. Percolating along cracks in the limestone such water rapidly enlarges the cracks to crevices and the crevices to passageways, domes, and rooms. As Green river gradually lowered its level the higher passageways were abandoned and new ones cut at lower levels. Five levels of passageways have thus been formed in Mammoth cave. The lowest level is still being enlarged by Echo river, Styx river, and other underground streams, tributaries of Green river. One hundred and fifty miles of explored and partly explored passages are claimed for Mammoth cave, the largest cave of the region.

The surface rock at Mammoth cave, as elsewhere on the plateau, is Cypress sandstone. A thickness of 101 feet was measured for it above the "Corkscrew." This thickness increases to over 120 feet in front of Mammoth Cave post office, due to two factors: (1) a slight, local, southeasterly dip of the beds, and (2) the increasing elevation of the surface in that direction. The Cypress sandstone here is underlain by 130 feet of Renault-Paint Creek (Gasper) limestone. Beneath it in turn the Ste. Genevieve limestone extends to an unknown depth below Echo river. Mammoth cave is thus cut entirely from these two limestones.

Rock Asphalt

The most valuable economic deposit of the area is the rock asphalt found in western Edmondson county. The petroleum found elsewhere in the underlying Devonian and Silurian rocks appears to have broken through the capping of Chattanooga shale and migrated upwards, finally coming to rest in the sandstones of the Pottsville formation. These in turn were truncated by Green river as it cut downward. Oil seeps were thus produced, the volatile constituents of the petroleum escaped, and the tarry residues were left behind as coatings on the angular sand grains and fillings for the pore spaces in the sandstones. The bitumen content ranges from 0 to 12 per cent, averaging between 7 and 8 where commercially available.

The rock is quarried by open-cut methods. Simple crushing then makes it immediately available for surfacing roads, station platforms, etc. The rock is simply spread out over a limestone base, rolled twice with a five-ton steam roller, and thrown open to traffic. The angular sand grains pack tightly to make a hard, very resistant road surface. The thin, bitumen coatings of the grains form a perfect binder, giving the material its remarkable permanence and freedom from repairs.

Three companies are at present operating quarries in this area: the Kentucky Rock Asphalt Company, the Kentucky Natural Rock Asphalt Company, and the United Rock Asphalt Company. Their combined output approximates 2,000 tons a day.

GEOLOGY OF PART OF THE FALCONBRIDGE AND ERRINGTON PROPERTIES IN THE VICINITY OF SUDBURY, ONTARIO

By J. B. Mawdsley

Introduction

During the month of July, 1929, investigation in magnetic and electrical methods of prospecting under the joint auspices of the United States Bureau of Mines and the Geological Survey was carried out on the Falconbridge and Errington properties in the vicinity of Sudbury, Ontario. The two properties were chosen because they were believed to be suitable for the general magnetic and electrical prospecting problems to be investigated and for the purpose of ascertaining the suitability of these methods of prospecting for the two chief types of ores now being worked in the vicinity of Sudbury. The Falconbridge property was taken as an example of the pyrrhotite-rich nickel-copper deposits of the district and the Errington property as an example of the iron, zinc, copper, and lead sulphide deposits. The geology of the two deposits is quite dissimilar and they were found to differ markedly from one another in their magnetic and electrical properties. The Falconbridge properties lie 11 miles east and 6 miles north of Sudbury and the Errington property 13 miles west and 4 miles north of the same town. Both properties are easily reached over good roads about 15 and 17 miles in length, respectively. Railway facilities are now within a short distance of both properties and arrangements for the construction of spur lines to these properties are now in hand.

The Falconbridge Nickel Mines, Limited, and the Treadwell-Yukon Company, Limited, very kindly allowed the use of their properties for this investigation. Every available facility was given the investigation in the field by the superintendents of these two properties, Mr. E. Craig of the Falconbridge mine and Mr. V. C. Clauson of the Errington mine, Treadwell-Yukon Company. Various members of the technical staffs of these two mines assisted the work in many ways.

GENERAL GEOLOGY

The town of Sudbury lies about 3 miles south of the centre of the south side of what has been aptly called by Bell[1] the Sudbury basin. This square-ended, boat-shaped basin is 36 miles long by 16 miles wide. The long axis of the basin has a direction of about 30 degrees north of east and the square end of the boat-like basin is at the east end. The rim of this basin is an intrusive sheet 1 to 4 miles wide of norite and micropegmatite. The outer part of this rim is norite and the inner part micropegmatite with a more or less gradational change from one to the other.[2] This gradation from one to the other is by no means uniform and the change from one rock type to the other occurs usually within a comparatively short

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[1] Bell, R.: Geol. Surv., Canada, Ann. Rept., vol. V, pt. I, pt. F, p. 11 (1893).
[2] Coleman, A. P.: "The Nickel Industry"; Mines Branch, 1913, p. 33.

distance.[1] In places on the northwest side of the rim where the intrusive is comparatively narrow the micropegmatite forms the whole width of the outcrop.

The rock of the basic margin closely resembles and is related to diabase or gabbro. The feldspar of the rock is a basic plagioclase and much of the ferromagnesian mineral is orthorhombic pyroxene or its alteration products. Owing to the content of this type of pyroxene the rock is known as norite. The Sudbury norite in many cases contains a good deal of quartz. The micropegmatite contains a good deal more silica than a gabbro or norite and also in other respects resembles a granite. Besides quartz, both orthoclase and plagioclase feldspar are present, the latter in many cases intimately intergrown with quartz, the rock therefrom deriving its name of micropegmatite.

The central part of the basin is underlain by a series of sediments known as the Whitewater series and probably of late Precambrian age. This series is composed of four members which are believed to outcrop in elliptical belts concentric with the rim of norite-micropegmatite that intrudes the basal conglomerate member. These four sedimentary members dip inwards at generally low angles. Outside the norite-micropegmatite band, outside Sudbury basin, are a great variety of sedimentary, volcanic, and igneous rocks of Precambrian age and considered to be older than the Whitewater series, with the exception of certain areas of granite found along parts of the south margin of the basin and which are younger than the Whitewater beds.

The structure of the annular outcropping intrusive norite-micropegmatite mass is by no means certain. As far as known from diamond drilling and mining operations along the outer norite margin, the outer edge of the north part of the rim of intrusive rock dips inward at an average angle of probably about 45 degrees, and a section 7 miles long of the outer edge of the south part of the rim just north of the town of Sudbury dips inwards at an angle somewhat greater than 45 degrees and the edges of the two sections respectively east and west are vertical or nearly so, or even dip outwards. The south contact is, therefore, dyke-like in nature, whereas the north contact is sill-like. The dip of the inner, micropegmatite edge of the intrusive is not known, as no mining exploration or drilling has been done in that section.

Coleman considers that the igneous mass is a sill-like intrusion between the basal conglomerate member of the Whitewater series and the older underlying rocks, and that it differentiated on cooling into the two rock types. This theory is widely accepted. The structure, although probably largely of this nature, may in part be more complicated, as suggested by others.[2]

The ore-bodies of nickel and copper-rich sulphides are located along the outer margin of the norite or on masses of norite projecting into the older surrounding rocks. The norite everywhere carries a small proportion of pyrrhotite—an important constituent of the sulphide ores—and in many places the pyrrhotite content increases as the ore deposits at the margin are

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[1] Coleman, A. P., Moore, E. S., Walker, T. L.: "The Sudbury Nickel Intrusive"; Cont. to Can. Min., 1929, University of Toronto Press, Fig. 1, p. 32.

[2] Rept. Ontario Nickel Commission, 1917, p. 122.

approached, but this is not always the case, as for example on the Falconbridge property where the sulphide body is in contact with norite quite low in pyrrhotite.

Undoubtedly there is a genetic relationship between the norite and the sulphide ore, but what the exact relationship is, is still a matter of controversy. An able summary of the most important theories dealing with this problem has been offered by Roberts and Longyear.[1]

The iron, zinc, copper, and lead sulphide deposits found within the Whitewater sediments within the basin, and of which the Errington mine is an example, have a different origin. These sulphides are not related to the norite, but may be related to the micropegmatite or to a rock of similar chemical nature. Unimportant deposits of sulphide have been found close to the micropegmatite contact, which suggest strongly this probable relationship.[2]

Falconbridge Mine

Falconbridge Nickel Mines, Limited, control a tract of territory in Garson and Falconbridge townships along the norite contact near the sharp-pointed southeast corner of the boat-shaped basin. This contact is sinuous, but in the south parts of lots 10, 11, and 12, concession IV, Falconbridge township, it has a general east-west trend and along this part of contact the E. J. Longyear Company of Minneapolis, Minn., during 1916 and 1917, traced by diamond drilling a nickel-copper sulphide ore-body having a length of 7,500 feet. Much information was gathered by this company regarding the relationships of the ore-body and this has been ably summarized by Roberts and Longyear.[3] The writer has freely drawn on this article in the following section.

The 1,000-foot shaft of the Falconbridge mine is in the southwest corner of lot 12, about 150 feet south of the ore-body. About 3 miles a little south of west from this shaft is the Garson nickel-copper mine which has been a producer for many years.

The magnetic property of the Sudbury nickel-copper ore, due to its pyrrhotite content, has long been used in the search for these ore-bodies. The magnetic effect in the vicinity of what afterwards became the Creighton mine was noted by a surveyor in 1856.[4] These magnetic surveys have proved of considerable value and have been used systematically by at least two companies.[5] In the vicinity of the Falconbridge property an extensive magnetic survey was carried out under the direction of T. A. Edison and a test pit was started on what is now the Falconbridge property, but owing to quicksand did not reach bedrock. This test pit, which still can be seen, was sunk about 200 feet north of the Falconbridge shaft immediately over one of the widest sections of the ore-body.

In the vicinity of the Falconbridge mine shaft the surface is marked by a remarkable series of kettle-holes. They vary in size between 350

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[1] Roberts, H. M., and Longyear, R. D.: "Genesis of the Sudbury Nickel-Copper Ores"; Trans. Am. Inst. Min. Eng., vol. 59, pp. 44-50 (1918).

[2] Coleman, A. P.: "Nickel Industry"; Mines Branch, Dept. of Mines, Ottawa, 1913, p. 101.

[3] Roberts, H. M., and Longyear, R. D.: "Genesis of the Sudbury Nickel-Copper Ores"; Trans. Am. Inst. Min. Eng., vol. 59, pp. 27-56 (1918).

[4] Malcolm, Wyatt, and Robinson, A. H. A.: "Canada, Geology, Mines, and Metallurgical Industries"; Dept. of Mines, Ottawa, 1927.

[5] Coleman, A. P.: "The Nickel Industry"; Mines Branch, Dept. of Mines, Ottawa, 1913, p. 126.

feet and 1,300 feet in diameter, have steeply sloping, regular sides and attain depths of as much as 120 feet. They are separated from one another by very narrow ridges. They contain no ponds or muskegs, for their sides and bottoms are of gravel and coarse sand that allow the moisture that falls into them to drain away underground. East of this area of kettle-holes is a comparatively flat plain with a gentle slope to the southeast. The elevation of this plain is only slightly lower than that of the tops of the ridges separating the kettle-holes.

There are no rock outcrops in the vicinity of the shaft nor for a mile east of it on the level plain just mentioned. The drift cover has been found by drilling to be from 50 to 250 feet deep. In the area studied electrically, (*See* Figure 15), which is on a section of the flat plain just described, the thickness of the drift as found by drilling ranges between 98 feet and 156 feet.

The material forming this drift is coarse gravel and sand occasionally containing large boulders. That water action had something to do with its deposition can be seen in the walls of excavations in this material which often display fine examples of bedding.

The drift and the topography are due to the events of the last stages in the retreat of the Pleistocene ice-sheet which once covered this region, together with nearly all eastern Canada and adjacent sections of the United States. At the end of the Glacial period, when the waters from the melting ice were flowing south, blocks of ice must have been buried by outwash material from the great ice-sheet. The level plain was formed of deposits of such material and the kettles were eventually formed by the later melting of the buried ice blocks. On the floors of many of these kettles, whose sides show no dissection by stream action, are small mounds which probably represent the thin drift cover that once overlaid the ice blocks.

Drilling at intervals of 200 feet in an east and west direction near lot line 10/11 and concession line III/IV, a litle over half a mile east of the Falconbridge shaft, shows that the sulphide body over which the electrical work was carried out lies along the east-west contact between norite to the north and quartzite-greywacke of the Sudbury series to the south. The ore-body has a dip of 80 degrees to the north as indicated by two drill holes at one locality.

Roberts and Longyear[1] state that the quartzite-greywacke is composed of about equal proportions of quartz grains and altered ferromagnesian minerals. In some parts the quartz is in excess and the rock grades towards a true quartzite, whereas in others the ferromagnesian minerals predominate, giving a more typical greywacke. Some phases of the formation have a marked schistosity approximately parallel to the bedding which is stated to strike north 80 degrees east and to be vertical. A highly chloritized greenstone is in some places associated with the quartzite-greywacke. Greenstone occurs in the vicinity of the shaft, but is not known to be present near the area electrically surveyed, although it may occur there to the south of the ore-body in the strata not explored by diamond drilling.

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[1] Roberts, H. M., and Longyear, R. D.: "Genesis of the Sudbury Nickel-Copper Ores"; Am. Inst. Min., Eng., vol. 59, p. 33.

The norite intrudes the quartzite greywacke and greenstone assemblage. On the Falconbridge property the rock is of medium grain and granitic texture. Its composition is somewhat more acid than that of the norite usually found in Sudbury district. The feldspar is andesine (An_{40}) to oligoclase (An_{25}). The pyroxenes have been almost completely replaced by hornblende, uralite, chlorite, and serpentine. A small amount of olivine is present in some cases. Quartz usually forms an appreciable proportion of the rock and occurs as interstitial grains and as fine aggregates due to crushing. The quartz has the typical opalescent blue colour characteristic of the Sudbury norite. Considerable brown biotite is always present. Blebs of pyrrhotite and chalcopyrite are visible in the norite, but are seldom found more than a few hundred feet from the ore-body. It was noted by the writer that near the 1,000-foot level of the Falconbridge the contact between the sulphide ore and norite was sharp and that the adjacent norite carried not more than 7 per cent of the sulphides. Minor amounts of apatite, magnetite, and other accessory constituents are found in the norite.

The Falconbridge ore-body is 7,500 feet long and in the vicinity of the locality electrically investigated is dyke-like in form and dips about 80 degrees to the north. As indicated by diamond drilling the width of this part of the body at short distances below the rock surface is 7 to 45 feet. Evidence afforded by the 1,000-foot shaft and general considerations indicate that the body of sulphides is not only long horizontally, but probably also extends to considerable depths with a varying width.

The sulphide minerals comprising the ore are, in order of abundance, pyrrhotite ($Fe_{11}S_{12}$), pentlandite ($Fe\ Ni\ S_2$), and chalcopyrite ($Cu\ Fe\ S$). The relative proportions of the three sulphides vary, but on an average are probably about 80 per cent pyrrhotite, 14 per cent pentlandite, and 6 per cent chalcopyrite. A little magnetite and pyrite are present. The amount of sulphide in the ore-body varies between 25 and 56 per cent,[1] the balance of the ore being silicates usually in the form of rock fragments. These fragments are of the country rocks, norite, quartzite, and greenstone, and also of quartz. The fragments are rounded, subangular, or angular and the relations exhibited by them generally suggest that the ore-body has formed by replacement of the country rocks by the sulphides.[2]

The order of crystallization of the sulphides is pyrrhotite, pentlandite, and chalcopyrite. The pentlandite occurs as irregular masses and veinlets within the pyrrhotite. The pentlandite although slightly later or overlapping the pyrrhotite was closely associated with it and the two occur in a nearly constant ratio. The chalcopyrite was apparently somewhat later and is more abundant in rocky sections of the ore than elsewhere.

Errington Mine

The Treadwell-Yukon Company, Limited, are now carrying out extensive mining operations on their Errington mine property in the central part of the Sudbury basin. This property consists of nearly 7 square miles and its centre lies about 13 miles west and 3 miles north of the town of Sudbury. It comprises in concession VI, Creighton township, part of

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[1] Ibid., Figure 6, p. 39.
[2] Ibid., p. 37.

lot 2 and lots 4 to 10 inclusive and in concession I, Balfour township, lots 2 to 5 inclusive and the south halves of lots 6, 7, and 8. The property is easily reached by good roads from Sudbury and is about 5 miles southwest by road from Chelmsford station on the main line of the Canadian Pacific railway.

The company have sunk three shafts which are in a line and lie south of the main mineralized zone. The three shafts are known from west to east as No. 1, No. 2, and No. 3, respectively. The distance between Nos. 1 and 2 is about 3,700 feet and between Nos. 2 and 3 about 10,000 feet. Considerable underground work has been done from all three shafts. A considerable amount of diamond drilling had been carried out before the sinking of the shafts and a program of exploration is still in progress.

Trending east-northeast and forming the south half of the property are low, irregular, wooded hills of tuffs and on the north flank of this rocky area are situated the three shafts. North of the hills is the southern margin of the plain-like country which occupies the central part of the "basin." Traversing this plain a few hundred feet north of shafts Nos. 2 and 3 and continuing southwestward between shafts Nos. 1 and 2 is a southwestward flowing, meandering stream, 20 to 40 feet wide, entrenched about 20 feet below the level of the plain. There is a small rapid in this stream just to the east of shaft No. 1. In the vicinity of shafts Nos. 2 and 3 the mineralized zone lies below the valley of this stream.

The surface material of the part of the plain north of the shafts is an extremely fine, sandy silt containing considerable clay. This material was deposited in a post-Glacial lake. When saturated with water it is a veritable quicksand. Although dry and baked at the surface the water-table must be close to the surface. The drift where it overlies the mineralized zone south of No. 1 shaft is only a few feet or at most a few tens of feet thick. Northwest of No. 2 shaft its depth, as indicated by drilling, is 50 to 118 feet thick about 300 feet south of the mineralized zone. It is probably about 100 feet thick over the mineralized zone. Northeast of No. 3 shaft where most of the electrical work was carried out the depth of the drift is 45 to 130 feet. No detailed account of the geology in the vicinity of the mine has yet been published and the writer is indebted to the officials of the company for much of the following information and for elaborate surface and underground maps of the property.

The property lies wholly in the sediments within the igneous ring forming the Sudbury basin. As previously mentioned the inner margin of this ring is micropegmatite. The three shafts lie about 2 miles north of the inner contact.

About 800 feet north of No. 1 shaft and about 1,300 feet north of No. 2 shaft is believed to be the axis of a fault zone having a strike of 71 degrees. This fault is believed to be the east-northeast extension of what is termed the Cameron Creek fault which intersects the southwestern apex of the igneous margin of the basin some 13 miles to the west-southwest and there has a throw that is believed to amount to thousands of feet. On the Errington property the throw is believed to be much less and to be taken up in a series of parallel and closely spaced faults. The dip of the fault planes is believed to be steep, probably 80 degrees to 85 degrees, to the south-southeast, and the strata on the south side are believed to have moved upwards relative to those on the north side.

The fault zone is believed to be, approximately, along the contact between the overlying black Onwatin slates on the north and the underlying fine, dark Onaping tuffs. Both are members of the Whitewater series which is of late Precambrian age and occupies the central part of the Sudbury basin.

The Onwatin slates exposed on the property are fine-grained black slates with a fairly good cleavage which is usually nearly horizontal and is believed to closely parallel the bedding. The slates have a high graphitic content. An analysed sample from this property contained 2·92 per cent graphite.[1] Slips are common in these slates and are coated with graphite. The graphite content where slips are numerous must be much greater than in the above-mentioned sample.

The Onaping tuffs seen on the property are in part fine grained and where these are slaty-looking they can not be distinguished from the Onwatin slates. Coarser phases have visible fragments of volcanic rocks in a fine-grained, dark matrix. The graphite content of these rocks as a whole is not as high as that of the slates. In the vicinity of the fault zone what are believed to be tuffs contain white specks, a millimetre in diameter, of calcite or siderite, which, probably, were produced by mineralizing solutions that entered the fault zone. Bedding is difficult to detect. North of No. 3 shaft the rocks are sheared along planes striking parallel with the fault zone and dipping about 60 degrees east-southeast.

The mineralized zone has been traced the length of the property and lies along the fault zone. The mineralized zone is sinuous and is in the form of irregular bands that are of varying widths and commence and end in an ill-defined way. The finding and development of the ore-bodies in the mineralized zone is a difficult matter.

The ore-bearing zone consists of extensive quartz and carbonate mineralization in which sulphides occur both disseminated and in solid bodies of various irregular shapes. The gangue minerals quartz and carbonate form a considerable portion of the zone, although shreds and fragments of the country rock are common and graphite is nearly everywhere present. The chief sulphides are pyrite, sphalerite, and galena. A little pyrrhotite is occasionally present. The relative amounts of the various sulphides and the total amounts of sulphides vary considerably in the different ore-bodies.

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[1] Coleman, A. P., Moore, E. S., and Walker, T. L.: "Sudbury Nickel Intrusive"; University of Toronto Studies, Geol. Ser. No. 28, p. 39 (1929).

CHAPTER III

INVESTIGATIONS IN APPLIED GEOPHYSICS

RADIO AND ELECTROMAGNETIC WAVES AT MAMMOTH CAVE, KENTUCKY

By A. S. Eve and D. A. Keys

The problem of the penetration of electromagnetic waves through earth and rocks is of both scientific and practical interest. All the so-called induction methods of geophysical prospecting involve the use of alternating current of various frequencies produced in a loop, either horizontal or vertical, near the earth's surface. The effects of this electromagnetic field, whether of an induction or of a radiation type, have to pass through the earth and stimulate the conducting ore-body. These secondary effects have in turn to pass back to the surface where they can be detected or measured by a suitable receiving coil, often with the aid of an amplifier, and galvanometer, or head phones.

The rate at which the electromagnetic disturbances are absorbed by the earth, on their double journey, must necessarily have a profound influence on the intensity of the final reception by the observer. The problem is in some cases a purely mathematical calculation using Maxwell's equation. The absorption coefficient depends upon: (1) the frequency of the alternating current; (2) the conductivity of the earth and rocks; (3) the dielectric constant; (4) the magnetic permeability.

It is, however, often difficult to assign correct values for these three quantities and the figures obtained from laboratory measurements may differ widely from those assignable to rocks in situ.

There is a much greater difficulty in the fact that the distances used in geophysical prospecting amount to a few hundred feet, whereas the wave lengths of the radiations are often measurable in thousands of feet or even in miles. Yet the mathematical calculations involve the stipulation that the distance from the source shall exceed several wave lengths. Under such conditions it is wise to turn to experiments. Indeed some research work has been carried out by the United States Bureau of Mines[1] (*a*) at their coal mine near Pittsburgh,[2] (*b*) in Caribou Mine, Colorado. On two separate occasions combined efforts have also been made in the Mount Royal tunnel by the Canadian National railway, the Canadian Corps of Signals, and McGill University, in order to ascertain the extent to which radio waves can penetrate rocks. These experiments have always had a dubious interpretation owing to the presence of pipes, cables, and rails which might act as conveyors or re-radiators. Certainly the results proved

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[1] Tech. Paper, 434, Dept. of Commerce, U.S.A.

[2] Proc. Inst. Radio Engineers, vol. 17, No. 2 (Feb., 1929).

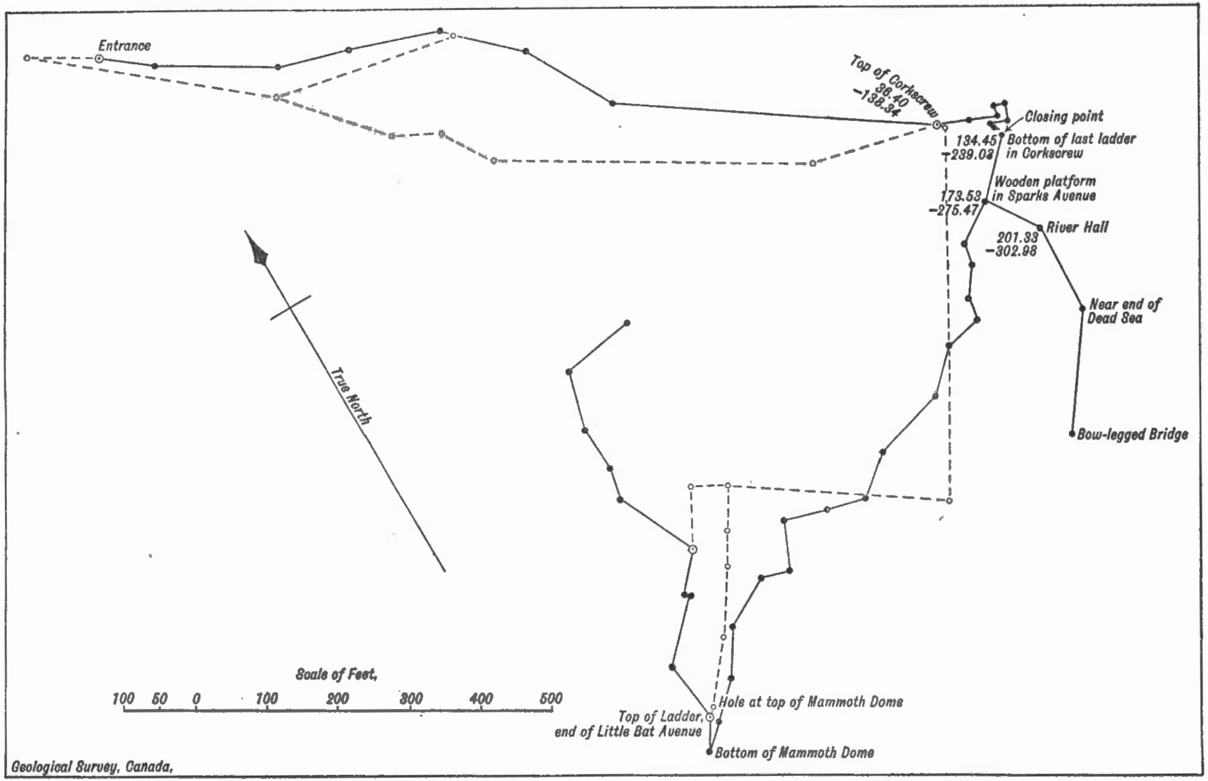

FIGURE 9. Surveyed lines, Mammoth cave, Kentucky. Solid lines are surveyed lines in the cave, stations thereon are marked by black dots. Pecked lines are surveyed lines on the surface, stations thereon are marked by circles. Depths, in feet, of stations below the entrance to the cave are written thus, 201·32; depths below the surface, thus, −302·98.

that short waves (30 to 40 metres) could not enter the tunnel more than a few hundred feet either through the rocks, or by the entrances, or along the various conductors. On the other hand it was possible to detect without difficulty, and throughout the tunnel, the longer waves of broadcasting range or from transatlantic signal stations. But the method of entry to the tunnel was under dispute.

It was, therefore, decided to search for a mine, tunnel, or cave entirely free from all metallic conductors. The quest was a difficult one, but finally Dr. Lee visited the Mammoth cave, Kentucky, and there found an entire absence of rails, wires, or pipes, except for a short telephone wire which the manager was good enough to remove. In this large cave or series of caves there were only a few short lengths of iron hand-rails in the region which was selected for work in June, 1929. A survey was immediately made, and in Figure 9 is a diagram showing the essential places and their depths below the surface.

It was thus possible to place loops directly above a station 300 feet underground, using coils for detectors with amplifiers, rectifiers, and galvanometers. It was known from the resistance experiments that the resistivity of the overlying sandstone and limestone is about 10,000 to 100,000 ohm-cm., and that the permeability is close to unity, but it was necessary to be content with an estimate of the dielectric constant[1] as about 8, for the limestone and sandstone were rather dry. The calculations and results are set forth in Appendix 1.

Throughout this work an endeavour was made to attack and solve different definite problems and it will make for clearness in this report to state each problem, to quote the method used, the apparatus employed, and the answer to the problem, at least in the present state of our knowledge, with suggestions as to future investigation.

Problem I

TO WHAT EXTENT DO RADIO (WIRELESS) WAVES OF BROADCASTING FREQUENCY PENETRATE INTO THE EARTH?

(a) Loop Reception

It will be understood that the degree of penetration must involve: (*a*) the intensity of the entering radiation, (*b*) the thickness of the rock or earth penetrated, (*c*) the sensitiveness of the receiving apparatus. It is, therefore, necessary to introduce the idea of an absorption coefficient of which the definition will be found in Appendix II.

In the present problem, however, we need not trouble about any exact mathematical considerations.

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[1] Ambronn, V.: "Elements of Geophysics"; transl. Cobb, McGraw-Hill, 1928.

The sources available were:

Station	Place	Direction	Distance in miles	Frequency in kilocycles	Wave length in metres
W.L.W.	Cincinnati	N. 36° E.	200	700	429
W.H.A.S.	Louisville	S. 10° W.	90	820	366
W.S.N.	Nashville	N. 36° E.	100	650	461

For reception a No. 26 Portable Radiola super-heterodyne six-tube set was used, and bearings were taken of the source with the small loop which is part of the apparatus. The directions obtained were not at all satisfactory. In a wooden annex of the Mammoth Cave Hotel was found for Nashville 31 degrees, 42 degrees, 64 degrees, east of north, with a mean of 46 degrees as against 36 degrees true bearing. The directions found in the cave were even more erratic, and have no significance, but those for Cincinnati (W.L.W.) are here placed on record.

True bearing	N. 36° E.
Hotel, wooden annex	N. 63° E.
Cave, entrance steps	N. 54° E.
15 feet outside iron gate	N. 12° E.
15 “ inside “ “	N. 3° E.
115 “ “ “ “	N. 17° W.
	N. 51° E.
215 “ “ “ “	N. 63° E.
315 “ “ “ “	N. 52° and 38° E.
Mammoth Dome	N. 85° W.
100 feet nearer cave entrance	N. 80° E.
200 “ “ “ “	N. 38° W.
250 “ “ “ “	N. 45° W.
280 “ “ “ “	N. 2° W.
330 “ “ “ “	N. 35° E.

It would be better on a future occasion to have a larger and separate loop instead of the small loop attached to the receiving set for the determination of bearings.

It should be stated that on July 21, 1923, the *Louisville Courier* obtained radio reception about 800 feet within Mammoth cave, and there is a tablet in the cave recording the fact. But reception was then achieved with the aid of a long wire laid into the cave from the entrance. With the portable set and loop the broadcasted music or speech was traced to 515 feet within the cave, where the overburden was about 100 feet; after that no signals could be obtained. After proceeding far into the cave to Mammoth Dome and near the top of it reception was regained, audible to those present by loud speaker, with about 70 feet of overburden. Reception was then traced from the Dome back towards the entrance of the cave for 300 feet. It should be stated that above the Dome is what geologists call a “ sink ”, so that the surface water drains into the Dome, while the sides of the sink rise fairly rapidly so that the overburden increases to 150 feet at a distance of 300 feet from the Dome, and no doubt the waves were coming through the sides of the sink to us underground near the top of the Dome.

Mammoth cave has two entrances about 2¾ miles apart, but 6 or 7 miles apart by the routes in the cave. The exits are sealed by Echo river and by the Styx. There is no question whatever that the broadcasting waves came through the earth, and not by 1,000 feet or more along tortuous passages and down the narrow winding "corkscrew". If such had been the route the radio waves would have been intercepted, and the writers failed to do so.

(b) *Aerial Reception*

At River hall, about 1,200 feet from the mouth of the cave and 303 feet underground, an aerial was suspended on wooden poles, mainly along the axis of the tunnel or cave, and the farther end was connected to Bow-legged Bridge about 300 feet away. A short "ground" was made to a spike driven into the moist floor of the cave, and a much longer "earth" was joined to some iron railings around the Dead Sea. Messrs. Joyce, Barlow, and Kydd gave three turns of the aerial round the circumference of the loop of the portable set so as to secure close coupling. At night they thus secured admirable reception with loud-speaker broadcasting of speech and music from Cincinnati and from Nashville.

Indisputably these signals came through 300 feet of sandstone and limestone. The next night these observations were repeated, and a move made to Echo river, reputed to be 350 feet underground. Using a poorer antenna, for local conditions were not easy, feeble but certain reception of the above stations was again obtained.

Problem II

THE QUESTION OF THE PENETRATION OF WAVES OF LENGTH ABOUT 17 TO 20 THOUSAND METRES (15 KILOCYCLES)

For waves longer than the broadcasting the party were dependent upon code signals from about six stations sending messages to ships or across the Atlantic. The signals are easy to pick up and the stations can be quickly recaptured, but it is not so easy to identify them. Reception was made both above and below ground on a loop with a Model RE Low Frequency Receiving Equipment, consisting of an antenna coupling unit, a radio frequency amplifier, a low frequency receiver, a tuned audio amplifier, and a vacuum tube voltmeter for measuring signal strength. The signals were clear enough to hear, but their intensities were hard to measure, partly owing to static. A three turn square loop was made with each side 4 feet long, and connecting this with the receiving apparatus a direction was obtained of about north 63 degrees east (i.e. 63 degrees east of north) both above and below ground, suggesting a source on Long Island. It is known that wireless waves in the earth should theoretically be of a complex character, having elliptical polarization.[1] The wave front in the earth drags behind the wave front in the air; underground the vector is revolving like the hand of a clock, not, however, describing a circle but an ellipse, with its plane in the direction of the advancing signal. Measurement was not made of the tilt of the wave or the ratio of the axis major to axis minor, but certainly this work should be attempted on some future occasion, for the theory has not yet been checked by experiment.

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[1] *See* Fleming, "Principles of Electric Wave Telegraphy and Telephony", 2nd Edition 1910, p. 741, or Dr. J. Zenneck, Annalen der Physik, vol. 23, p. 846 (1907).

Reception was better on a vertical loop, properly orientated, than on a horizontal loop; and the height from the slightly damp floor of the cave was a factor in the intensity of reception. It was, however, clear that the longer waves (15 kilocycles) like the broadcasting signals (700 kilocycles) penetrated the earth to more than 300 feet and that these waves came strongly to the observers, not through the entrances of the cave, and not through conductors, but through the sandstone and limestone overlying the cave.

This main point was then settled beyond further question.

The following table may be of service for reference.

——	Wave length in metres	Frequency
Short waves	30	10,000 kilocycles
Broadcasting	300	1,000 "
Low radio frequency	10,000	30 "
	30,000	10 "
Audio "	600,000	500 cycles

(Wave length in metres) × (Frequency in kilocycles) $= 3 \times 10^5$

Problem III

TO COMPARE BY ACTUAL MEASUREMENTS THE RELATIVE INTENSITIES OF THE EFFECTS, 300 FEET DOWN IN THE CAVE, FROM A CURRENT IN A HORIZONTAL LOOP ABOVE GROUND, USING FREQUENCIES 20, 30, 40—100, 110 KILOCYCLES

A loop of ten turns, 100 feet in diameter, of well-insulated cable was laid on the ground 303 feet above River hall in the Mammoth cave. It was found desirable to use but one turn of this coil which was excited with an oscillating set with electron tubes or valves, tunable with capacity and inductance. The receiving set was that used in Problem II. A coil of three turns, rectangular, 40 by 10 feet, was placed on the floor of the cave and connected to the receiving apparatus. The best results were obtained with one side of this loop grounded. The first day the results were remarkable and read as follows:

Kilocycles	15	35	65	95	108
Mean reading	1·21	0·61	0·1	0·76	70·9

It was obvious to a listener on head phones, as was shown, too, by the recording microammeter, that the 15 and the 108 kilocycles were surprisingly strong signals compared with those of the intermediate frequencies, and it was quite necessary to follow up this remarkable result.

In order to avoid resonance effects in the receiver "untuned" measurements were made of the continuous wave signal. It was necessary also to calibrate the receiving instrument above ground using a pick up from the oscillator. The various quantities to observe were: (1) the frequency of the current in the loop; (2) the strength of the current in the loop above ground; and (3) the microamperes indicated underground. The value is then determined and the whole series of observation may be illustrated by a table, and by a graph in Figure 10.

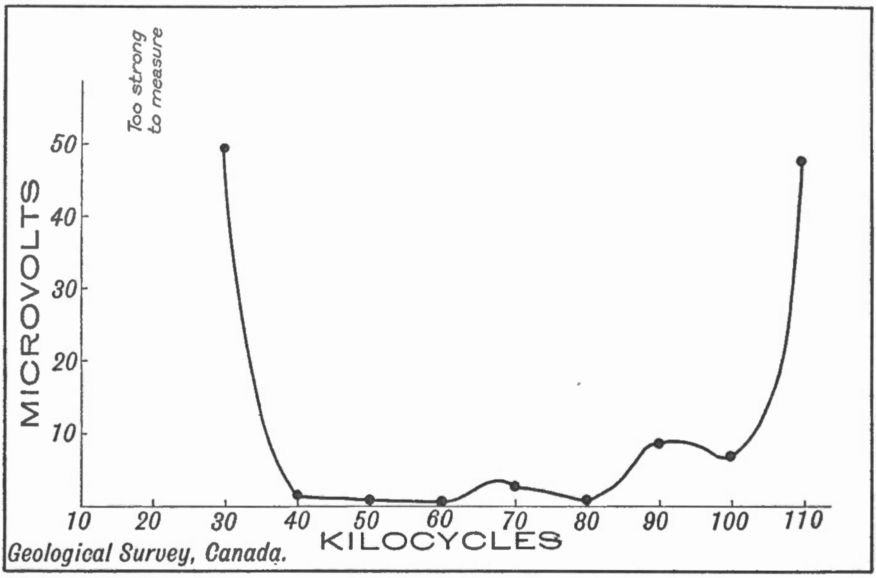

Figure 10. Graph illustrating relative intensities, for different frequencies, of signals from loop above ground, observations made 300 feet underground.

TABLE I

Frequency in kilocycles	Current on loop in amperes	Reading under-ground	Reading as per 1 amp. in loop	Cali-bration factor	Microvolts in cave
30	0·47	1·41	2·66	18·5	49·3
40	0·54	0·025	0·046	35·4	1·62
50	0·52	0·03	0·059	11·2	0·65
60	0·51	0·04	0·074	3·69	0·27
70	0·36	0·11	0·306	7·34	2·28
80	0·20	0·05	0·166	5·52	0·94
90	0·26	0·36	0·137	6·11	8·4
100	0·23	0·53	2·30	3·01	6·9
110	0·22	0·40	1·82	26·7	48·0

We then used a triangular vertical loop and measured reception above ground and repeated the above series, receiving on a 24 turn, 4-foot square vertical coil 55 feet from the triangular loop. The final values assigned were, for reception above ground.

Kilocycles	Above ground	Kilocycles	Above ground
20	too small	70	101
30	"	80	61
40	"	90	11
50	2·28	100	60
60	29·5	110	1068

These rather erratic results (*See* Figure 11) are not wholly satisfactory, and we could not repeat them as our valves had come to an untimely end by various unavoidable disasters. The conclusions may, however, be drawn—

(I) Underground, the response to 110 kc. was 12·3 times the average of 50, 60, 70, 80, 90, 100 kc.; namely 48/3·9. Above ground it is 11·6 times, namely 1068/92. This good response to 110 kilocycles is, therefore, a function of the receiving instrument, and has nothing to do with selective absorption by the ground.

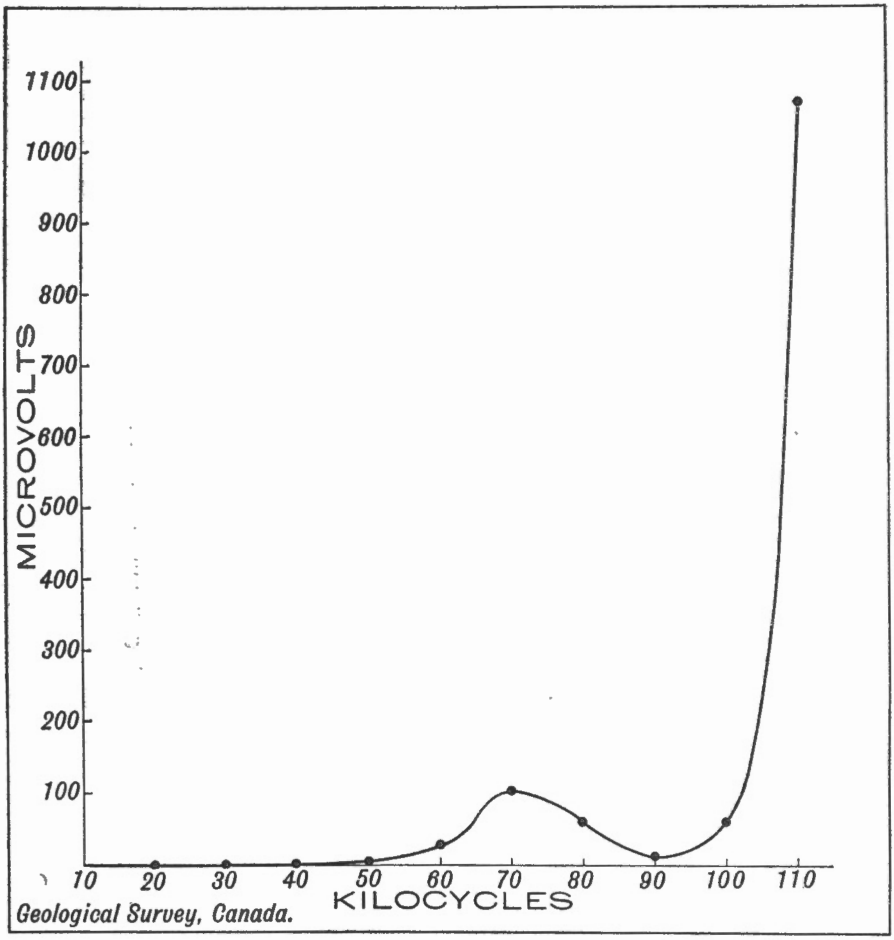

Figure 11. Graph illustrating relative intensities, for different frequencies, of signals from loop above ground, observations made above ground.

(II) The booming strong signals underground on 20 and 30 kc. relative to higher frequencies, were not obtained above ground, and there is here a strong suggestion of selective absorption.

(III) Calculations made with the formulæ set forth in Appendix II, however, indicate that for permeability 1, resistivity 10^5 ohm-cm., dielectric constant 8, the percentages transmitted for various frequencies on passing through 100 metres should be those set forth in the right column below.

TABLE II

Wave length in metres	Frequency	Kilocycles	Attenuation factor	Percentage transmitted
30	10^7	10,000	$1/10^7$	Practically none
300	10^6	1,000	1/500	Half of 1 per cent
3,000	10^5	100	1/7·4	13½ "
20,000	15,000	15	1/2·15	47 "
30,000	10,000	10	1/1·87	53 "
600,000	500	½	1/1·01	99 "

It is here seen at once that 10 kilocycle waves should traverse the earth four times as well as 100 kilocycle waves, and it is possible that the strong effects in the cave with 20 and 30 kilocycles were due to this natural superiority, not to any selective absorption.

It is clear that these experiments need repetition with a wider range of frequency, say 5 to 150 kilocycles. This will require careful planning and skilful work, both in generator and oscillator, and also in the receiving measuring instrument.

The work this year was to some extent of a pioneer character.

Problem IV

TO INVESTIGATE THE PENETRATION OF ROCKS USING ALTERNATING CURRENT OF AUDIBLE FREQUENCY (500 CYCLES A SECOND) IN A HORIZONTAL LOOP ON THE GROUND

A 500-cycle generator was driven by a gasoline engine, and the alternating current, about 2·35 amperes, was passing round all the ten turns of the horizontal loop (100 feet diameter) placed on the ground 303 feet above River Hall. Observations were taken with the so-called Pittsburgh coil,[1] 2 feet by 3 feet, 400 turns, mounted on a transit tripod, so that azimuth and dip could be measured. With this apparatus it was possible to verify the survey of the cave, as the coil, when exactly below the centre of the loop, would give no signal to the headphones when the coil was upright and rotated about a vertical axis.

Reception was good and loud when the coil was properly orientated, and there was no need of an amplifier. The coil was next taken to a station 12 feet short of Mammoth Dome, about 800 feet horizontally from River Hall, and the direction of the centre of the surface loop was read as north 67 east, while the true direction was north 68 east. Indeed a coil of this character could be used for surveying purposes to replace the compass when

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[1] Tech. Paper 434, Dept. of Commerce, U.S.A. (p. 5).

local magnetic disturbances prevent the use of a compass survey. Bearings are better taken with minima rather than maxima receptions. At Mammoth Dome, 900 feet from the centre of the loop in a straight line, we were able to hear the loop signals without difficulty and using no amplifier.

Clearly, with only a coil and headphones used underground, it would be easy to read code messages from a loop laid on the surface, with a few amperes passing through it. The question of signalling back to the surface is a more difficult one, however. Both theory and experiment indicate clearly enough that the audio-frequency electromagnetic effects, whether we deem them due to inductance or radiation, pass through great thicknesses of rock with little or no absorption (*See also* Table II).

Reception in the cave was also observed with vertical loops employed above ground. The magnetic field strengths H, 300 feet underground, were calculated in gauss, as explained in Appendix I. The following is a summary:

TABLE III

Position	Shape	Number of turns	Side	Diameter	Current amperes	Area sq. ft.	H in gauss
Vertical.........	Square..........	24	4·4 feet	....	6·0	18·36	$3{\cdot}1 \times 10^{-7}$
Vertical.........	Triangular......	8	20 "	....	7·2	120	$8{\cdot}5 \times 10^{-7}$
Horizontal......	Circular........	10	....	100 feet	2·37	850	$4{\cdot}2 \times 10^{-4}$

This calculation is for direct current, whereas alternating current was actually being employed, but the received signals corresponded well with the magnetic intensities in the right column. The coefficient of absorption is so small that it would be hopeless to attempt to measure it using so small a thickness as 300 feet.

Appendix I. The Magnetic Field in the Cave below a Small Loop on the Ground (a) Loop Horizontal (b) Loop Vertical

A loop far from the observer may be regarded as a small magnet of moment $\frac{1}{10}$ AI, where A is the product of area and number of turns, and I the continuous current in amperes. The magnetic intensity from such a loop placed (*a*) horizontally on the ground is, therefore, $\frac{2AI}{10z^3}$, and (*b*) vertically, $\frac{AI}{10z^3}$, where z is the depth directly beneath in the earth.

If the horizontal loop is large as compared with the depth, then the magnetic intensity is given by

$$\frac{2\,AI}{10} \Big/ (r^2 + z^2)^{\frac{3}{2}}$$

where r is the radius of the loop.

These relations have been used in obtaining the right-hand column of Table III.

The horizontal loop was also used to calibrate the Askania vertical magnetometer. When the current was 0·237 amperes the deflexion on the magnetometer placed at the centre of the loop was 2·7 divisions, and hence 1 division corresponded to $36 \cdot 3 \times 10^{-5}$ gauss or 36·3 gamma.

At a depth of 300 feet below the ground the magnetic field would be much less, or about $\frac{1}{200}$ of the above, and, therefore, beyond possible detection of the magnetometer.

Appendix II. On the Absorption of Radio Waves in Rock, and the Calculation of Their Attenuation, in the case of Horizontal Waves going Vertically Downwards

R. de L. Krönig in his article on the " Quantum Theory of Dispersion in Metallic Conduction "[1] clearly recapitulates the old classical theory due to Maxwell.

In the usual notation, we have

$$\operatorname{curl} E = -\frac{1}{c}\dot{B};\ \operatorname{curl} H = \frac{1}{c}(\dot{D} + 4\pi I)$$

$$\operatorname{div} D = 4\pi\rho;\ \operatorname{div} B = 0$$

while $D = \epsilon E,\ B = \mu H,\ I = \sigma E$

hence $\operatorname{curl} \dot{E} = -\frac{\mu}{c}\dot{H}$

$$\operatorname{curl} H = \frac{1}{c}(\epsilon \dot{E} + 4\pi\sigma E)$$

$$\operatorname{div} E = 4\pi\rho/\epsilon$$

$$\operatorname{div} H = 0$$

The solution for a plane wave gives for the electric vector along Ox

$$E_x = F e^{-\frac{2\pi\nu K z}{c}} \cos\left(2\pi\nu\left(t - \frac{nz}{c}\right) + \gamma\right)$$

with a similar expression, but a different γ, for the magnetic intensity along the y axis. The advance of the wave is along the z axis, vertically downward. F denotes an amplitude.

This report is solely concerned with the attenuation factor $e^{-\frac{2\pi\nu K z}{c}}$ Here K is defined by

$$K^2 = \frac{\mu}{2}\left(\sqrt{\epsilon^2 + \frac{4\sigma^2}{\nu^2}} - \epsilon\right)$$

Certainly the permeability μ is almost equal to 1; and $\varepsilon = \frac{10}{4\pi}$, where the dielectric constant has been taken to be 10, following Ambronn, so that $\varepsilon = 0 \cdot 80$ in Heaviside units.

The resistivity $\rho = 10^5$ ohm-cm.
$= 10^{14}$E.M.U.

as found for the rocks in situ, so that the expected conductivity is $\sigma = 10^{-14}$, but electrostatic units have to be used and, therefore, $\sigma = 9 \times 10^{20}/10^{14}$, and this is the chief snag in the calculation.

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[1] Proc. Roy. Soc., ser. A, vol. 124, A 794, p. 409.

For a frequency of 10^7 cycles per sec. so that $\lambda=30$m. we get

$$K^2 = \tfrac{1}{2}\left[\sqrt{\cdot 64 + \frac{4\times 81\times 10^{12}}{10^{14}}} - 0\cdot 80\right]$$

so that $K=0\cdot 765$

Whence the attenuation factor becomes

$$e^{-\frac{2\pi\times 10^7\times \cdot 765\times 10^4}{3\times 10^{10}}}, \text{ or } \frac{1}{10^7}$$

and this is the fraction that gets through 100 metres; practically nothing, as our Mount Royal Tunnel experiment showed.

Similar calculations for each frequency have been made and the results are set forth for $z=100$ m$=10^4$ cm.$=328$ feet.

Dielectric constant.........	10
Permeability....................	1
Resistivity........................	10^5ohm-cm.

TABLE IV

Wave length in metres	Frequency	Kilocycles	K	Attenuation per 100 m.	Percentage transmitted
30..........................	10^7	10,000	0·765	1/10^7	None
300..........................	10^6	1,000	2·93	1/500	Half of 1%
3,000..........................	10^5	100	9·5	1/7·4	13·5%
20,000..........................	15,000	15	24·5	1/2·15	47
30,000..........................	10,000	10	30	1/1·87	53
600,000..........................	500	½	134·5	1/1·01	99

In Appendix III will be found Dr. L. V. King's statement for induction between loop and coil, which involves distance and, therefore, differs from a vertical plane wave as given below.

For 10 kilocycles he finds 50 per cent transmitted through 100 metres; but for 100 kilocycles, only about 1 per cent.

These calculations are beginning to throw much light on our experimental results, and in the Mammoth Cave experiments they accord, theory with practice, in the striking fact that 100 kilocycle signals came through the overburden much attenuated, compared with the 20 kilocycles.

There is one point to bear in mind, Dr. King stipulates that the plane of the receiving coil shall pass through the generating loop. In our experiment, both loop and coil were horizontal, the one on the surface of the ground, the other on the floor of the cave.

Appendix III. Mutual Inductance of Two Small Coils at a Great Distance Apart in a Slightly Conducting Medium, Loop and Coil Vertical

Let a current I flow in the primary loop and an induced current I′ flow through a secondary coil (impedance Z) at a distance r from the loop.

Let M_0 be the mutual inductance between loop and coil in air

Let M be the mutual inductance between loop and coil in air the medium (rock)

where $M_0 = \frac{nn^1AA^1}{r^3}$

Then $I^1 = \frac{M\,I\,p}{Z}$ where $p = 2\pi$ times the frequency

and $Z = \sqrt{R^2 + L^2 p^2}$

This result holds only if the plane of the coil passes through the distant loop, and if the conducting medium is of infinite extent. When a separating plane exists between two media, one of finite and the other of infinite resistance, the problem becomes very complex. The above, however, gives a fair approximation if the resistivity of the rock is not too large.

The effect of the medium is to introduce an attenuating factor multiplying M_0 so that $M = M_0\ F(r)$ when $F(r)$ is a function of the distance between loop and coil.

Dr. L. V. King finds that F(r) is not a simple exponential factor, but that it is given by

$$F(r) = e^{-\frac{r}{c\sqrt{2}}/(\cos\alpha - \sin\alpha)}$$

where c is the attenuation constant of the medium given by

$$c = \sqrt{\rho\,(\text{ohm-cm.}) \times 10^9} \Big/ \sqrt{8\,\pi^2 f}$$

and for $\rho = 10^5$, $f = 10^4$, $c = 110$ metres

$\rho = 10^5$, $f = 10^5$, $c = 35$ metres

while the auxiliary angle α is defined by

$$\tan\alpha = \frac{\frac{r}{c\sqrt{2}}}{1 + \frac{r}{c\sqrt{2}}}$$

Using this result of Dr. King's the writer calculated F(r) as follows

ρ in ohm-cm.	f in kilocycles	c in metres	F(r)
10^5	10	110	0·98
10^5	100	35	0·49

and this means in plain language that only 2 per cent of the 10 kilocycle effect should be absorbed, while 51 per cent or about half the 100 kilocycle effect should be absorbed in passing through about 100 metres (328 feet) of rock of resistivity 10^5 ohm. cm.

This result may be compared with that given in Table IV. It is clear that steps should be taken in the near future to test the applicability of these formulæ in practice.

Appendix IV. The Absorption Coefficient of the Limestone and Sandstone above Mammoth Cave May Be Estimated in This Way

One half ampere, in a one-turn 100-foot horizontal circular loop, gave an average of 3·9 microvolts on a 40 by 10-foot, three-turn, rectangular loop at a depth 300 feet underground. But the effective volts equal

$$\frac{2\pi}{\sqrt{2}} \text{f A B n}/10^8 \qquad \therefore \frac{3\cdot 9}{10^6}=4\cdot 4\times 75000\times\frac{400\times 900\times B\times 3}{10^8}$$

whence $B=10^{-9}$ lines per square centimetre down in the cave. The average frequency has here been taken as 75 kilocycles. At the centre of the circular loop, with the same current (0·5 amp.), the field would be about $2\cdot 2 \times 10^{-4}$ gauss, whereas straight below at a depth of 100 feet the field would be about 10^{-6} gauss. If then γ is the coefficient of absorption we have $e^{\gamma z}=1{,}000$ and hence $\gamma=7\cdot 7\times 10^{-3}$ as a rough approximation. The reduction to half the surface value would take place, therefore, in 90 metres, and this experimental result is in fair agreement with calculated values, *See* Appendix III.

Appendix V

When radio waves are moving horizontally over the sea, with the plane of the waves vertical, there is little penetration, only a few feet in fact, into the conducting seawater, and the electric vector is upright.

The case is very different when the waves pass over dry land. The bottom of the wave drags behind. There is a horizontal vector as well as a vertical vector, alternating and out of phase with each other, so that there is elliptic polarization. The shape of this ellipse is different in the air and in the ground.

A rigorous discussion, due to Zenneck, will be found, pages 623-631, in Fleming's " Principles of Electric Wave Telegraphy and Telephony ", 4th edition, 1919 (Longmans).

The particular point to be considered is the depth to which radio waves, say from a broadcasting station a few hundred miles away, will penetrate into the earth. The value of a quantity d is determined from a relation.

$$d = A \sin \psi$$

$$\text{where } A=\frac{\sqrt{2}\,\pi f}{3\times 10^{10}\sqrt{k}}\,\frac{\sqrt{s^2+4\pi^2 f^2 (k^1)^2}}{\sqrt[4]{s^2+4\pi^2 f^2 (k+k^1)^2}}$$

$$\text{and } \psi=\varphi_1-\frac{\varphi_2}{2}-\frac{\varphi}{2}$$

$$\text{where } \varphi=90^\circ,\ \tan\varphi_1,=\frac{2\pi f k^1}{s},\ \tan\varphi_2=\frac{2\pi f (k+k^1)}{s}$$

Here f is the frequency, s is the conductivity of the rock in electrostatic units,

k is the (dielectric constant of the air)/4π

and k^1 is the (dielectric constant of the rock)/4π.

Having found d we state that $\frac{1}{d}$ is the depth at which the effect is reduced to $\frac{1}{e}$ times the surface value, where e is the Napierian base, and $\frac{1}{e}$ has the numerical value 0·367, so that the waves have fallen to about 37 per cent of their surface value. All this is rather complicated to the average man, and the writer has, therefore, made the calculations, then determined the thickness to half value, and stated these values in Table V.

For example, suppose that we have dielectric constant 8, and resistivity 10^5 ohm-cm., then for 1,000 kilocycles it is seen that, at a depth of 13 metres, the effect is reduced to half value, therefore, at

26 m. to quarter value
39 m. to one-eighth
52 m. to one-sixteenth
104 m. to $\frac{1}{256}$

and so on.

It will be noted that the depth attained is very sensitive to frequency, and quite dependent on the dielectric constant and conductivity also.

There is much better agreement between the calculations by various methods than was anticipated. Z_1 is the depth to half value in metres for waves travelling horizontally, when the dielectric constant is 8 and the resistivity 10^5 ohm-cm.; Z_2 is a similar result for dielectric constant 4, and resistivity 10^6 ohm-cm. V is the depth to half value for horizontal plane waves plunging vertically into the earth, when the dielectric constant is 10, and the resistivity 10^5 ohm-cm. The small value in this case for 10^7 cycles per second is remarkable.

TABLE V

Penetration of Radio Waves into the Earth

Frequency	1,000	10,000	100,000	1,000,000	10,000,000	—
Kilocycles	1	10	100	1,000	10,000	—
Wave length	300,000	30,000	3,000	300	30	Metres
Z_1	350	110	35	13	10·5	"
Z_2	1,200	350	94	22	11·5	"
V	....	110	34·6	11·5	1·1	"

Here Z_1 is the depth in metres at which the surface effect is reduced to *half value* when the dielectric constant is 8, and the resistivity of the rock is 100,000 ohm-cm.

And Z_2 is the same depth to half value when the dielectric constant is 4 and the resistivity is 1,000,000 ohm-cm.

V is for a vertical plane wave entering the earth, still expressed as number of metres to half value. Dielectric constant 8; resistivity 10^5 ohm-cm.

Appendix VI

Since writing the above Dr. L. V. King has succeeded in solving our problem for the case of a horizontal loop and a horizontal coil in an infinite slightly conducting medium. This closely approaches the conditions of the large loop on the earth, and of the receiving coil straight beneath it, and 300 feet below, in the cave.

If I is the current in the loop, then the induced current, in the parallel coil straight beneath it, is given by

$$I^1 = \frac{M I p}{\sqrt{R^2 + L^2 p^2}},$$

where $p = 2\pi$ times the frequency, M is the coefficient of mutual inductance, and L, R are the self inductance and resistance of the receiving coil.

In his calculations the co-efficient of self inductance has been ignored, and, therefore, in making future measurements the different turns of the receiving coil should be loosely coupled.

The value of M has been calculated as

$$M = \frac{2AA^1}{z^3} (1+x)\ (1+x^2)^{\frac{1}{2}}\ e^{-x}$$

where

$$x = \frac{z}{\sqrt{2}\ c}$$

and z is the depth of the coil beneath the loop, and c is given by

$$\sqrt{\frac{\text{resistivity in E.M.U.}}{8\,\pi^2 \times \text{frequency}}}$$

As to A, A^1 they are the areas of loop and coil, multiplied, of course, by the number of turns.

TABLE VI

Values of c in Metres

f........	10^3	10^4	....	....	....	....	....	......	....	....	10^5	......	10^6	10^7
Kc.....	1	10	20	30	40	50	60	70	80	90	100	110	1,000	10,000
c.......	354	113	80	65	56	50	47	42·5	40	37	35·5	34	11·3	3·55
c.......	1127	354	253	206	177	158	149	135	127	117	113	108	35·5	11·3

The values for c are in metres and the upper row gives values when the resistivity ρ is equal to 10^5 ohm-cm. or 10^{14} E.M.U., and the lowest row when $\rho=10^6$ ohm-cm.$=10^{15}$ E.M.U.

It is interesting to note that the function $(1+x)\ (1+x^2)^{\frac{1}{2}}\ e^{-x}$ has a maximum when $x=1$, its values being 1 when $x=o$, 1·04 when $x=1$. This slight rise occurs then when the depth$=\sqrt{2}\,c$. Now in our case the depth Z was about 100 m. and, therefore, c should be 71 metres and looking at the table for c means that when $\rho=10^5$ ohm-cm. a maximum should occur for about 25 kilocycles, which is indeed about the observed frequency. In the present state of our knowledge it would be rash to assert that this is more than a coincidence.

This appendix is inserted as a guide to future experiments.

Some recent results suggest that 10^4 ohm-cm. is nearer the true resistivity than 10^5 ohm-cm.

EARTH RESISTANCE METHODS

METHODS EMPLOYED

Much knowledge of the nature of the terrain and the presence of mineralized zones can be obtained by various electrical methods of geophysical prospecting. Among such schemes, that of measuring the electrical resistance of the ground offers many advantages, especially when it is desired to locate and determine the depth of overburden above a massive deposit of good conducting ore such as chalcopyrite, galena, pentlandite, and other conducting sulphides or oxides. The sulphide of zinc, sphalerite, being a very poor conductor of electricity, is not detectable by such electrical means.

There are several different arrangements by which the electrical resistance or average resistivity of the ground may be obtained. By resistivity is meant the resistance in ohms of a cube of one centrimetre edge and it will be expressed in ohm-cm. One of the most successful methods was that described by Gish and Rooney,[1] in which four equally spaced electrodes are placed in the ground in the same straight line. The two outer ones act as current electrodes by means of which a current of electricity is introduced into the ground. This current is frequently alternating in order to avoid polarization effects at the electrodes, though direct currents are also used. In order to obtain the current two to fourteen B batteries were used, each 45 volts. It is to be remembered that these have a comparatively long life provided the current drawn from them is less than 200 milliamperes. They should be used for as short a time as possible, and only when taking readings. A switch and a reversing key are placed in the circuit so that the current is left on only when the readings are made, and these keys also provide for reversing the direction of the current in order to compensate for any natural currents in the ground that are present at times. The strength of the current is read on a milliammeter in thousandths of an ampere. The two inner electrodes are connected to a potentiometer by means of which the potential difference between them is found. It may be proved[2] that the mean resistivity ρ of the intervening ground between the two potential electrodes is given by

$$\rho = 2\pi A \frac{E}{I}$$

In this formula A is the interval between neighbouring stakes and 3A will be the distance between the two outer current electrodes. V is the potential difference between the two inner potential stakes, and I the current passing through the ground. Rooney found an empirical rule that holds in many cases, namely, that this formula gives the mean resistivity to a depth A. In practice the stake interval A is increased in a regular way, and the resistivities calculated for each separation, thus finding the mean resistance to increasing depths. Since the resistivity of many ores is less than that of the surrounding rocks, when the stake interval A equals the depth of the ore-body then the value of ρ the mean resistivity, decreases. Hence plotting ρ as ordinate against A as abscissa, the resulting curve will show a fall when the stake interval A equals the depth of the conducting ore-body, provided, of course, Rooney's rule holds.

Another method is the single electrode probe.[3] One current electrode is driven into the ground where the survey is to be made, and the other current electrode is placed so far away that for all practical purposes it may be considered at infinity. This interval of separation is equal to about five times the depth to which it is intended to carry the survey. Two non-polarizable electrodes act as potential stakes. The one is placed at a dis-

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[1] "Terrestrial Magnetism and Atmospheric Electricity", vol. xxviii, pp. 89–108 (1923). Eve and Keys, "Applied Geophysics", p. 92.

[2] Eve and Keys: "Applied Geophysics", p. 240.

[3] *See* Eve and Keys: "Applied Geophysics", p. 107.

tance a and the other at a distance b from the central current stake. The potential V between a and b is found by a potentiometer, and the current I flowing into the ground is measured with a milliammeter. The mean resistivity ρ between two hemispherical bowls described with radii a and b with the current electrode as centre, is given by

$$\rho = 2\pi \frac{V}{I}\left(\frac{a\,b}{a-b}\right)$$

In practice it is convenient to make a=2 b and then the above equation becomes

$$\rho = 2\pi\, a \frac{V}{I}$$

The values of ρ for increasing values of a are found. The results are plotted using ρ as ordinates and 'a' as abscissæ. When the length a is approximately equal to the depth of the ore-body below the central current stake, then the value of ρ will tend to diminish. This fact will be shown by the change in the slope of the curve.

An interesting set of experiments was carried out by Bowen and Gilkeson[1] who grounded both ends of a line 8,500 feet long, 34 feet above ground. At distances varied from 20 to 1,000 feet a parallel insulated wire, 500 feet long, laid on the ground, was used as a receiver, each end grounded but with A.C. potentiometers in series at each end to measure the induced voltage and the phase difference between it and the current in the long line.

The impedances were calculated and the resistivity of the earth deduced for varying frequencies. The results given are

Frequency	Resistivity in ohm-cm.
0	2,400
200	2,700
500	3,600
1000	5,000

The change with frequency is interesting, but the values of the resistivity are distinctly low compared with those usually found with the Rooney-Gish and analogous methods[2], when the lowest values are about 10,000 ohm-cm.

The parallel line method can be used in the search for oil and ore and geological discontinuities a few hundred feet deep, but the above discrepancy in resistivity values demands investigation.

It is noteworthy that Dr. King, using the 1930 values obtained in the experiments at Mammoth cave, deduced a value for the resistivity distinctly smaller than that obtained from direct measurements of specimens and of the lime and sandstones in situ.

Dr. F. W. Lee, of the United States Bureau of Mines, has introduced a modification of the Gish-Rooney method which gives better results in many cases.[3] The arrangement is practically the same as the four electrode method of Gish and Rooney, except that a fifth electrode is placed midway between the two potential electrodes. The scheme is illustrated

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[1] "Mutual Impedances of Ground-Return Circuits," Bell System Tech. Jour., vol. IX, 4, pp. 628–651, Oct. 1930.

[2] *See* for example Lee and Swartz: "Resistivity Measurements of Oil-bearing Beds"; Tech. Paper 488, U.S. Bureau of Mines, 1930.

[3] F. W. Lee and others: U. S. Bureau of Mines, Information Circulars Nos. 6171 and 6235, Oct. 1929, and Feb. 1930.

diagrammatically in Figure 12. The current from a few B batteries is introduced into the ground through C_1 and C_2. P_1 and P_2 are two non-polarizable potential electrodes. Porous pots filled with a concentrated copper sulphate solution into which dips a copper wire for connecting purposes were used in these experiments. A third similar potential electrode P is placed half-way between P_1 and P_2. P is kept stationary and the equal intervals, C_1 P_1, P_1 P_2, and P_2 C_2, are increased by stated steps. The value of this interval is called A. It has been found convenient in practice to give definite values to A in succession, namely, 40, 80, 100, 120, 160, 200, 240, 300, and 400 feet. This method thus investigated the conductivity of the ground to a maximum depth of 400 feet when these intervals are used.

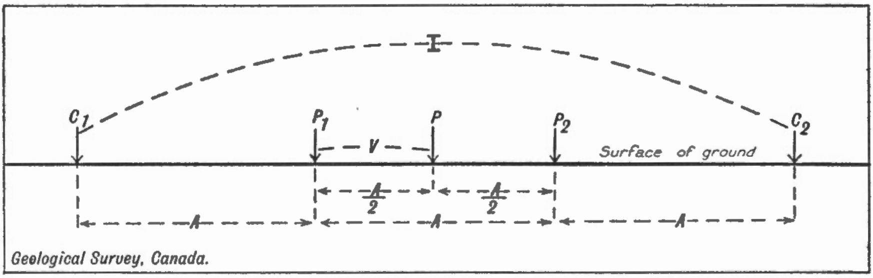


Figure 12. Lee modification of the Gish-Rooney resistivity method.

Instead of taking the potential between P_1, P_2, and the current between C_1, C_2 as in the Gish-Rooney method, Lee takes first the potential between P_1 and P, and then between P and P_2, thus differentiating between the resistivity to the right and to the left of the central stake P. If I is the current and V the potential between P_1 and P, then the mean resistivity for the region between P_1 and P is given by

$$=4.\ \pi.\ A.\frac{V}{I}$$

because the half potential is measured and stated in the tables.

The advantage of this method is that it distinguishes on which side of P the better conducting material lies. It may happen (*See* Lee, Information Circular, No. 6171, U.S. Bureau of Mines) that there is a body of low resistivity on the right and a high resistivity on the left of P. The average might be that of normal ground and consequently by the Gish-Rooney method, measuring between P_1 and P_2, the discovery of this good conducting mass on the right of P would not be made. This was shown to be the case in some work carried out by Lee in Pennsylvania. There is the further advantage to the geologist, inasmuch as it is possible to deduce the dip of an ore vein or body beneath the station, or possibly to locate a fault to the left or right.

During the application of these methods a number of different problems arose, and these will now be dealt with each in turn. The solution of these problems will serve as typical cases of the application of resistivity methods to geophysical prospecting. Various steps were also taken in order to ascertain the correlation between magnetic and electrical surveys, and furthermore, to find how various electrical methods checked with one another.

Problem I

TO FIND THE THICKNESS OF THE CYPRESS SANDSTONE ABOVE THE MAMMOTH CAVE LIMESTONE

The Mammoth Cave region provided a suitable place to investigate the problem of determining the thickness of one geological layer above another. As has been pointed out in the geological section (*See* pages 80, 81) the limestone lies nearly horizontally beneath a cover of Cypress sandstone. The electrical resistance of sandstone differs from that of limestone, so that a resistivity method appeared to be a possible way of finding the thickness of the sandstone layer.

The single electrode probe method was tried at a point in the camping ground near the Mammoth Cave hotel. Two B batteries were found sufficient to give currents that produced measurable potential differences between the two potential stakes. The distant electrode was 800 feet away in a westerly direction. The potential differences were measured along four lines approximately north, east, south, and west. The following Table VII is inserted as representative of the type of readings and results which are obtained with this method. The readings of the potential differences and currents were taken when the current was reversed, and the mean values are given in the table. The mean resistivity values (ρ) were calculated as explained above.

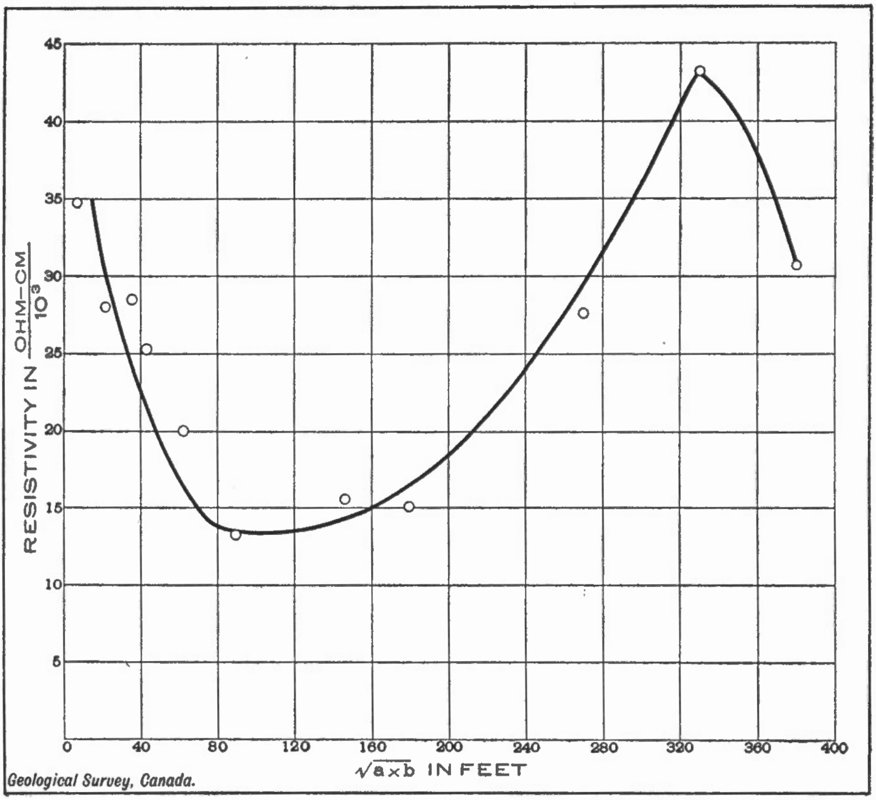
TABLE VII

a	b	$\sqrt{ab}$	North	Resistivity in ohm-cm.		
				East	South	West
10	5	7·1	37,200	35,000	34,300	34,700
30	15	21·2	26,900	26,500	30,000	28,000
45	30	36·8	17,400	19,200	32,500	28,200
60	30	42·3	15,000	17,600	21,000	25,200
90	60	73·5	9,750	12,000	[1]7,500	19,800
120	60	85	12,000	11,200	6,750	13,000
120	90	104	13,500	12,400	9,000	[2]
180	120	147	....	....	....	15,500
270	120	179	....	....	....	15,000
400	180	268	....	....	....	28,000
400	270	329	....	....	....	43,000
540	270	381	....	....	....	31,000

[1] Low value due to the presence of a buried iron pipe crossing the field cutting the south line 60 feet and the west line 90 feet from the central stake. The presence of this iron pipe was deduced from the measurements, and subsequently verified from one of the old inhabitants.

[2] Too small to measure, due to the iron pipe, *See* note above.

The above results are plotted using mean resistivity values vertically and $\sqrt{ab}$ horizontally. The question as to the relation between depth and the values a, b will be discussed later. Except where the buried iron pipe interfered with the readings, the curves seem to be quite similar. From graph, Figure 13, the thickness of the sandstone is seen to be at the point where $\sqrt{a\,b}=80$ feet. It will be shown later that more exact results are obtained when one uses $\sqrt{2ab}$, and in that case the thickness, as determined from the curve, is found to be $80\sqrt{2}=113$ feet. The actual thickness was determined by Dr. Swartz as follows. The point of contact between the Cypress sandstone and the Mammoth Cave limestone was found near the entrance to the Mammoth cave. By survey the level of the surface at the place where the experiments were carried out above this contact point was found to be 94 feet. From an examination of the limestone deposit in the cave, and by observation of the dip which the layers have, it was found that the true thickness of the sandstone would be approximately 101 feet. This is in good agreement with the thickness determined by the single electrode probe method, and illustrates the application of the scheme for determining geological structure.



Geological Survey, Canada.

Figure 13. Resistivity curve by single electrode probe method, to find thickness of Cypress sandstone at Mammoth cave, Kentucky.

The depth of the water-level underground may also be estimated by the single electrode method. The curves obtained at Mammoth Cave railway station showed a much smaller drop than in Figure 13, suggesting that the water was drained away in that region, so that the cost of boring for water at the station was not justifiable.

Problem II

THE INFLUENCE OF RAIN ON RESISTIVITY MEASUREMENTS

The day following the resistance experiments described in Problem I a heavy rain storm of short duration occurred. Previous to this shower there had been hot fair weather for at least two weeks, so that the ground was exceptionally dry. The influence of rain on the measurements has been a matter of some doubt, and so advantage was promptly taken of this opportunity of testing the influence of surface moisture. Readings were repeated using exactly the same intervals and the same method as on the previous day. The survey was made along the west line. The results are given in the following table for comparison purposes.

TABLE VIII

Intervals in feet		Resistivity in ohm-cm.	
a	b	Wet	Dry
10	5	37,700	34,700
30	15	28,000	28,000
45	30	27,600	[2]
60	30	24,700	[2]
90	60	20,500	19,800
120	60	12,300	13,000
120	90	[1]	[1]
180	120	15,400	15,500
270	120	14,400	15,000
400	180	24,000	28,000
400	270	49,000	43,000
540	270	24,000	28,000

[1] Potential difference too small to make reliable readings (iron pipe).
[2] Measurements not taken for this interval.

It will be seen from this table that the rain had very little effect on the resistivities as determined by the single electrode probe method. Although the rain was not sufficient to materially alter the moisture content of the subsoil, it did change the conductivity of the surface soil. It is interesting to note that this did not modify readings to any material extent. Now this result might be anticipated, because the resistances of very large masses of underground rocks are really involved, and the thin surface soil is but a moderate item in the total account.

Problem III

THE RELATION IN RESISTIVITY DETERMINATIONS BETWEEN THE DEPTH OF A CONDUCTING LAYER AND THE STAKE INTERVAL

When using any of the resistivity methods the question arises as to how to determine the depth of an ore-body from the resulting readings. The mathematical theory of such determinations is quite complex in all practical cases.[1] Working rules may be found that are based on experience gained in the field, and these would be of great assistance in interpreting the results of resistivity measurements, if they were known and their limitations recognized. One of the best known is Rooney's rule (*See* page 105) which was found to hold in cases where he had tested it. In the single electrode method the values a, $\frac{a+b}{2}$, $\sqrt{a\,b}$ or $\sqrt{2\,a\,b}$* might be empirically suggested with almost equal reasons. Work has, therefore, been done over regions where the thickness of the overburden above the conducting ore-body is known from diamond drill records. The experience gained has shown that it is most appropriate to plot mean resistivities vertically and the corresponding values of $\sqrt{2\,a\,b}$ horizontally. The change in the slope of the curve will then occur at a value of $\sqrt{2\,a\,b}$ which will be the approximate depth of the conducting body below the surface. It should be noted that in practice it is convenient to make $a=2b$, so that the value of $\sqrt{2\,a\,b}$ reduces to a. In this case 'a' is plotted horizontally, and the depth is given by the value of a at which the change in the resistivity curve occurs. This 'a' will then be equivalent to 'A' which is the electrode separation in the Gish-Rooney method of determining ground resistivities. Justification for this procedure is given by the practical experience of Lee in the U.S. Bureau of Mines, Information Circulars Nos. 6171 and 6235. Additional evidence in favour of this empirical rule was obtained during this summer's work. The reader must remember that it is only by wide field experience, and from a knowledge of the types of curves to be found in ground free from conductors, that any adequate empirical rules can be formulated. It is quite possible that better and perhaps more justifiable (mathematically and physically) rules for determining depth of overburden will be evolved as more results are gathered together and analysed. But for the conditions investigated in this report the procedure as described above gives depths which agree with the true values to an accuracy well within that claimed by the methods and applications used in this investigation.

Problem IV

TO DETERMINE THE RESISTIVITY OF ROCKS IN SITU

In all resistivity methods of locating discontinuities in geological structure, whether caused by the intrusion of a conducting ore-body, or by a fault, the complete interpretation of the results will depend upon a knowledge of the resistivities of the various rock formations concerned.

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[1] *See* Eve and Keys, "Applied Geophysics", p. 91.

*The reader is reminded that 'a' is the distance of the further potential porous pots from the central electrode; and 'b' is the distance of the other potential electrode from the central electrode.

Resistivities of the same type of rock vary considerably, depending upon their locality, and also to some extent upon the amount of water they contain. When determinations are made on specimens in the laboratory, the results are often at variance with the values found in the field. It is, therefore, important that methods should be adopted for rapidly obtaining the resistivity of rocks in situ.

The single electrode probe method offers a convenient and rapid way of obtaining the resistivity when a mass of the rock can be found exposed with no overburden. Such outcrops can be obtained in many cases. The resistivities of both the Cypress sandstone and of the Mammoth Cave limestone were thus obtained by the single electrode probe method in the neighbourhood of the Mammoth cave. These deposits served our purpose admirably, and the results of our measurements on two quite separate outcrops are given in the following table.[1]

TABLE IX

Resistivity of Cypress Sandstone and Mammoth Cave Limestone

a	b	Resistivity in ohm-cms.	
Feet	Feet	Sandstone	Limestone
20	10	370,000	75,000
40	20	228,000	106,000
80	40	102,000	67,000

It should be noted that the sandstone may have been dry on the top and yet damp beneath. The limestone probably holds the water more than the sandstone, which may in part account for the lower resistivity of the limestone. The sandstone was over 100 feet thick at the place where it outcropped, according to Dr. Swartz' estimate, so that the resistance probe did not reach the limestone below when working over the sandstone.

Specimens of limestone and sandstone from these outcrops were collected, and after two or three days their resistivities were determined approximately by a direct method. Each specimen was placed in a shallow dish of water and mud with a sheet of tinfoil acting as electrode. The top was similiarly connected with a sheet of tinfoil. A "B" battery, e.m.f. 88·1 volts, was connected in series with the voltmeter (resistance 15,000 ohms) and with the specimen. The drop across the voltmeter, in the case of the sandstone, was 16·7 volts. Hence if R is the resistance of the block, we have

$$\frac{R}{15{,}000} = \frac{88{\cdot}1 - 16{\cdot}7}{16{\cdot}7}$$

from which R may be calculated. The value of the resistivity is then obtained from the dimensions of the block. The calculated values are given in Table X.

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[1] The value of ρ found in the experiments on the camping field described in Problems I and II was about 30,000 ohm-cm. No doubt the surface grass kept the moisture content higher, while the exposed rock plateau would be thoroughly dried out. This fact may account for the difference in the values obtained in the two cases.

TABLE X

Material	Resistivity in ohm-cm.
Mammoth Cave limestone	480,000
Cypress sandstone	120,000

By this method the limestone has a resistivity of roughly four times that of sandstone, whereas in situ the sandstone had the greater resistivity. From Table VII the resistivity of the sandstone on the camping ground had a value 30,000 to 40,000 ohm-cms. These results emphasize the variation in resistivity with the conditions under which the measurements are made. They indicate, also, the necessity for making resistivity determinations of rocks in situ.

Problem V

THE DETERMINATION OF THE DEPTH AND THICKNESS OF STRATA OF HIGH RESISTANCE IN LAYERS OF LOWER RESISTANCE

In the neighbourhood of Bowling Green, Ky., there are large deposits of natural asphaltic sands. In some places these deposits outcrop, but in others there is an overburden of sand that may be 20 feet thick or more. The application of resistivity methods to determine: (a) the depth to the top of the deposit, and (b) the thickness of the deposit, presented an interesting problem of geological as well as of economic importance. In such a case the geophysicist has to deal with a poorly conducting deposit surrounded by or embedded in the better conducting rock. This is just the converse of locating good conducting ore in poorly conducting rock. In the present case the problem is much more difficult owing to the fact that the difference between the resistivity of dry sandstone, which occurs as the overburden, differs only slightly from that of the asphaltic sands. Water may collect on the top of the asphaltic sand, and act as a screen for the material below. The presence of a conducting layer beneath the asphalt would introduce further complications. However, the situation appeared interesting and Dr. Swartz, with the help of Messrs. Kidd, Barlow, and Dent, carried out a number of determinations of resistivity in this region using the single electrode probe method.

Two typical curves are given in Figures 14 and 15. In using the method, the potential electrodes were placed at distances a and b from the central stake and a was always made equal to 2b. The values of a are plotted horizontally and the corresponding resistivities vertically. The earth current electrode was 1,500 feet away. Figure 14 shows the result of such a survey made on the R. Willis farm, near drill hole No. 2. In this case the asphaltic sand was covered with 10 feet of soil and waste, as indicated. The increase in resistivity due to the asphalt is clearly noticeable, although the thickness of the layer is not readily inferred from the graph.

In Figure 15 there is an interesting case. The water lying on top of the asphalt brings down the value of the resistivity, and the juncture

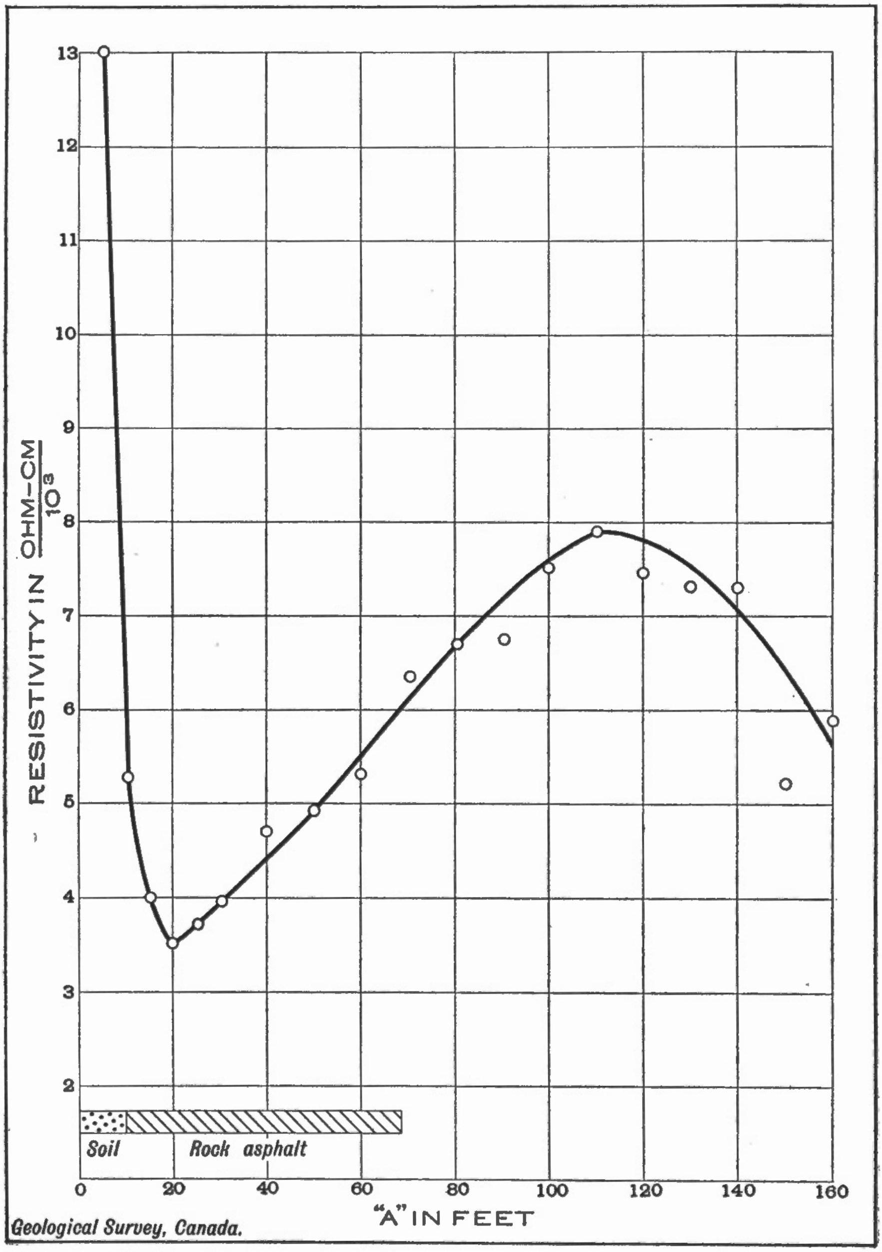
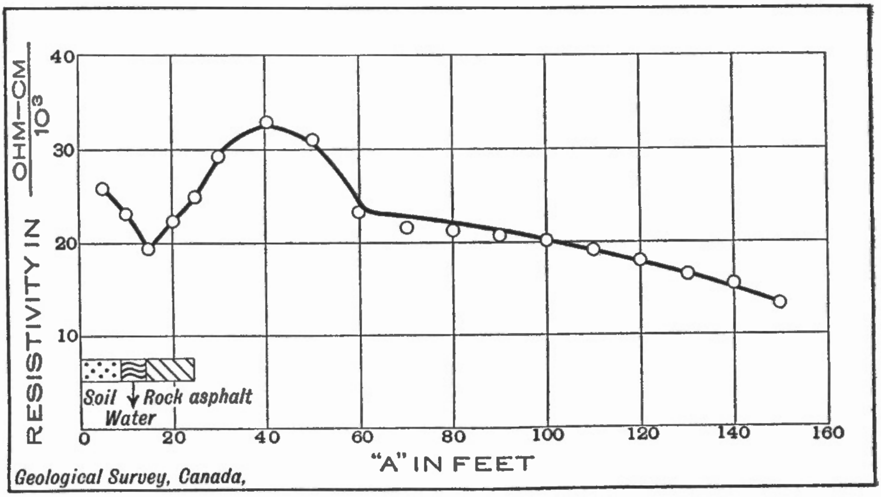


Figure 14. Resistivity curve by single electrode probe method, to find depth to top of rock asphalt.

of the asphalt below the water is strikingly shown by the sudden rise in the resistivity at 14 feet. The layer of high resistivity asphaltic sand keeps the mean value of the resistivity high until the part of the asphalt in the depth surveyed becomes small. The lower resistivity of the underlying layers then makes the mean resistivity decrease, as shown by the curve.



Geological Survey, Canada,

Figure 15. Resistivity curve by single electrode probe method, to find depth to top of rock asphalt.

A further study of numerous curves will be necessary before the thickness of the asphaltic sand layers may be inferred from the graphs. A fuller monograph on this particular investigation will appear in due course. It is important to point out again that dry sandstone and asphaltic sandstone have about the same resistivity, which makes the line of demarcation between the two layers extremely difficult to determine by a resistance method.

Problem VI

THE DETERMINATION OF THE DEPTH OF OVERBURDEN ABOVE A SULPHIDE ORE-BODY

The Falconbridge nickel mine provided an ideal situation to investigate how the resistivity methods could be used in finding the location and depth of a conducting sulphide body. A station, which we shall call A, was chosen at concession III-IV, lot 10-11, as indicated in Figure 16. Lines were cleared north, east, south, and west from this point. The single electrode probe method was used with the central stake placed at the point A. The distant electrode consisted of four iron stakes driven well into the ground 1,800 feet to the west of station A. Surveys were then made in all four directions east, west, north, and south from A, using potential stake intervals such that a = 2b, as explained on page

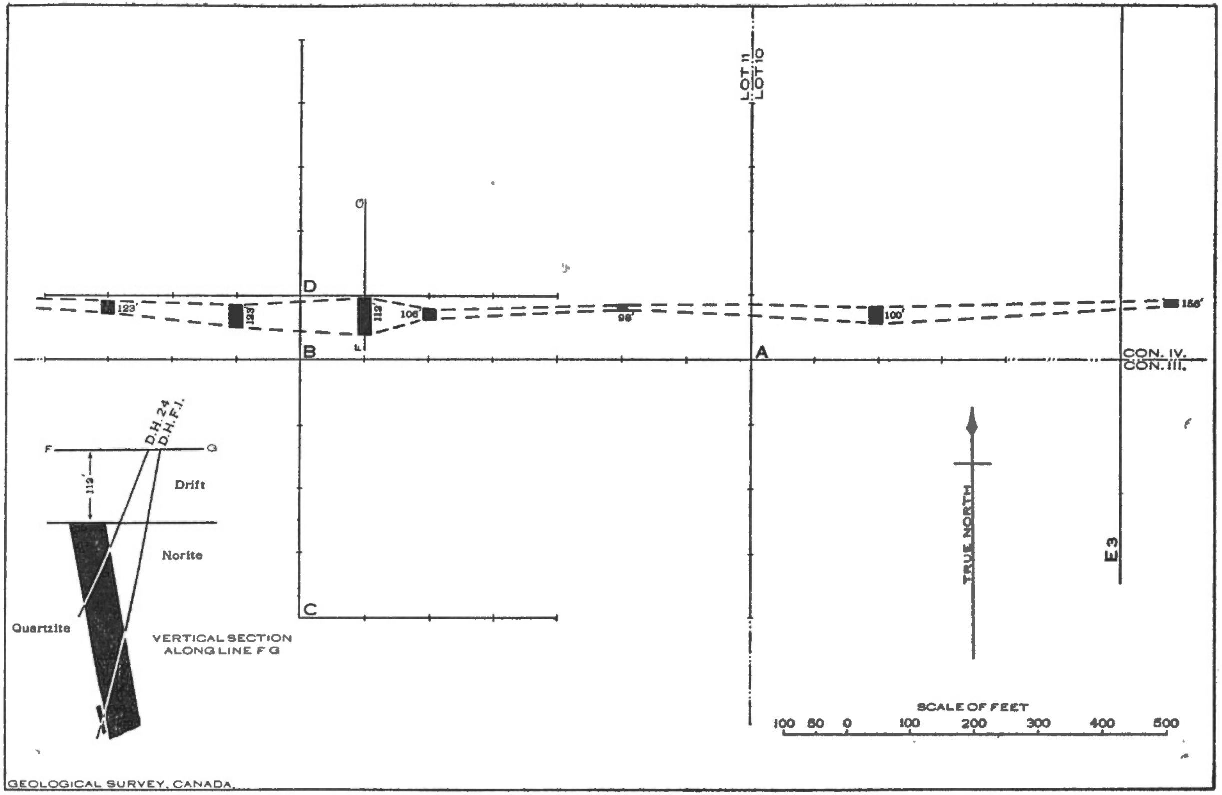


Figure 16. Plan and vertical cross-section of part of Falconbridge nickel mines ore-body.

106. Direct current was supplied by B batteries, and readings repeated with the direction of the current reversed, so as to eliminate the effects of the natural currents present in the earth.

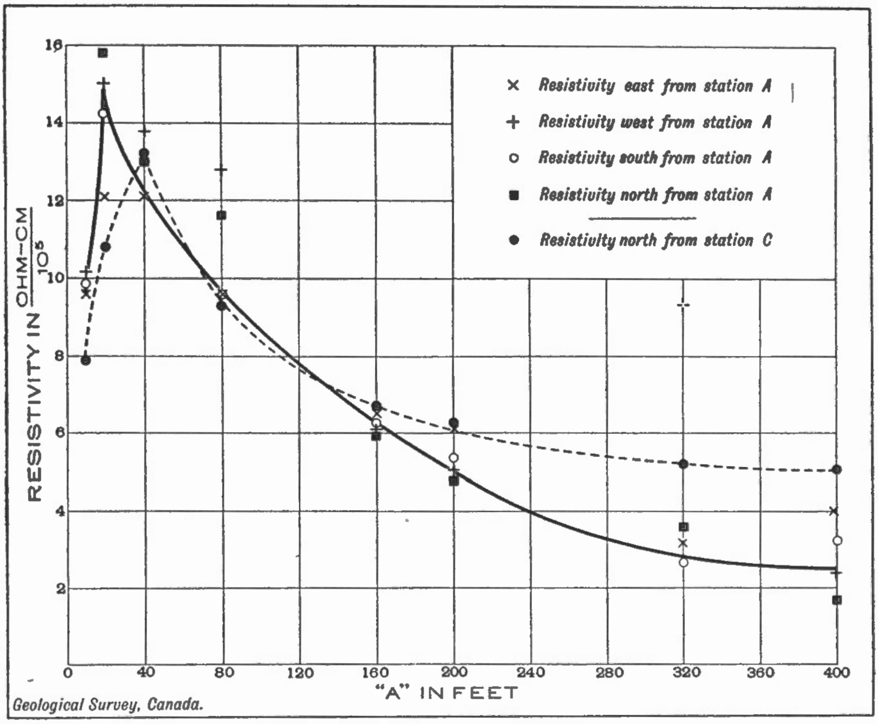


Figure 17. Resistivity curve by single electrode probe method, to find depth to top of sulphide ore-body, in vicinity of station A, Falconbridge mines, Ontario.

The results of this survey are plotted in Figure 17. The ore-body lay about 80 feet north of A, and had an overburden of approximately 100 feet, as indicated on Figure 16. The strike of the ore-body is east-west, and it should, therefore, be expected that the resistivity measured in this direction would be less than that measured at right angles to the strike. Especially should this be so at depths of 150 feet and more. The results indicate, however, that the resistivity is about the same in all four directions. This result is rather unexpected, but the explanation may lie in the fact that the ore-body is only about 15 feet wide, and may have less conductivity than at the other places where measurements were made.

In order to obtain the depth of the ore-body, it was necessary to obtain a typical resistivity curve for the same type of formation as that in which the conducting ore-body lies, but where no ore-body is present. A curve (Figure 17) showing the variation in resistivity with depth, was obtained by proceeding to station C indicated on Figure 16. This station was far enough from the ore-body, so that any resistivity measurements made there to a depth of 400 feet would not be affected by the ore-body. The resistivities in a north and east direction were taken in the usual manner, using the single electrode probe method. The results are tabulated in Table XI. These results illustrate symmetry of resistivity about the stake C, as may be expected. The curve plotted from values along the north line is shown in Figure 17 and indicates higher resistivities at depths below 160 feet than the values found at station A. This divergence between the curve for normal ground obtained at station C and the curve found at station A gives an indication of the presence of a better conductor near station A. The depth of this conductor can also be deduced from the point where the two curves diverge. In Figure 17 this is seen to be somewhere near the point 140 feet. The actual distance as estimated from the diamond drill records of holes in the vicinity is about 130 feet.

TABLE XI

Stake interval in feet		Resistivity in ohm-cm.	
a	b	North	East
10	5	785,000	820,000
20	10	1,080,000	1,000,000
40	20	1,310,000	1,450,000
80	40	932,000	1,000,000
160	80	671,000	590,000
200	100	620,000	570,000
320	160	527,000	528,000
400	200	505,000	500,000

To confirm this interpretation a second survey was made at station B, Figure 16. The station was 100 feet south of the north edge of the ore-body. The results of this survey by the single electrode probe method are given in Table XII. The resistivities were measured in the four directions from the central stake, north, east, west, and south. It is again surprising that the values of the resistivities in the four directions are so much alike. The ore-body runs east-west, and it might have been expected that the survey would indicate lower resistivities for the east-west directions than for the north-south. The table indicates a slightly lower value for the readings to the north, indicating a better conducting zone in that direction, but the differences are not sufficiently great to be positive.

TABLE XII

Electrode separation in feet		Resistivities in ohm-cm. directions			
a	b	East	West	South	North
10	5	1,010,000	756,000	900,000	865,000
20	10	1,250,000	1,180,000	1,200,000	1,140,000
42	20	1,280,000	1,600,000	1,270,000	1,250,000
80	40	820,000	1,050,000	1,020,000	1,030,000
160	80	414,000	570,000	575,000	523,000
200	100	386,000	452,000	435,000	418,000
320	160	288,000	239,000	242,000	175,000
400	200	79,000	? 163,000	232,000	133,000

The results of this survey are plotted in Figure 18, the normal curve as found from the survey at station C being shown for purposes of comparison. It will be seen that there is a deviation of the two curves at A = 140 feet, the curve taken at station B having the lower resistivities. The result indicates the presence of a conducting ore-body at a depth of approximately 140 feet from station B. The ore-body is actually 150 feet from station B. The agreement is good.

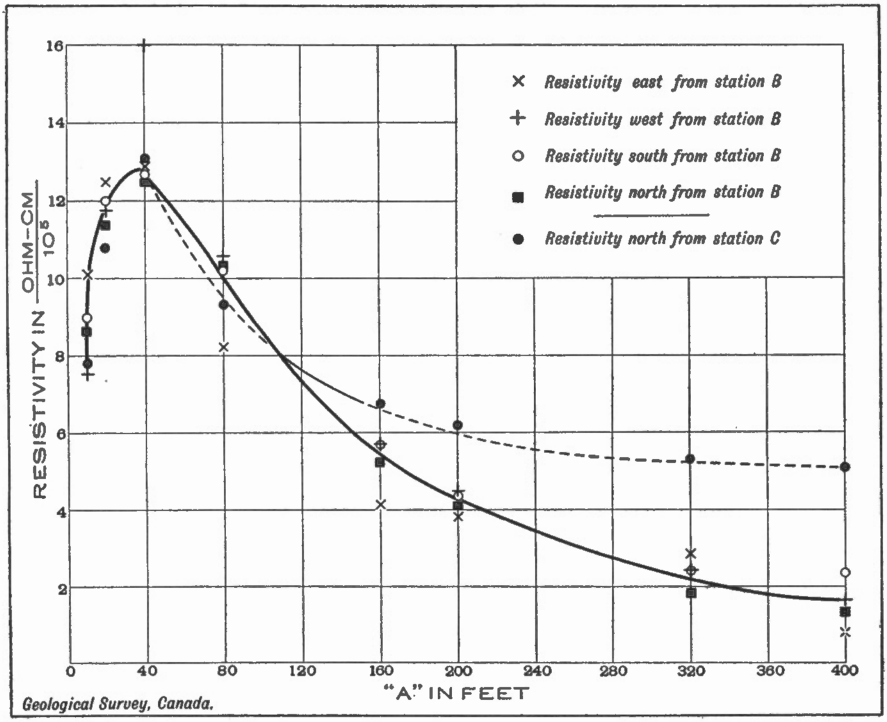


Figure 18. Resistivity curve by single electrode probe method, to find depth to top of sulphide ore-body, in vicinity of station B, Falconbridge mines, Ontario.

The two surveys described in this section give a fair idea of the application of the resistivity methods to the location of conducting bodies and to the determination of the depth of overburden above them.

Two specimens of the ore, which makes up the conducting body that was sought in the above experiments, were obtained. The resistivity of each specimen was obtained by direct measurement, as indicated in section 4. One specimen was from the Falconbridge mine, and the other from the neighbouring Garson mine. The results are given below.

Falconbridge ore	7,500 ohm-cm.
Garson ore	8,060 ohm-cm.

The results show that the resistivity of the ore is very much less than that of the rock that surrounds it.

Problem VII

TO FIND THE EQUIPOTENTIAL LINES AROUND A SINGLE ELECTRODE

One method of locating a good conducting ore-body is to lay two long, parallel, bare copper wires on the ground and connect them to a source of alternating current of 500 cycle frequency. The equipotential lines are then traced by means of two prodders connected by a wire and pair of telephone receivers.[1] In homogeneous ground the equipotential lines will be parallel to the electrodes. The deviation of these equipotential lines gives indication of the presence of a conductor.

Another method of locating a good conducting body is to find the equipotential lines around a single electrode. To do this a central stake is driven well into the ground in the middle of the region to be surveyed. Another stake or group of iron stakes is driven into the ground at a far distant point. The two stakes are used as electrodes for introducing into the ground an alternating current of 500-cycle frequency. Equipotentials are then plotted round the central stake by means of two metal probes connected together through a pair of headphones. If necessary an amplifier may be inserted in this circuit to increase the sensitivity of the method. One probe is inserted in the ground and the observer with the headphones and the other probe walks away about 100 feet, and locates a point on the same equipotential. If the second probe is not on the same equipotential, there will be a note of 1,000 frequency heard in the 'phones. The observer tries different points with his probe until he obtains silence, or at least a minimum intensity in the headphones. His position is noted and the first probe advanced to this point, and the equipotential traced for another 100 feet.

In homogeneous ground the equipotentials will be circles about the central electrode. If, however, there is a good conductor near the surface on one side, the equipotential lines will be deflected from it. In this way the plotting of equipotentials gives some indication of the presence of a good conducting body.

This method was investigated at the Falconbridge mine. The central electrode was driven into the ground at station B, Figure 16. The distant

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[1] *See* Eve and Keys: "Applied Geophysics", pp. 66–72.

electrode was 1,800 feet east from the central one. The generator gave 360 volts which produced a current of about 40 milliamperes through the ground. The frequency of the current was 500 cycles. The equipotential was commenced at 100 feet north of B and traced around. The connecting wire along the east direction made surveying in its vicinity difficult, so only the western half of the equipotential lines was plotted. It should be remembered that the conducting ore-body was about 100 feet north of B and its strike was east-west. The depth of the vein was 113 feet below the surface. The results of the survey for two equipotential curves are shown in Figure 19.

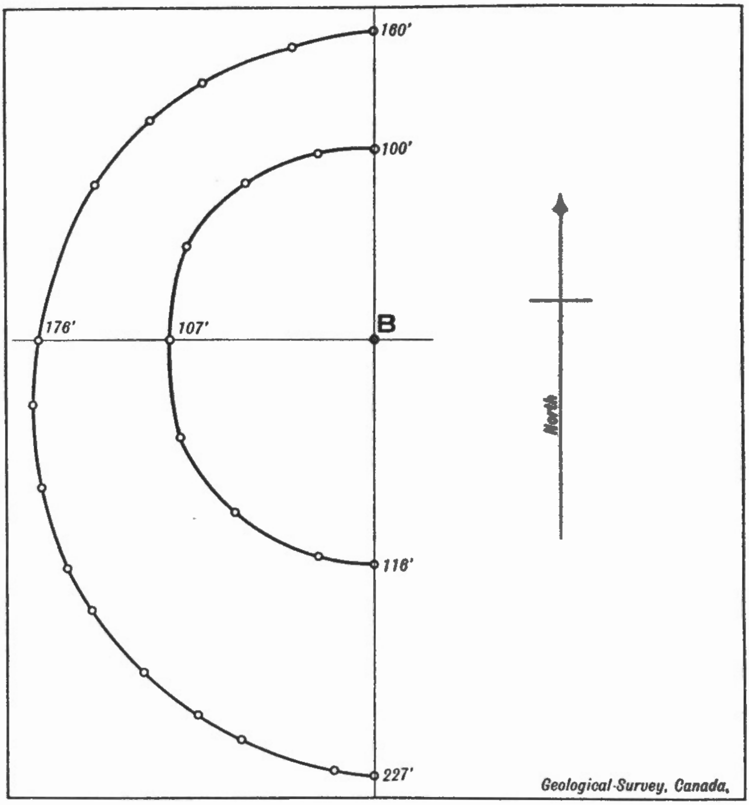

Figure 19. Equipotential curves about a central electrode at station B, Falconbridge mines, Ontario.

An examination of Figure 19 will show that the equipotentials are farther away from the central stake on the southern side than on the north. This result indicates the presence of better conducting material to the north, which is known to be the case. Many more equipotentials are required for a complete survey, but the two given in Figure 19 will indicate the possibilities of the method.

A second investigation by this method was made at the Errington mine on the Treadwell-Yukon property at Bradley, Ontario. The central electrode was placed at a point in a hay field which shall be called B. This station B was northeast of shaft No. 3, and the distant electrode was 2,000 feet east of station B. Two equipotentials were plotted here, and the results are shown in Figure 20. It is evident in the case of the equipotential through the 180-foot north point, that there is material of high resistivity towards the southwest. This result is confirmed by the indications found using the Lee method described in Problem IX. It is also of interest to note that in the immediate vicinity of the electrode, the ground is pretty uniform, as indicated by the equipotential line, though the 100-foot north point is very nearly circular in shape. The conductivity of this region is mainly governed by the amount of graphite present in the slates and tuffs.

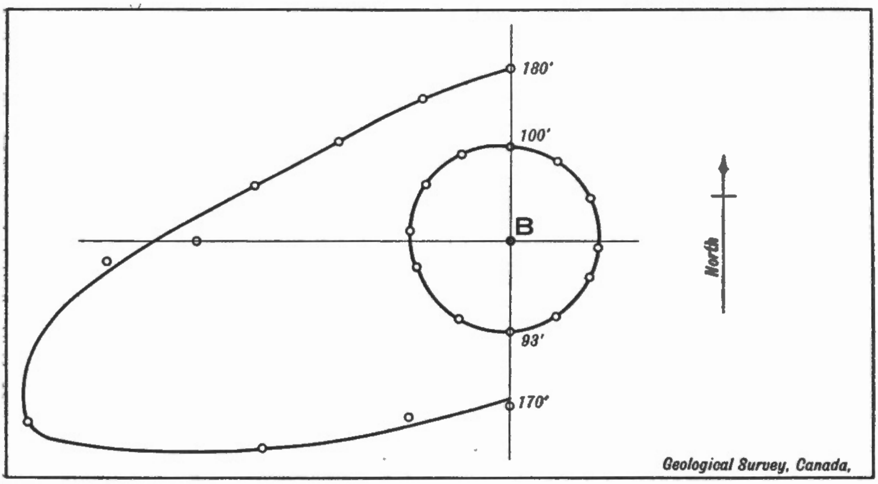

Figure 20. Equipotential curves about a central electrode at station B, Errington mine, Ontario.

Problem VIII

THE APPLICATION OF DR. LEE'S MODIFICATION OF THE GISH-ROONEY FOUR ELECTRODE METHOD OF MEASURING EARTH-RESISTIVITY WITH A VIEW TO DETERMINING THE DEPTH OF A CONDUCTOR

Dr. Lee's modification of the Gish-Rooney method[1] has already been explained on page 106. Several surveys were made using this scheme both at Falconbridge mine and at the Errington mine of the Treadwell-Yukon Company. The results of these surveys show that the method is promising and for certain types of ore-formation gives the depth of the overburden with remarkable precision. As examples only three surveys will

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[1] *See* Eve and Keys: "Applied Geophysics", p. 92.

be given, but these will be sufficient to illustrate the possibilities and limitations of the scheme.

A survey was made on the Falconbridge Mine area at station B, Figure 16. The central porous pot P, Figure 11, was, therefore, placed permanently at B, while C_1, C_2, P_1, and P_2 were moved along a north-south line, the intervals $C_1 P_1 = C_2 P_2$ being kept equal to $2P_1 P = 2P P_2$. The current was supplied by B batteries and read on a milliammeter. The potential differences between P_1 P and P P_2 were obtained with a Leeds and Northrup portable potentiometer, and the mean resistivities to the north and south of P were calculated as described on page 106. The results of this survey are given in Figure 21, where the mean resistivities are

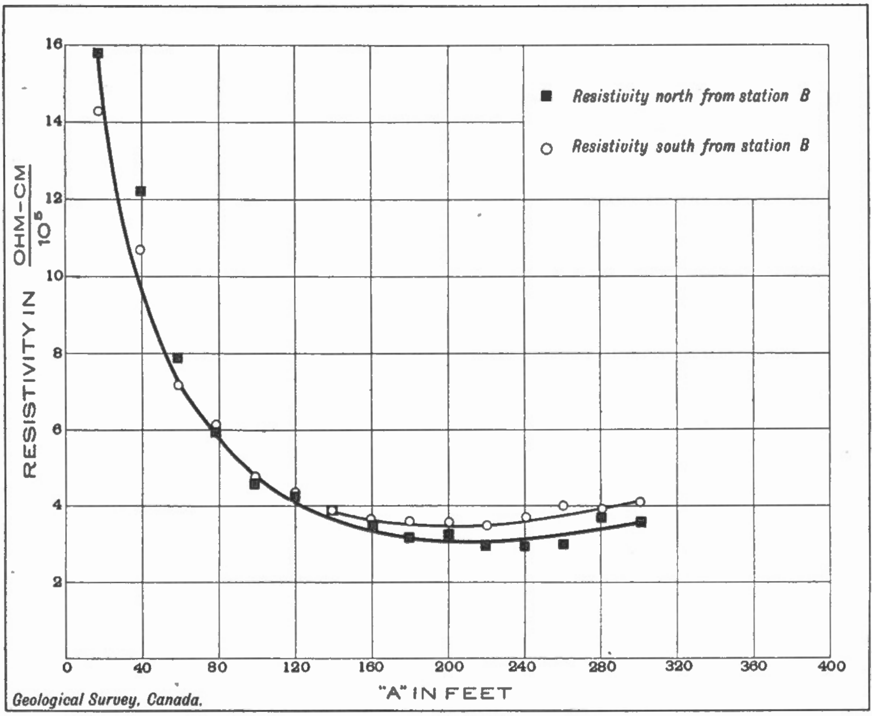

Figure 21. Mean resistivity curves by Lee method, north and south of station B, Falconbridge mines, Ontario.

plotted vertically, and the electrode separation " A ", which the reader will remember is equivalent to the depth of the survey, is plotted horizontally. It will be noticed that the two curves deviate from one another at a point where A is between 140 and 150 feet. The resistivity to the north becomes less when the greater depths are reached. On looking at Figure 16 again it will be seen that the north edge of the ore-body lies about 100 feet north of B, and has an overburden of approximately 112 feet. The width of the body is 20 to 30 feet in this region. The body has a dip to the north of about 80 degrees with greywacke quartzite on the south side and norite on the north. The actual distance of the body from B as determined by diamond drill records in the vicinity is about 150 feet, agreeing well with the value of 140 feet obtained by the resistivity method. It should be remembered that the survey was made using 20-foot steps, so that a closer agreement is not to be expected.

The difference between the two curves obtained to the south and north of the central stake P, gives a good indication of the better conducting material lying to the north, and also of its approximate distance. The conducting body having been located in the above manner, a more accurate determination of its depth below the surface is obtained by moving P from B to a point D (*See* Figure 16) 100 feet north of B and almost directly above the ore-body. The resistivity survey was repeated here, going first north and south and then east-west. The readings along the north-south line will give some idea of the dip of the body, for if the body goes vertically down, the values of the mean resistivities to the north and to the south of the central stake P will be the same. On the other hand, if it dips to the north, the resistivities should be less on the north than on the south side of P, a result which is actually indicated in Figure 22, though not very markedly. The dip being 80 degrees would account for this difference in resistivities being small. The survey along the east-west line gives by comparison some idea of the strike of the body. It will be seen from the graph shown in Figure 22, that the values of the mean resistivities along

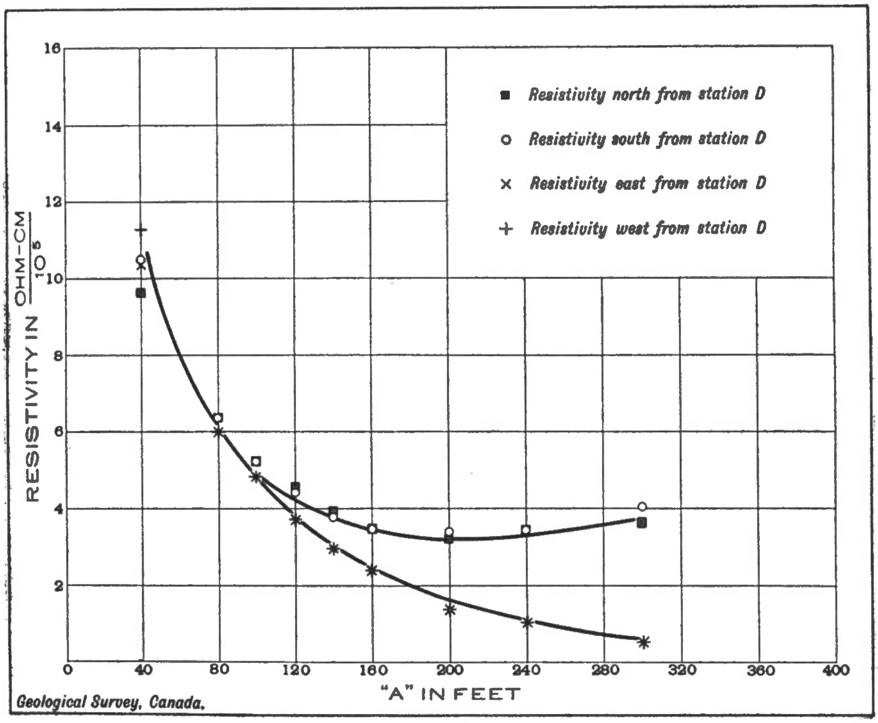

Figure 22. Mean resistivity curves by Lee method, over an ore-body striking east, dipping north, and covered by 112 feet of drift, Falconbridge mines, Ontario.

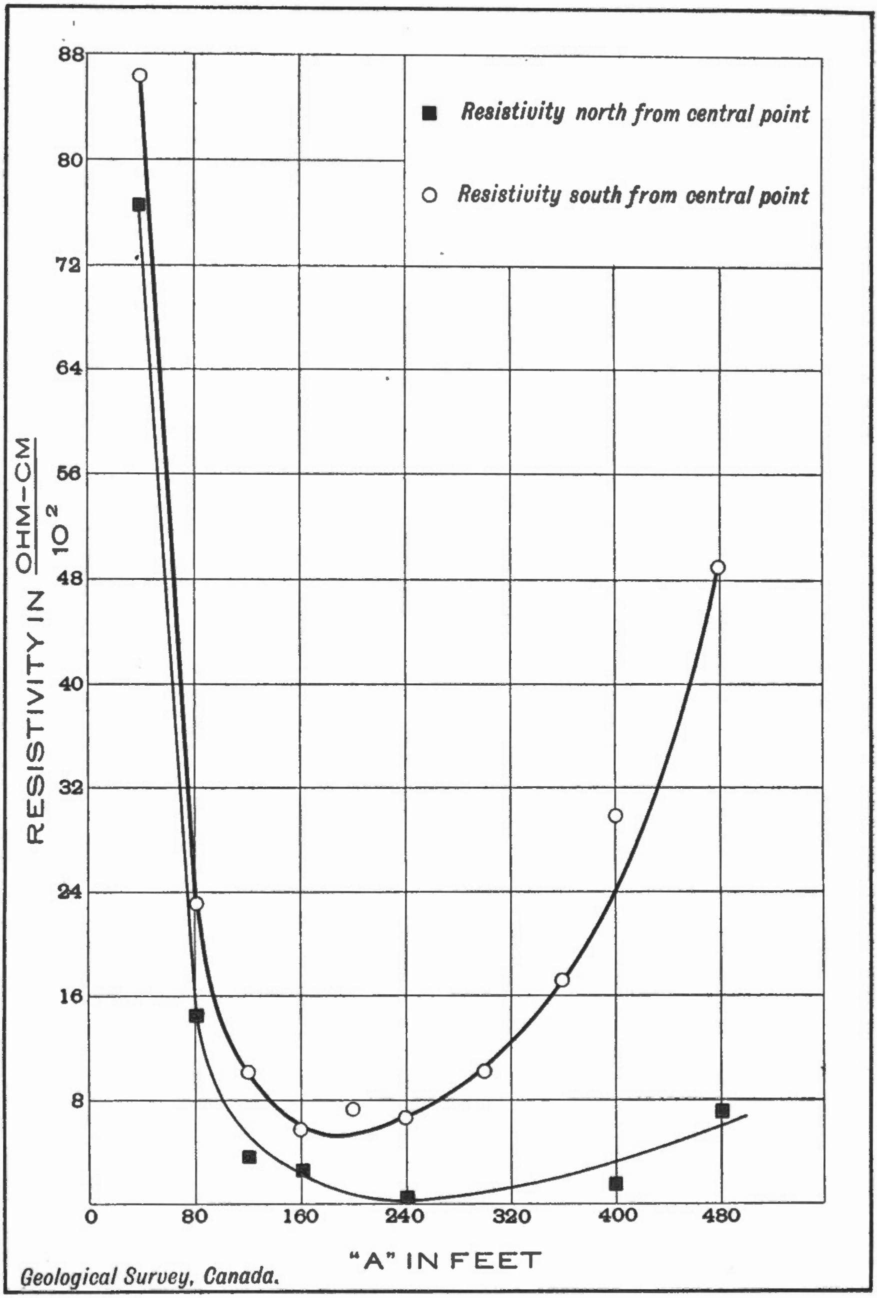

Figure 23. Mean resistivity curves by Lee method, indicating presence of a better conductor to the north—probably graphitic slate—Errington mine, Ontario.

the east and west directions from P, are approximately the same. Such a result is to be expected, since the strike is along this direction. In Figure 22 there has been plotted, also, the values of the mean resistivities along the north-south directions (which is across the strike of the body) vertically and the corresponding electrode separation or equivalent depth "A" horizontally. When A becomes equal to the depth of the body below the surface, the values of the mean resistivities along the body, that is along the east-west line, will become less than those along the north-south line which cuts across the body. The point where these two curves diverge gives the approximate depth of the body below D. This divergence occurs between 100 and 120 feet, the actual depth being about 112 feet. The agreement is a striking verification of the principles underlying the method and gives an excellent idea of its possibilities.

Numerous surveys were made at the Errington mine near Bradley, Ontario. The geological structure here makes it difficult to find the " pay-ore " by any resistance or electrical conductivity method. There are numerous sheets of good conducting graphitic slate and tuff as well as small scattered veins of pyrite. The good ore from the mining point of view consists of a quartz-carbonate gangue which contains sphalerite, galena, and chalcopyrite, but is a poor electrical conductor. The resistivity and induction methods will locate the good conducting sheets or layers of graphite and not the quartz-carbonate bodies. However, it is of interest to give an example of how good conducting areas were located, though in this case their practical value was of little account.

One survey will suffice as an illustration. A point was chosen 240 feet southeast of drill hole No. 828, which lies north of No. 3 shaft. The resistivity curves for a survey north from this point, and also south, are shown in Figure 23. The curves indicate that the resistivities rise slightly to the south, a fact which is confirmed by the underground workings of this shaft. The low resistivities to the north are probably due to the layers of graphite and pyrites lying to the north. A river passed the north line 610 feet from the central stake, but its presence would have little effect on the intermediate readings. The results here are as good as they were at the Falconbridge mine from a scientific point of view, but a conductor at Errington does not mean valuable ore as was the case at the Falconbridge. Hence the warning to all who employ electrical means of geophysical prospecting that though electrical conductors are found their value is only determined by the diamond drill or other development work.

Problem IX

ON THE MULTIPLE WING, SINGLE ELECTRODE METHOD OF GROUND RESISTIVITY SURVEYING

Dr. L. Gilchrist suggested that the use of two or more distant electrodes instead of only one[1] as employed in the single electrode probe method would enhance the value of the results to be obtained from such surveys. The presence of the second distant electrode on the opposite side of P, the central electrode, would make the equipotential bowls[2] more circular

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[1] *See* the report on the work done at Abana, p. 167.

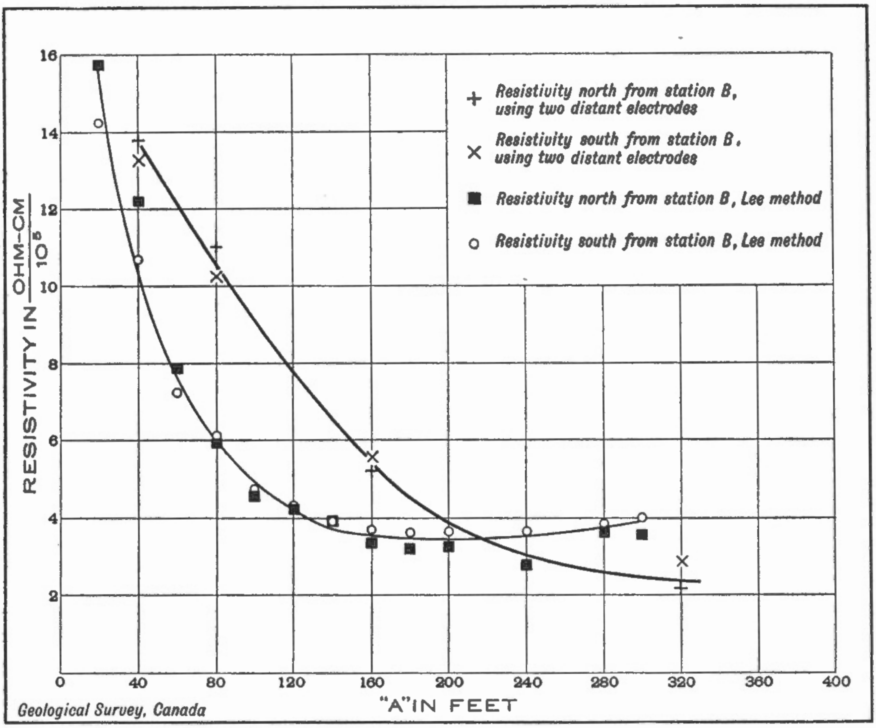
[2] *See* Eve and Keys: "Applied Geophysics", pp. 107-108.

or spherical in homogeneous ground. Theoretically the larger the number of distant stakes that are placed symmetrically about the central electrode, each with the same resistance so as to supply the same current, the more accurately will the resulting equipotential curves or mean resistivities calculated therefrom, disclose the presence of a disturbing conductor. To what extent this multiple or two-wing electrode method affects the resistivity measurements is the object of the present investigation.

As explained in the work done with the megger at the Abana mine (*See* pages 163-178) this method has distinct advantages under certain conditions. In applying it to the usual resistivity measurements as carried out in former problems the procedure is as follows. The resistances of each circuit to the two or more distant electrodes are made of the same, either by alternating the amount and number of stakes driven into the ground, or by inserting auxiliary resistances in each circuit. When such a balance is obtained, the same current will flow from each of the distant stakes to the central electrode. This will make a symmetrical distribution of potential towards each of the distant electrodes starting from the central one. Any inhomogeneity in the ground will disturb the distribution of potential in its vicinity. In these experiments from 10 to 16 B batteries were used as the source of current, a reversing switch being inserted in the circuit with the ammeter for changing the direction of the current. Each distant electrode was connected with the batteries by a single pole switch, so that either one, two, three, or four electrodes could be connected simultaneously. This also permitted the far electrodes to be used in pairs as well. The other terminal of the battery was connected to the central electrode P.

It is desired to investigate now the effect on the resistivity measurements when two distant electrodes are used instead of one. To do this the central stake or electrode was set up at B (*See* Figure 16) on the Falconbridge Mines property. One distant electrode was placed 900 feet east of B and the other 900 feet west of B. Surveys were then made north and also south of B in exactly the same manner as when the single electrode probe method was used. The results of this survey are plotted in Figure 24, which gives the mean resistivities as vertical distances and the electrode separation or depth as horizontal distances. For comparison purposes the results of a survey over the same line using the Lee modification of the Gish-Rooney method are also given. The curves differ from one another, but it cannot be inferred from the results of this experiment what the depth of the ore-body is. There is some indication, however, as the Lee curve also shows, that at lower depths the resistivities to the north become less than they are to the south, the presence of the conducting ore-body 100 feet to the north being the probable explanation of this fact. It is fairly obvious, however, that more information is to be gained from the Lee curve than from the two electrode ones (*See* page 124).

To test the method further, a second and more extensive series of experiments were made on the Errington Mine property over a hay field about 1,300 feet north of the river which flows north of shaft No. 3. The area had previously been surveyed by the Lee modification of the Gish-Rooney method and found to contain a deposit of good conducting material, probably graphitic, about 150 feet or more beneath the surface. This point was made the centre of the survey where the central electrode was placed. An insulated wire was run out 911 feet north from this point, and attached to a group of iron stakes driven well into the ground. A second wire was carried 915 feet east and connected to another iron stake. Two other wires, one 874 feet to the south, and the other 1,200 feet west of the central electrode, were laid out and each attached to a well-grounded electrode.



Geological Survey, Canada

Figure 24. Resistivity curves using two distinct electrodes and the Lee method, station B, Falconbridge mines, Ontario.

The stake resistances of each of the four distant stakes were adjusted until the current flowing from each one to the central electrode was approximately the same. The following table gives the values of the currents through each stake when a set of B batteries was connected between the central electrode and each of the four distant stakes in turn.

Direction	Current in milliamps
North	77
East	75
South	75
West	75

The above table shows that the four circuits were fairly well balanced. The potential porous pots were placed one at 50 feet and the other at 150 feet from the central stake, first along the west line and then along the south line. The mean resistivities were calculated from the currents and corresponding potential readings in the usual way. Various combinations of the stakes were made and the corresponding resistivities calculated. The results are tabulated in Table XIII. The figures indicate that there is no marked difference introduced by any of the combinations. In other words, so far as this region is concerned and for this particular depth of survey, there is nothing additional to be gained by using more than one distant electrode. There is a difference of roughly 90 ohm-cms. between the readings taken along the north line and those taken along the west line. The resistivities by the previous survey using the Lee method also showed that the resistivities were greater towards the north.

TABLE XIII

Distant stakes connected	Mean resistivities in ohm-cms. with porous pots along the lines	
	North	West
Only north	1,233	1,140
" east	1,227	1,145
" south	1,240	1,140
" west	1,233	1,145
North and south	1,233	1,145
East and west	1,230	1,128
North + south + east + west	1,227	1,138

The series of measurements was repeated with the potential porous pots at 100 feet and 400 feet, respectively, from the central stake. The resistivities were calculated this time when the potential electrodes were placed along the north, south, east, and west line. The four distant stakes were again connected in the circuit in the various combinations used in the previous series. The results are tabulated in Table XIV.

TABLE XIV

Distant stakes connected	Mean resistivities in ohm-cms. Potential porous pots placed along the line			
	North	East	South	West
Only north	2,730	3,290	5,080	4,870
" east	2,908	2,860	5,130	5,000
" south	2,808	2,930	5,050	5,080
" west	3,010	3,462	5,110	5,120
North and south	2,908	3,060	5,130	4,890
East and west	2,930	3,190	5,030	4,970
North + south + east + west	2,930	3,060	5,120	4,770

The values given in Table XIV indicate that the value of the resistivity obtained with a single electrode in any of the four directions with respect to the line along which the potential readings are taken is practically the same as that found when two or more electrodes are used. It can, therefore, be stated that in so far as these experiments are representative of practical surveys, the single distant electrode gives the same values for the mean resistivity as the multiple electrode method.

The resistivities are seen to be higher in the south and west directions, a result which is the reverse of that found in the previous table. But the reader is reminded that the values given in Table XIII are the mean resistivities to a depth of 123 feet, whereas the values given in Table XIV are the mean resistivities to a depth of 283 feet.

It was desirable to investigate the effect of bringing the distant electrodes closer to the central electrode on the mean resistivities obtained from the current and potential readings. Theory indicates that the potential bowls[1] will no longer be spherical when the distance of the far electrode becomes less than four times the distance of the potential electrodes from the central stake. To test this point, the four distant electrodes were moved in to 600 feet from the central stake. The resistance in each circuit was adjusted until the currents were as follows:

Stake	Current in milliamps
North	104
South	109
East	112
West	116

These are not equal, but are sufficiently well belanced for the present purpose. The two potential porous pots were placed 100 feet and 400 feet, respectively, from the central stake. A series of readings was taken similar to that shown in Table XIV. The results obtained under the present conditions are shown in Table XV.

TABLE XV

Distant stakes connected	Mean resistivities in ohm-cms.
Only north	4,870
" east	5,000
" south	5,080
" west	5,120
North and south	4,890
East and west	4,970
North + south + east + west	4,770

These results are rather remarkable, for they indicate that there is no appreciable difference in the mean resistivities obtained when the electrodes are 900 feet and 600 feet away from the central stake. Whether this is true in general is open to question. Further experiments in different localities will have to be carried out before such a result can be accepted as holding absolutely. The resistivities in this region (Bradley) are unusually low, due to the abundance of graphite, so that the fall of potential, as a and b are increased, is small.

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[1] *See* Eve and Keys: "Applied Geophysics"; pp. 107–110; also U.S. Bureau of Mines, Information Circular No. 6171, 1929.

Problem X

THE RESISTIVITY OF GRAPHITIC ROCKS

The difficulty of finding ore at the Errington mine by a resistivity method has already been mentioned in Problem VIII, page 122. The slate and tuff which occur in this region contain besides the occasional veins of pyrites, an unusual amount of good conducting graphite. According to analyses of typical specimens,[1] the slate contains 2·92 per cent and the tuff 0·48 per cent carbon. This carbon is present in the form of graphite. Two specimens were picked up at random from a heap of diamond drill cores and their resistivities measured by the plan described in Problem IV, page 111. The values found were: (1) 0·815, and (2) 4·73 ohm-cm. These remarkably low values would account for the indications obtained by resistivity measurements in Bradley region. The quartz-carbonate gangue of the veins on the other hand has about the same resistivity as the surrounding slate or tuff and so its location is obscured.

As a result of these preliminary experiments, a number of typical specimens of diamond drill cores of tuffs, slates, and vein material were selected by Dr. J. B. Mawdsley. The resistivity of each specimen was obtained by either a potentiometer method or by a direct method. The potentiometer method was used in the cases where the resistance of the sample was low and the other scheme when the resistance was high. The results of this investigation are given in Table XVI.

An inspection of this table will show that there is considerable variation in the resistivities of the different samples of tuff and slate. On the average the tuffs have the higher values.

TABLE XVI

Mean Resistivities in ohm-cm.

Tuffs	Slates	Contact or vein material
159×10^6	163×10^6	11×10^6
33×10^6	110×10^6	greater 900×10^6
55×10^6	1·27	25×10^6
223×10^6	3·46	279×10^6
90×10^6	0·95	57×10^6
280×10^6	0·82	32×10^6
52×10^6	4·62	39×10^6
13×10^6		greater 3600×10^6
248×10^6		
12×10^6		
15×10^4		
67×10^3		
91×10^3		
3610		
465		
78·5		
0·82		

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[1] "The Sudbury Nickel Intrusion" by A. P. Coleman, E. S. Moore, and T. L. Walker, p. 39: University of Toronto Press, 1929.

The vein material has a uniformly greater resistivity. The low values of the slates and the high values of the tuffs and vein material make it an exceedingly difficult problem to locate ore. It can safely be concluded from the resistivity work done in Bradley region that ore cannot be located by a resistivity method. The same statement may perhaps equally well be applied to an induction method.

THE SELF-POTENTIAL METHOD

When masses of metallic sulphides are exposed to oxidation by water or other means, they behave like large batteries in the ground and become sources of electric currents. As a result there is usually a current flowing through the ground from the lower parts of the deposit to the upper parts. The upper part becomes what is usually called a negative centre[1] because the currents all flow into that region from the ground around. Such currents may be detected by using as electrodes two non-polarizable porous pots.[2] These pots are placed in small holes scooped out of the ground and well watered. Copper electrodes in the pots are connected by wires to either a portable potentiometer or a portable microammeter. When the pots are placed 100 feet apart the potential difference between them may be found by means of the potentiometer.

The object of the survey by this self-potential method is to find the negative centres, for the ore is usually found beneath such points. When the ore is oxidizing and within 100 feet of the surface with ordinary ground as overburden, the method is quite successful. In practice there are two ways of making a rapid survey to locate areas of negative centres. The one is to locate equipotential lines on the surface, which form closed curves. This is done by placing an electrode in one hole and moving the other 100 feet away, hunting for a position so that there may be no potential difference between the two holes. The stationary pot is then advanced to the hole occupied by the other and the forward one is carried on 100 feet to another point on the same equipotential curve. Proceeding thus the curve is completed and will be found to close. Next one electrode is left in one of the holes on this curve and the other carried about 100 feet or less away in a direction at right angles to the curve. The direction, whether to the right or to the left of the equipotential line, will depend upon the way the potential decreases. The pot is carried to the side on which the potential becomes less, as indicated by the reading of the potentiometer. The new point having been found in this way, a second closed equipotential is surveyed as already explained. This second curve will lie entirely within the first. Proceeding thus the negative centre is gradually approached and may be identified.

A second way is simply to choose a given direction and find the potential drop for every 100 (or possibly 50) feet along this line. When the line crosses a point near the negative centre and then begins to leave it behind there will be a reversal in the direction of the potential. Thus the reversal in the direction of the flow of the current gives an indication of the presence of the oxidizing ore-body. There are often

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[1] *See* Eve and Keys: "Applied Geophysics", p. 54.

[2] *See* p. 107, or Eve and Keys: "Applied Geophysics", p. 58.

natural currents in the earth due to other causes, but these are of relatively small intensity. Indications of less than 20 millivolts per 100 feet are in most cases unreliable as far as being evidence of the presence of an oxidizing ore-body.

Several surveys were made using this method both at the Falconbridge nickel mines and at Bradley. Since the ore at the Falconbridge mines contains sulphide, the method was used first here as a check on the electrical methods already described. A survey using 100-foot intervals was made along the line C B D shown in Figure 16. The survey commenced at station C and was carried north for 900 feet. The results are given in Table XVII and are also shown graphically in Figure 25,

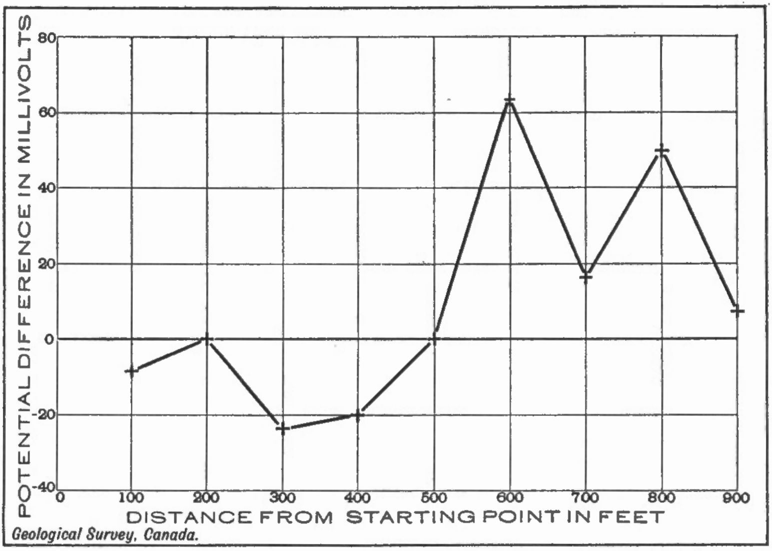

Figure 25. Results of self-potential survey along line C B D, Falconbridge mines, Ontario.

TABLE XVII

Stations	Potential difference in millivolts
(C) 0—100	— 9
100—200	0
200—300	—24
300—400 (B)	—20
400—500	0
500—600	63
600—700	16
700—800	50
800—900	7

where the distances are plotted horizontally and the potential difference for 100 feet interval vertically. It will be evident that there is a reversal at 500 feet north of station C which coincides exactly with the position of the ore-body as shown in Figure 16. This is a good example of the success of this method of geophysical prospecting when it can be used. A second survey was made starting from a point 400 feet south of station A (*See* Figure 16) and running directly north. The results of this survey are given in Table XVIII. The reversal this time takes place at Station A, which lies about 70 feet to the south of the ore-body.

TABLE XVIII

Stations	Potential difference in millivolts
0—100	0
100—200	−20
200—300	−17
300—400 (A)	8
400—500	30
500—600	25
600—700	34
700—800	33

It is concluded from these two surveys that the method is one that may be used with success under the conditions that exist at the Falconbridge mines, near Garson, Ont. The overburden is glacial drift, sands, and gravels, and the top of the ore-body is 100 feet down, so that detection by this method is remarkable.

The self-potential method was also applied on the Errington property in several places. The method appears to be the only reliable one to use over such a formation, where the presence of highly conducting slate and the absence of magnetic material with the ore, rules out the application of other electrical and magnetic methods. The only difficulty appears to be that in addition to the veins of ore, there are seams of pyrite which on oxidation produce currents in the ground, which give rise also to the potential-differences as well as the ore. Three examples will be given of surveys made over different portions of the Errington Mine property which will be sufficient to illustrate the possibilities of the method in this district.

The first survey was made with a potentiometer and porous pot electrodes along the road running past No. 3 shaft of the mine. The survey commenced 30 feet east of the bridge over the stream below the mine and continued east along the side of the road for 3,400 feet, readings being taken every 100 feet. When the current flowed to the west, the reading was called plus and when in the opposite direction, minus. The results of this survey for a distance of 2,500 feet are shown in Figure 26. The graph shows only one or two marked reversals of sufficient magnitude to give evidence of underlying ore. These effects were in all probability due to pyrite.

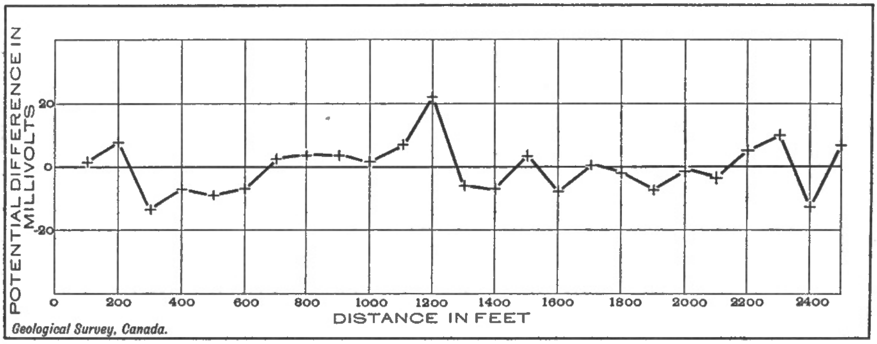

Figure 26. Results of self-potential survey along road east from No. 3 shaft, Errington mine, Ontario.

Two surveys were then made over a vein of ore which outcropped north of shaft No. 1. Both surveys gave definite evidence of the ore, as was to be expected since the conditions were so favourable. One of these is plotted in Figure 27. Two veins are indicated, the first just left of the road to shaft No. 1 and the second, where the reading was greatest, being directly over the vein that outcropped. The effects in this case are quite definite.

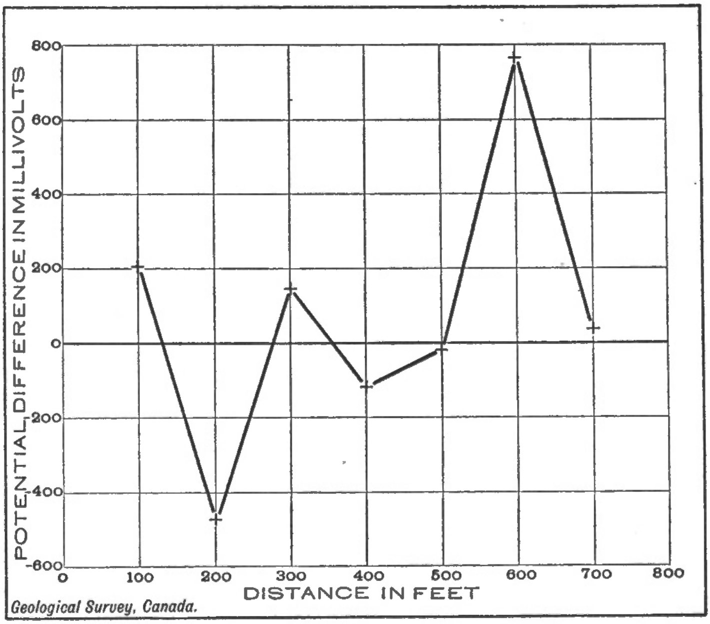

Figure 27. Results of self-potential survey along line crossing ore outcrop north of No. 1 shaft, Errington mine, Ontario.

A third survey was made with the self-potential method across the playing field near shaft No. 1. The results of this survey are shown in Figure 28. An inspection of this graph will show that there are no positive indications of anything except just at the end of the survey. This was near the river and may not have been caused by the presence of oxidizing ore. Ore was probably crossed about the 900-foot mark, but it should be remarked that what ore there is at this point is covered with an overburden of 50 feet or so of very dry, sandy soil. Such an overburden would be a poor conductor of electricity and it is not surprising that the indications in this case are so small. On the whole the indications obtained on this survey are sufficiently strong in the circumstances to indicate something and yet are not great enough to warrant assurance. In conclusion, it may be said that the self-potential method proved to be the only method of locating ore at the Errington mine and the results obtained were only satisfactory when the survey was made over oxidizing ore near the surface.

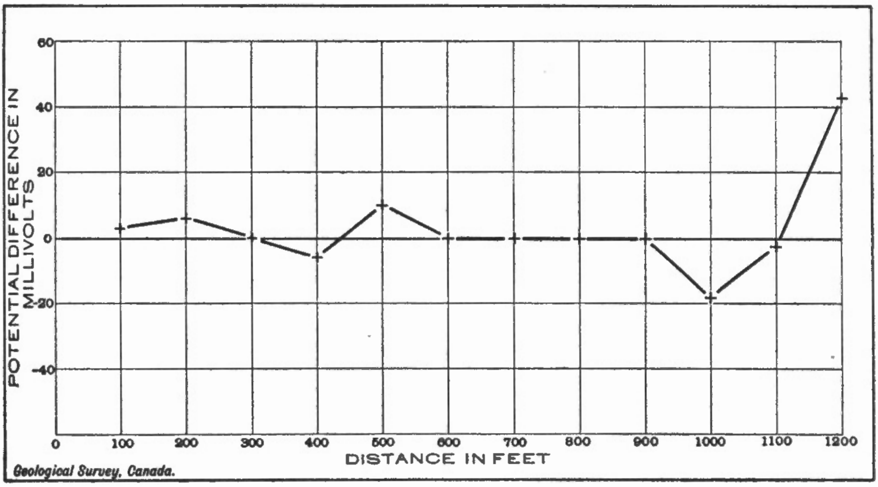

Figure 28. Results of self-potential survey along line crossing playing field near No. 1 shaft, Errington mine, Ontario.

It must be remembered that the current tends to flow along the upper layers of the earth *towards* an oxidizing sulphide ore-body underground, whereas the current tends to flow *from* a similarly situated carbon or graphite body.

MAGNETIC SURVEYS

The magnetic dip needle was the first instrument to be used extensively in connexion with geophysical prospecting and in the Thalen-Tiberg form is familiar to mining engineers. The magnetic inclinator is, of course, only useful in locating such magnetic ores as magnetite, pyrrhotite, and a few others. Large areas have been surveyed with this instrument, especially in Canada where the late Dr. Haanel was a pioneer in its use among the

English-speaking peoples. In recent years a much more sensitive form of magnetic balance or variometer has been developed. This instrument[1] may be constructed in such a way as to measure either the horizontal or the vertical component of the earth's magnetic field. Several surveys were made during the summer with the Askania type of vertical balance. The results of these experiments are contained in this section and these investigations will give some idea of the application and limitations of the instrument. The work naturally falls into certain divisions and will consequently be described under their appropriate headings.

Problem I

TO CALIBRATE AN ASKANIA VERTICAL VARIOMETER

In carrying out field work with a vertical variometer it may be desirable to calibrate the instrument and also to find its sensitivity. Incidentally it will be shown that the scale of the deflexion caused by a change in magnetic field is a linear one. The sensitivity is usually expressed in the strength of the magnetic field (in the present case the vertical component of the field) required to produce a deflexion of one scale division. The customary unit used for the strength of a magnetic field in this work is the gamma, γ, which corresponds to a field strength of 10^{-5} gauss. Since the deflexions observed are usually small, the readings should be directly proportional to the change in the strength of the vertical magnetic field. When the changes become too large, an auxiliary magnet is placed in the holder provided beneath the balance and its distance from the instrument adjusted until the zero reading of the needle is brought into the field of view. The magnetic moment of this auxiliary magnet is known and its distance from the axis of the balance observed, from which the vertical field produced by it may be calculated.

To test the linear nature of the scale, the magnetometer was set up at the centre of a circular coil of ten turns of insulated wire 50 feet in radius. Actually the coil used was the one described in section I, Problem III, page 94 of this report. A direct current from a number of B batteries was passed through this coil and the corresponding deflexion of the variometer observed. In table XIX the readings of the instrument for various currents through the coil are given.

TABLE XIX

Current in amperes	Askania instrument		
	Reading current on	Reading current off	Deflexion
0·237	25·2	22·5	2·7
0·473	28·2	22·5	5·7
0·752	31·0	22·3	8·6
0·960	33·8	22·3	11·5
1·276	36·5	22·4	14·1
1·435	39·5	22·4	17·1
1·673	42·4	22·3	20·1
1·980	45·3	22·3	23·0
2·130	48·2	22·4	25·8

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[1] *See* Eve and Keys: "Applied Geophysics", pp. 29–48.

These results are plotted in Figure 29. The magnetic field at the centre of the coil where the variometer is placed will be directly proportional to the change in the strength of the magnetic field.

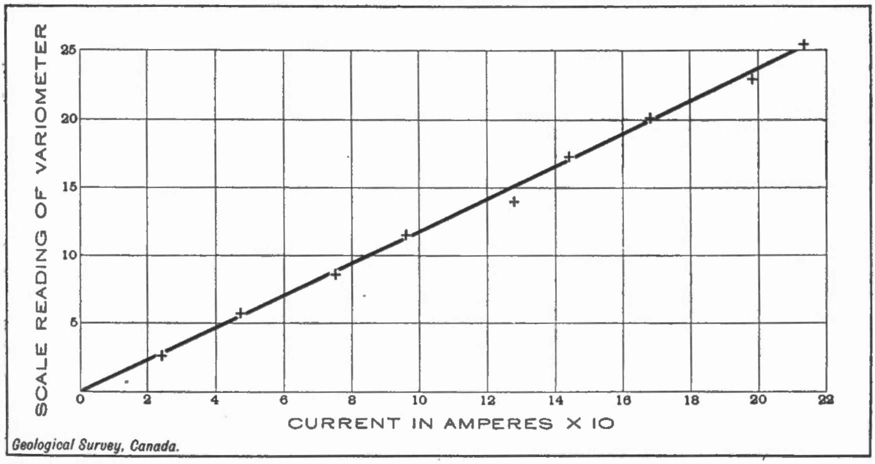


Figure 29. Calibration curve of Askania vertical variometer.

To obtain the sensitivity of the instrument, it is noted that the slope of this line will give the deflexion caused by the magnetic field produced at the centre of the coil of wire by a current of one ampere. The vertical field produced at the instrument by a current of one ampere passing through the coil may be calculated as follows. The height of the magnetic needle above the ground is 3 feet. The radius of the coil is 50 feet and the number of turns ten. Hence the field at the centre is

$$= \frac{2\pi \times 10 \times 50^2}{10\ (3^2+50^2)^{3/2} \quad \times 30{\cdot}5}$$

$$= 4{\cdot}10 \times 10^{-3} \text{ gauss.}$$

From the slope of the curve, it is found that a current of one ampere produces a deflexion of approximately 11·6 divisions. Hence

11·6 divisions are caused by 410 x 10^{-5} gauss

1 division is caused by 35·1 x 10^{-5} gauss

$= 35{\cdot}1\gamma$.

The sensitivity of the instrument is, therefore, about 35 γ a division. The calibration of the same instrument before leaving Germany a few months previously was 29 γ.

Problem II

THE USE OF THE VERTICAL MAGNETIC VARIOMETER IN THE LOCATION OF A BODY OF PYRRHOTITE

Already in section II, Problems 6, 8, and 9, it has been explained how the position and depth of a conducting body of pyrrhotite were determined by resistivity methods. The variometer may be used with equal success to locate the position of such bodies and surveying with it is both rapid and accurate. The vertical variometer, however, gives no indication of depth. The object of this investigation is to illustrate the application of the instrument and to confirm the work of the resistivity experiments.

To commence with, the variometer was set up at a point 200 feet south of station A (*See* Figure 16) and a survey made along the north-south line through this point. The results of this survey are shown in Figure 30. It will be seen that the maximum reading lies about 100 feet north of station A and a comparison with Figure 16 will indicate that this is about the actual position of the ore as determined by diamond drilling. The reader is reminded that the vein dips to the north at an angle of about 80 degrees.

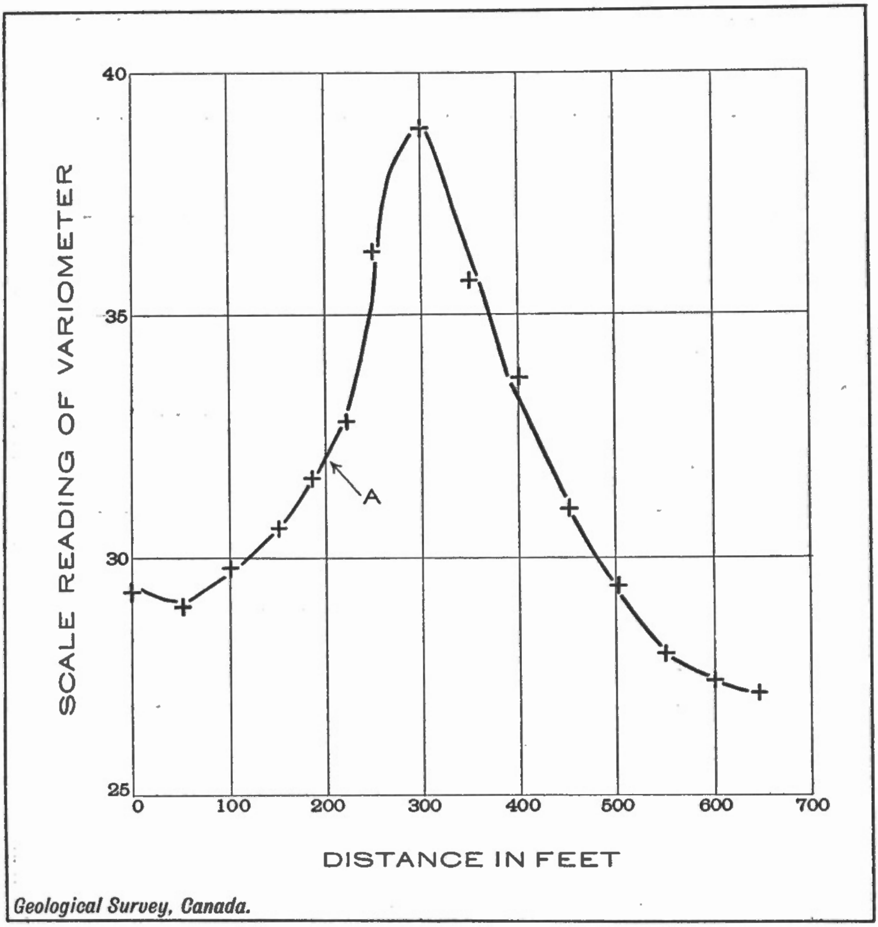


Figure 30. Results of magnetic survey with an Askania vertical variometer, along north-south line through point A, Falconbridge mines, Ontario.

A second survey was made along the north-south line through C, B, and D, commencing at the point C which lies 400 feet south of B. The survey was made running north from this point. It will be remembered that this is the same line surveyed by the resistivity methods, so there will again be obtained a comparison between the two methods. The readings at the various points are shown in Figure 31. The readings became so large that the compensating magnet No. 3 was placed 340 mms. below the instrument to keep the deflexions on the scale. Corrections were then added for the field due to this auxiliary magnet. This is simply made as follows. When the reading became 44·4 divisions, the magnet was screwed into position and the reading repeated at the same place. It was now 2·4 divisions. Hence to all readings taken with the auxiliary magnet in this position must be added 42·0 divisions. The points B and D are indicated on the graph

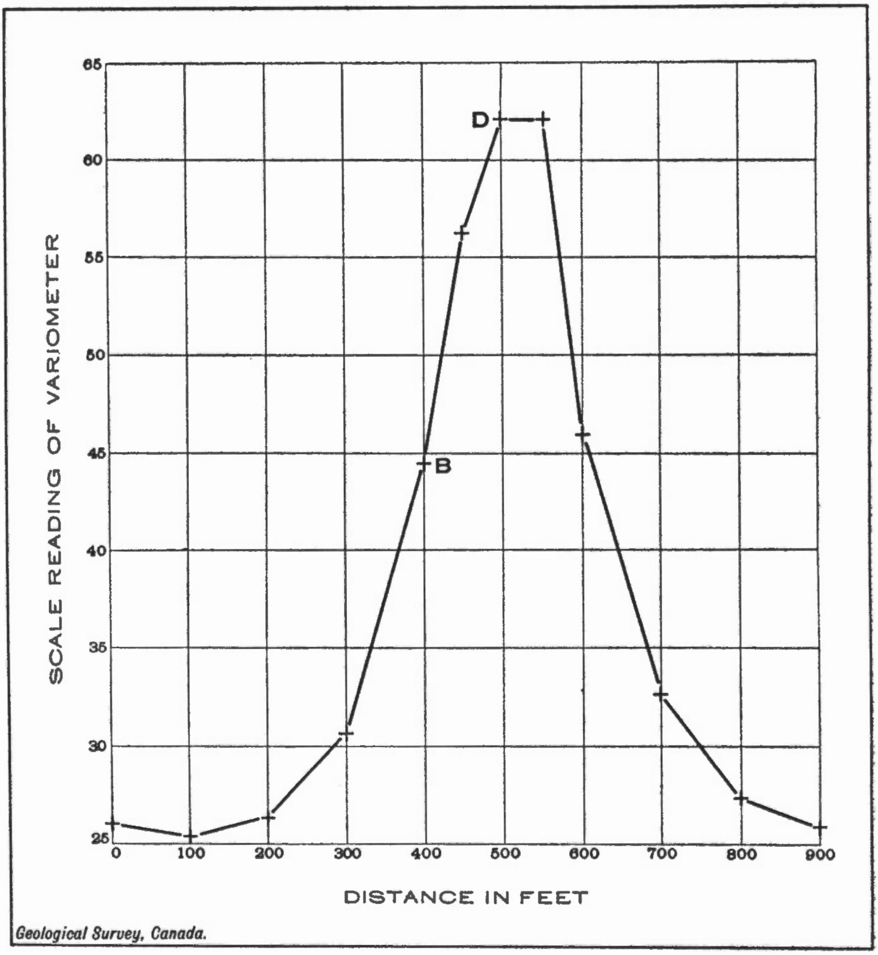
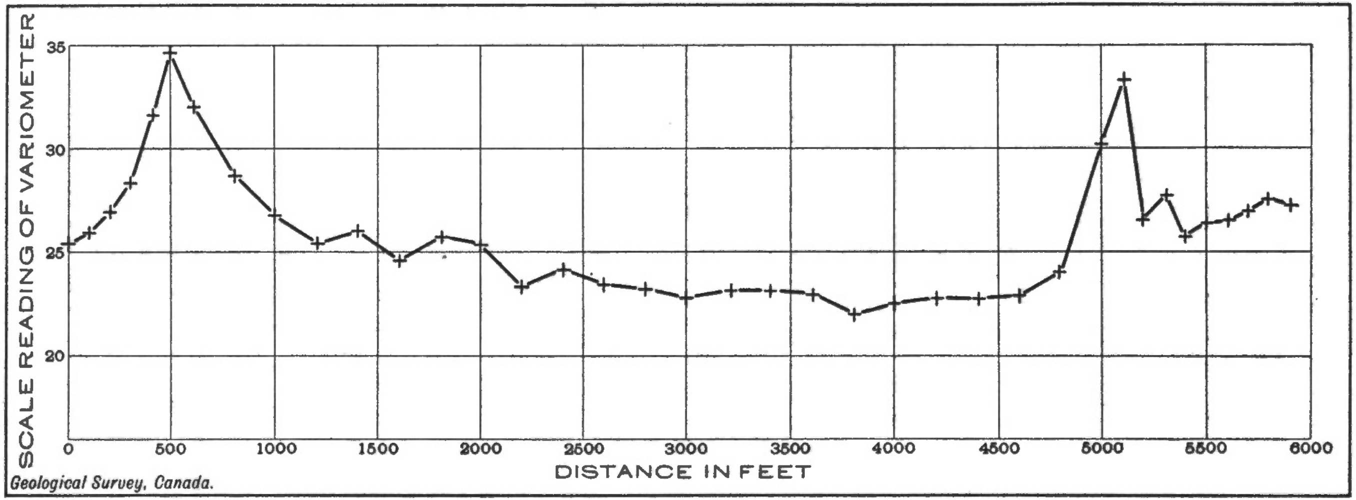


Figure 31. Results of a magnetic survey with an Askania vertical variometer, along line C.B.D., Falconbridge mines, Ontario.



Geological Survey, Canada.

Figure 32. Results of a magnetic survey with an Askania vertical variometer, along a line crossing the ore-body of Falconbridge mines, Ontario.

so that a comparison with Figure 16 will show how accurately the survey indicated the presence of the pyrrhotite body. Incidentally the effect on the reading of turning the instrument 10 degrees from the magnetic meridian was investigated. It was found that this only made a difference of 0·2 divisions in the reading. A slight error in levelling the instrument, however, made a relatively large change in the readings, so the instrument must be carefully levelled when taking any observations.

These two surveys will indicate to the reader the relative ease with which such a magnetic variometer may be used in the field for locating magnetic veins. The depth of the overburden can then be determined by the resistivity methods.

Problem III

THE DETECTION OF A NEW MAGNETIC ORE-BODY BY MEANS OF THE ASKANIA VERTICAL VARIOMETER

In problem II the use of the vertical magnetic variometer in locating a pyrrhotite-bearing body was indicated and the surveys were made over a region which was known from diamond drill records. The results, as have been seen, are in excellent agreement with the known facts. The present problem indicates the method of procedure to locate a new body. For this purpose a survey was made along a north-south line which crossed a swamp. The line lay about a quarter of a mile east of the point A shown in Figure 16. Readings were taken every 200 feet except for a few points at the extreme north end of the survey, which was 600 feet north of the main east-west line shown in Figure 16.

The results of this survey are shown in Figure 32. It will be seen that the known ore-body is readily found 500 feet south of the north end of the survey and that another vein or ore-body is indicated about the point 5,100 feet. The presence of this body was not previously known and no drilling has been done to confirm the results of the survey at this point. Time did not permit of other surveys being made in the region nor of any resistivity measurements being taken. There is a small outcrop of quartzite and conglomerate just south of the indication. Such a survey took less than four hours and was over a very difficult country for setting up the instrument. It is, indeed, a striking example of the use of the magnetic variometer in geophysical prospecting.

Problem IV

MAGNETIC WORK AT THE TREADWELL-YUKON ERRINGTON MINE

Several surveys were made with the vertical magnetic variometer near Bradley, Ont., but the results of these surveys have no relation to the presence of the ore which is sought in that region. The results only indicate local deposits of magnetite, apparently, which are scattered throughout the area. Two curves will be given illustrating the magnetic variations along two lines which were also surveyed by the self-potential method. The first of these is shown in Figure 33, which indicates the readings obtained going east along the road below the No. 3 shaft of the Errington mine. The survey along the same road by the self-potential method is shown in Figure 25.

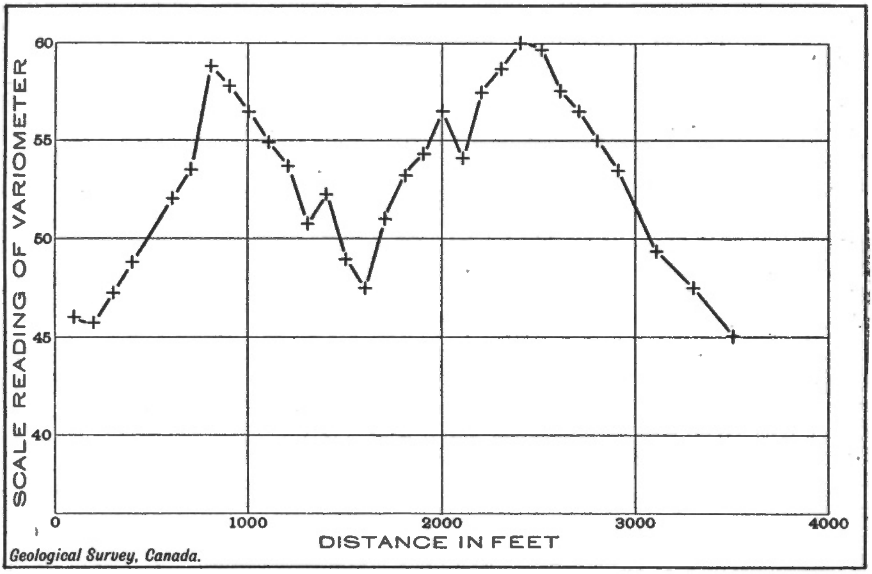


Figure 33. **Results of a magnetic survey with an Askania vertical variometer, along road east from No. 3 shaft, Errington mine, Ontario.**

A second survey along a line near Plan No. 2 shaft at the Errington mine is given in Figure 34. The readings are rather irregular and no significance can be attached to them.

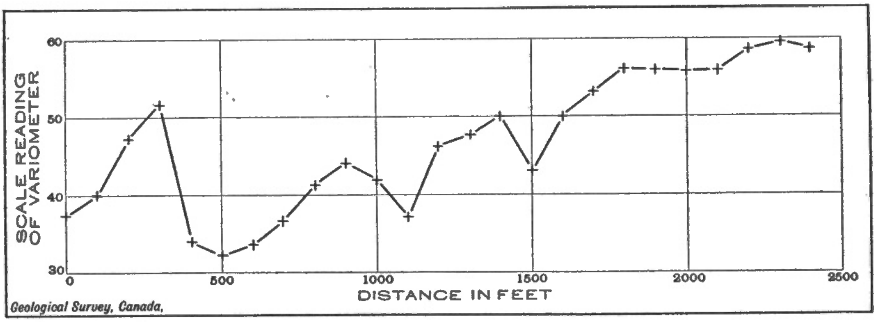


Figure 34. **Results of a magnetic survey with an Askania vertical variometer, along a line near No. 2 shaft, Errington mine, Ontario.**

The writers are forced to conclude from their magnetic work at Bradley that the variometer is of no practical aid in locating the quartz carbonate ore.

Problem V

LARGE SCALE MAGNETIC SURVEY

For the purpose of finding out what could be done by a large scale magnetic survey, readings were taken with the Askania vertical variometer every mile along the road that ran from Bradley to the Levack mine. Such large intervals are naturally of little use in making a detailed survey, but the curve obtained is interesting in that it shows two very distinct indications. The first occurred 4 miles from Bradley and was in a place surrounded with hay fields and with no outcrop of rock whatever. Several readings taken in the region showed that there was a very high indication at this point. What it was due to is not known. The second occurred about 1½ miles from the Levack mine when crossing over the ridge of the basin. This evidently is due to mineralization below. On making inquiries at the mine the writers were informed that no surveys had been made in that neighbourhood.

Such a result illustrates the possibilities of large-scale surveys. Twenty or 30 miles could be covered readily in a day and where the indications are large more detailed work could be carried out. If the results of the detail magnetic survey are promising, then resistivity measurements could be made for obtaining depth of the overburden. With the aid of the geologist and such magnetic and electrical surveys, much labour and time might be saved in the preliminary location of possible deposits.

THE BIELER-WATSON METHOD

By H. G. I. Watson

Introduction

This is a method which depends for its functioning on the existence of an elliptically polarized magnetic field.[1] Such a field is present in all alternating current methods whether a current is fed into, or induced in, the ground, although its existence in the former case is due to the creation of induced secondary currents by the original current. Up to the present the method has only been applied to inductive methods using a horizontal loop laid on the ground. Measurements are made of the ratio of magnitude of the minor to major axis of the polarization ellipse, the azimuthal direction of the minor axis, and the nature of the ellipse (whether it be formed by the clockwise or counterclockwise rotation of the generating vector). From these results it is possible to outline any lenticular conducting body in the area investigated or to give a plan of any conducting vein as well as an indication of its dip and depth.

Theory

To illustrate the principle of elliptical polarization the simplified case illustrated in Figure 35 is considered. It is a vertical section, E E represents the earth level, X and Y represent cross-sections of two sides of

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[1] *See* Eve and Keys: "Applied Geophysics", p. 113.

the loop. The primary field is shown being nearly vertical everywhere. The induced current tends to concentrate about the points P and Q in the ore-body. For simplicity the ore-body and the loop are considered to be infinite in extent, perpendicular to the paper, so that the end effects of the body can be neglected. For simplicity, the effect of the current

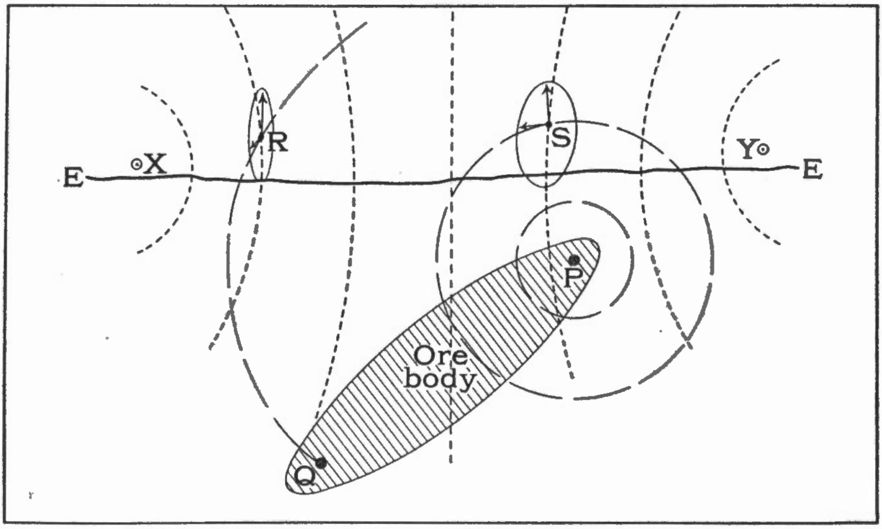

Figure 35. Diagram illustrating the principle of elliptical polarization, Bieler-Watson method.

in Q is also disregarded, so that the secondary field will be represented by concentric circles as shown (refractive effects are also omitted for simplicity). Due to transformer action alone, the E.M.F. in the ore-body is 90 degrees out-of-phase with the primary field and—if there are no appreciable reactive effects in the ore-body—the secondary currents and hence the secondary fields are also 90 degrees out-of-phase with the primary field. The result at points S, R, will be two linear harmonic magnetic fields at an angle to each other and out-of-phase 90 degrees. The resultant is a single rotating and varying magnetic field of which the extremity of the representative vector traces out an ellipse. Such a field is said to be elliptically polarized. It will also be noticed that the ellipse is " fatter " over the end of the body at S than at R. This fact is due to the decrease of field intensity with distance and to the fact that the two fields tend to become coincident in direction. This latter property is enhanced by the refractive effects of the rock.

It should be noticed that if the arrows at R, Figure 35, represent the two fields produced by the primary field and the secondary field of P then an arrow to represent the same effect due to the current in Q must point towards the right since it is in the opposite sense to that in P. In this way it is possible to distinguish which side of the body is represented by a certain indication.

Apparatus

To produce the primary field a loop consisting of a single turn of insulated wire is laid out in any desired shape—usually rectangular—and of size depending upon the power available, the sensitivity of the detector, and local conditions. The loop is formed of rubber-insulated, black-covered wire, of size capable both of withstanding dragging through timbered areas, and not causing too great a useless I^2R loss. Wire of No. 10 to 14 B and S gauge serves well.

As a source of power a 500-cycle generator (in this particular case one of the 200 watts capacity) is used and is driven by a small gasoline motor (an outboard motor suitably mounted upon a barrel, filled with water for cooling purposes, has served well) or an electric motor in localities supplied with electricity, as in the case to be discussed. It is important that this generator be as free from harmonics as possible. Usually a transformer of variable ratio is inserted between the generator and loop in order to get the maximum current through the latter.

To make the measurements on the polarization ellipse a device is used composed of two coils,[1] one of a large, fixed number of turns and the other of smaller and variable number of turns, mounted at right angles to each other. The whole is mounted on a Jacob's Staff with the smaller coil horizontal. The two coils are electrically interconnected through a phase shifting device so that the phase relation existing between the E.M.F.'s generated in the two coils is altered 90 degrees before they are brought together. The circuit contains a reversing switch, so that the manner in which the two coils are interconnected can be reversed easily. The number of turns used on the small coil is varied by a set of multicontact switches. To make a reading one rests the staff on the ground and, with its point as a pivot, oscillates the apparatus slowly back and forth about the position giving minimum response in the detector. The various switches are adjusted and the oscillating continued until a point of complete silence is obtained. The switch positions then give the required reading directly.

As a detector a pair of good headphones are used, preferably a pair tuned to 500 cycles, with a good two or three stage audion amplifier as an aid. The measuring device itself and the headphones are carried by the operator, and the amplifier, batteries, and notebook are carried by an assistant. In the case of a gasoline-driven generator another man is necessary to care for the gasoline engine and to see that it runs properly. There is nothing to prevent a dozen or more measuring devices being operated simultaneously about the loop.

Procedure

The area to be explored is first studied and due consideration given to known geological formation and general topography. If possible, the loop is laid out with its length parallel to the geological strike. Otherwise the length is run east and west since this is the most general strike of ore-shoots in northern Ontario and Quebec. The enclosed area is then marked out with

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[1] *See* Eve and Keys: "Applied Geophysics", p. 129.

lines parallel to one side of the loop, 100 feet apart. These lines are staked off every 50 feet to within 100 feet of the loop. Other than the above intervals may be used if desired. The generator is set up and adjusted to give 500 cycles. The transformer ratio is adjusted to give the maximum loop current.

The measuring device is taken and measurements made in a more or less orderly fashion at all staked points. If interesting indications are obtained additional readings are made at suitable points. At each point two readings are made, one along and one at right angles to the line of traverse. These two readings are plotted on squared paper and added geometrically to give the single resultant, in magnitude, direction, and sense. These two "right angle" readings are but a matter of convenience both in the making and plotting of readings, since a single observation made in the direction of the resultant is sufficient. But, at any point, the direction of the resultant is, at first, unknown, so that it is more convenient to make two readings at right angles and then compound them, than to hunt for the resultant direction first, and then make the single reading. The readings of magnitude are given in arbitrary units and must be multiplied by the constant of the apparatus if the absolute magnitude of the ratio is desired. So far no use is made of this absolute ratio. It is of interest to note that although readings have to be plotted before detailed information can be given, it is quite easy to form a general idea of conditions from the readings as they are taken in the field. This is of importance since indications can be recognized in the field and the advisability of additional readings determined while actually at work.

If the area being investigated is too big to be explored with one loop, several overlapping loops are necessary. So far no work has been done outside the loop, due chiefly to the rapid fall in primary field intensity as one moves away from the loop, whereas, within a loop, the primary field remains relatively constant for considerable intervals.

Use of Results

The results are plotted on three types of maps, the "Arrow map", the "Contour map", and the "Profile map". Of these the first is illustrative to the average person, but does not give much detailed information, beyond showing the location of the major disturbances. Its particular use is in cases where several conductors are present and produce contrary effects at the same points, giving rise to small readings at places where the single effects are really large. The second named map is also well suited for the uninitiated, but must be used with discretion since erroneous conclusions can be drawn therefrom. The profile map gives the greatest information and it is from it that all details are obtained.

The arrow map is obtained by plotting the results to scale on squared paper according to their magnitude and direction and obtaining the resultant geometrically (parallelogram law). Figure 36 represents the plotting of readings 4 north, 2 west, at a point O. OR is the resultant and points in general towards the centre of the ore-body if it be lenticular and in the direction of dip if the body be a vein. Moreover, they are longest over the extremities of a lenticular body or the strike of a vein.

The contour map is constructed by measuring the length of the arrows on the arrow map, assigning these values to the corresponding points on another map, and drawing lines through all points of equal magnitude just as the ordinary geographical contour map is made by drawing lines through points of like elevation.

These maps will show "cratered mountains" over lenticular bodies and "mountain ridges" along veins.

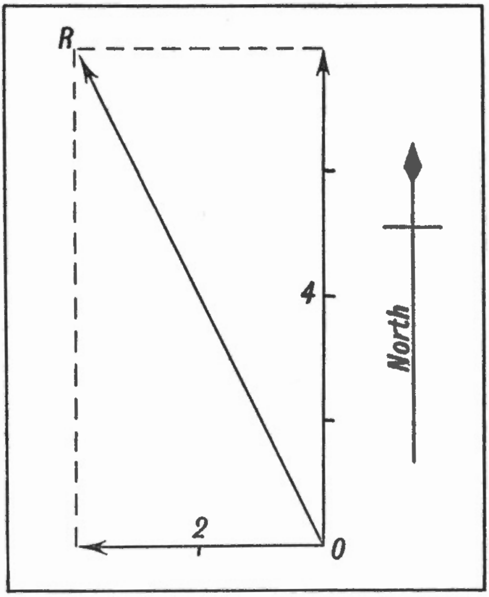


Figure 36. Method of plotting readings at a station, Bieler-Watson method.

The profile map is formed by plotting components of arrows, along lines of traverse. As stated previously, the lines of traverse are usually at right angles to the strike of the ore. The direction followed by the parallel traverse lines is referred to as north-south (N-S), though this direction may not be true north-south. The plotting of N-S components along N-S lines is sufficient to give all the necessary information if the body is of the vein type. However, if the body is lenticular or if the strike is other than east and west, then east and west components along east and west lines will be needed. As a matter of standardization, north or east components are plotted up and the others down. The resultant curve has the general appearance shown in Figure 37 where C C C C is the profile and O O is the zero line. Peaks as exhibited in Figure 37 are the result of the secondary conductor whose limits are defined approximately by the peaks as being at Y and Z. Depth is indicated by the shape of the curve, the flatter the peak, the deeper the body. Hence the point represented by Y in Figure 37 is nearer the surface than that represented by Z. In this way an estimate of dip can be made. An idea of the conductivity of the conducting body is obtained from the magnitude of the readings, due consideration being given to the depth. Veins give rise to only one peak. Care must be taken in interpreting these curves, since there is always a "background" due to currents induced in the surface soil and rock itself. These are not very troublesome over most rock formations, but are very bad over mineralized and wet clay beds.

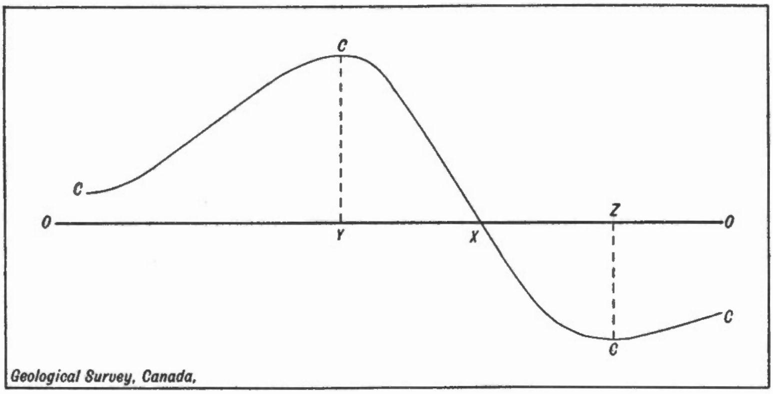


Figure 37. Method of constructing curve for "Profile map", Bieler-Watson method.

From these maps, especially from the profile map, a plan of the conducting bodies can be made and, if the conditions are not too complex, an idea can be formed of the depth and conductivity of the same. A reasonably accurate estimate of depth is not possible even in a simplified case unless the refractive index is known. To illustrate this effect of the refractive index the following table gives the multiplying factor for correcting the depth calculated assuming the index of refraction to be unity.

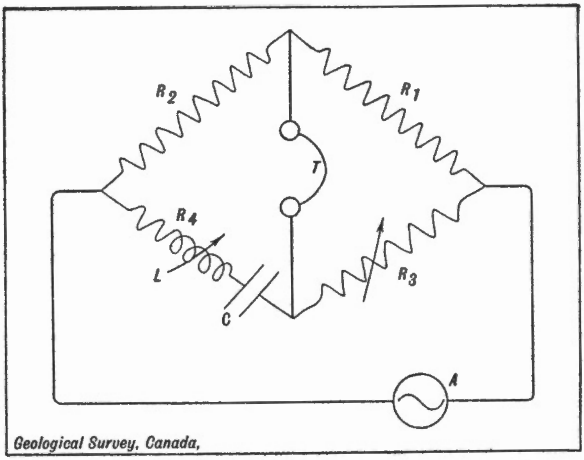
Index of refraction.	1	2	3	4
Factor.	1	2·15	3·43	4·74

It will be noted that the index has a marked effect on the calculated depth. Work done by the Radiore Company indicates an index of four for Arizona rock, using very high frequencies. It is doubtful if the value of the refractive index is as high as this in the regions where the surveys were made, which are described in the following sections.

Results at Abana Mine

The above paragraphs serve to clear up the general points of the method. The following paragraphs have to do with a practical example.

The Geological Survey received permission to carry out a survey employing this method on the property of the Abana mine, Dupuy, Quebec. The ore-body (*See* Part I, Chapter III) here is steeply inclined to the north and is elongated with a strike approximately 30 degrees south of east. It is divided into an eastern portion and a western portion by a large dyke. The strike is evident from outcrops, so a loop was laid 1,200 feet long, 600 feet wide, with the longer side run with the aid of a Berg compass as nearly 30 degrees south of east as possible. This line was staked at 100-foot intervals. From each of these points, lines were run at right angles to this line, using the same compass. These lines were staked, from the 100-foot point to the 500-foot point at 50-foot intervals with an additional stake at 600 feet. Some roundabout methods were used in staking points near the mine buildings with resultant inaccuracy. However, readings at such points are of little value due to local disturbances caused by pipes, rails, and electric power wires. A length of rubber-covered, No. 10 seven strand copper wire was laid for the loop, all joints being carefully taped. A 200-watt, 500-cycle airplane generator driven by a 60-cycle induction motor, operating from the lighting circuit of the mine, supplied the power to the loop through a transformer. It was placed at the southwest corner of the loop. An ammeter was used to determine loop current. The speed of the generator was adjusted by using wooden pulleys of suitable diameter until the proper values were obtained. The frequency was measured by a bridge circuit containing three resistance arms and a fourth arm of resistance, capacity, and variable inductance as shown in Figure 38. Such a circuit can give a sharp balance only when



Geological Survey, Canada,

Figure 38. Method of determining frequency, Bieler-Watson method. R_1, R_2, R_3, and R_4, known resistances; C, fixed capacity; L, variable inductance; A, source of A.C. whose frequency is to be measured; T, pair of telephones.

$$\frac{R_2}{R_1}=\frac{R_4}{R_3} \text{ and } 2\pi f=\frac{1}{\sqrt{LC}}$$

so that, L and C being known, f, the frequency, can be calculated.

The frequency having been adjusted to as nearly 500 cycles as necessary, the area within the loop was explored at the staked intervals specified above. In many cases readings were taken at 25-foot intervals. Along one line (that labelled 300 feet on Plans Nos. 9 and 10), which was a line surveyed by another method, the points established by the previous survey were used, the interval being 15 feet in some cases and 30 feet in others. Another earlier surveyed line (that at 360 feet, Plans Nos. 9 and 10) was also made use of. In several cases the readings extended beyond the normal range of the instrument and these had to be taken by a slow modified process.

The readings as made in the field are presented in Tables XX to XXIV, and the resultant arrow and profile maps are reproduced on, respectively, Plans Nos. 9 and 10. The readings recorded in Tables XX to XXIII were made employing the small loops; those recorded in Table XXIV were made employing a larger loop, the necessity for which will be explained later.

TABLE XX

Line 100 east				Line 200 east				Line 300 east			
Station	Readings		Remarks	Station	Readings		Remarks	Station	Readings		Remarks
100	4 E.	13 N.	Monday, June 17, 1929	100	7 W.	19 N.	Monday, June 17, 1929	105	5 E.	26 N.	Sunday, June 16, 1929
125	....	....		125	4 W.	4 N.		120	9 E.	40 N.	
150	18 E.	28 N.		150	4 E.	59 N.		135	9 E.	69 N.	
175	....	....	Pipes everywhere	175	....	....		150	2 W.	88 N.	
200	....	....		200	25 E.	80 N.	Noise from power line	165	1 E.	50, 26° E. of N.	
225	....	....		225	16 E.	38 N.		....		50, 23° W. of N.	
250	....	....		250	15 E.	12 N.		180		100,27° E. of N.	
275	....	....		275	13 W.	13 S.	Dump track power wires and hoist house	....		100,30° W. of N.	
300	64 W.	91 N.	Under pipe line	300	18 E.	45 S.		195		50,5° E. of N.	
325	....	....		325	....	....		....		50,21° W. of N.	
350	22 E.	7 N.	Pipe line 20 feet east	350	41 E.	16 S.		210	53 W.	50, 30° W. of N.	
375	....	....		375	....	....				50, 0° E. of N.	
400	17 E.	3 N.	*	400	28 E.	20 S.		225	34 W.	43 N.	
425	....	....		425	....	....		240	15 W.	11 S.	
450	20 E.	17 S.		450	20 E.	17 S.		255	8 E.	37 S.	Pipe from old pump-house to power house here
475	....	....		475	....	....		270	9 E.	47 S.	
500	12 E.	14 S.		500	12 E.	14 S.		285	22 E.	22 S.	
	70 E.	19 S.						315	3 E.	54 S.	
								345	20 E.	50 S.	
								375	17 E.	39 S.	
								405	18 E.	36 S.	
								435	17 E.	30 S.	
								465	9 E.	29 S.	

*Reading on pipe

TABLE XXI

Line 360 east				Line 400 east				Line 500 east			
Station	Readings		Remarks	Station	Readings		Remarks	Station	Readings		Remarks
90	12 E.	23 N.	Monday, June 17, 1929	100	12 E.	36 N.	Saturday, June 15, 1929	100	16 E.	36 N.	Saturday, June 15, 1929
105	18 E.	45 N.		125	10 E.	59 N.		125	11 E.	47 N.	
120	10 E.	71 N.		150	19 E.	100 N.		150	5 E.	60 N.	
135	23 E.	92 N.		175	12 E.	4° E. of N.		175	12 W.	70 N.	
150	50, 27° W. of N.			200	50, 33° W. of N.			200	20 W.	61 N.	
	50, 19° E. of N.				50, 23° E. of N.			225	29 W.	39 N.	
165	50, 29° W. of N.			225	31 W.	69 N.		250	29 W.	30 N.	
	50, 17° E. of N.			250	25 W.	33 N.		275	27 W.	13 N.	
180	50, 27° W. of N.			275	22 W.	3 N.		300	24 W.	3 S.	
	50, 16° E. of N.			300	15 W.	15 S.		325	....	....	
195	50, 39° W. of N.			325	....	....		350	20 W.	14 S.	
	50, 20° E. of N.			350	4 W.	27 S.		375	....	....	
210	19 W.	70 N.		375	....	....		400	4 W.	19 S.	
225	22 W.	42 N.	50 feet east of old pump-house	400	1 E.	37 S.		425	....	....	
255	15 W.	6 S.		425	....	....		450	4 E.	21 S.	
285	7 W.	24 S.		450	5 E.	28 S.		475	....	....	
315	3 E.	33 S.		475	....	....		500	4 E.	16 S.	
345	3 E.	36 S.		500	9 E.	17 S.					

TABLE XXII

Line 600 east				Line 700 east				Line 800 east			
Station	Readings		Remarks	Station	Readings		Remarks	Station	Readings		Remarks
100	11 E.	30 N.	Saturday, June 15, 1929	100	6 E.	24 N.	Saturday, June 15, 1929	100	5 W.	20 N.	Saturday, June 15, 1929
125	8 E.	32 N.		125	....	....		125	....	....	
150	4 W.	32 N.		150	4 E.	26 N.		150	10 W.	19 N.	
175	7 W.	28 N.		175	....	....		175	....	....	
200	4 W.	24 N.		200	0	23 N.		200	9 W.	18 N.	
225	5 W.	28 N.		225	3 W.	20 N.		225	....	....	
250	10 W.	26 N.		250	5 W.	17 N.		250	12 W.	12 N.	
275	13 W.	16 N.		275	4 W.	14 N.		275	....	....	
300	13 W.	10 N.		300	4 W.	10 N.		300	12 W.	5 N.	
325	14 W.	2 N.		325	7 W.	4 N.		325	12 W.	0	
350	12 W.	5 S.		350	5 W.	0		350	13 W.	5 S.	
375	9 W.	6 S.		375	....	....		375	15 W.	6 S.	
400	7 W.	9 S.		400	9 W.	8 S.		400	....	....	Pool room
425	5 W.	12 S.		425	6 W.	11 S.		425	....	....	
450	7 W.	12 S.		450	6 W.	10 S.		450	16 W.	9 S.	
475	....	....		475	....	....		475	....	....	
500	5 W.	10 S.		500	0	11 S.		500	22 W.	24 S.	Pipe to pool room

TABLE XXIII

Line 900 east				Line 1,000 east				Line 1,100 east			
Station	Readings		Remarks	Station	Readings		Remarks	Station	Readings		Remarks
100	10 W.	15 N.	Sunday, June 16, 1929	100	13 W.	7 N.	Sunday, June 16, 1929	100	8 W.	7 N.	Sunday, June 16, 1929
125	....	....		125	....	....		125	....	....	
150	16 W.	13 N.		150	15 W.	3 N.		150	9 W.	1 S.	
175	....	....		175	19 W.	5 N.		175	....	....	
200	22 W.	13 N.		200	19 W.	6 N.		200	7 W.	2 N.	
225	25 W.	10 N.		225	24 W.	7 N.		225	....	....	
250	26 W.	16 N.		250	25 W.	9 N.		250	12 W.	2 N.	
275	28 W.	13 N.		275	28 W.	10 N.		275	....	....	
300	23 W.	8 N.		300	28 W.	8 N.		300	11 W.	1 S.	
325	24 W.	5 S.		325	28 W.	2 N.		325	....	....	
350	24 W.	9 S.		350	26 W.	5 S.		350	13 W.	1 S.	
375	25 W.	16 S.		375	22 W.	12 S.		375	....	....	
400	23 W.	17 S.		400	17 W.	11 S.		400	10 W.	5 S.	
425	21 W.	22 S.		425	16 W.	8 S.		425	9 W.	2 S.	
450	19 W.	16 S.		450	15 W.	8 S.		450	5 W.	2 S.	
475	....	....		475	....	....		475	6 W.	4 S.	
500	15 W.	14 S.		500	10 W.	6 S.		500	7 W.	4 S.	

TABLE XXIV

Line 800 east				Line 900 east				Line 1,000 east			
Station	Readings		Remarks	Station	Readings		Remarks	Station	Readings		Remarks
100	4 W.	28 N.	Saturday, July 6, 1929	100	11 W.	23 N.	Saturday, July 6, 1929	100	11 W.	14 N.	Saturday, July 6, 1929
125	....	....		125	....	....		125	....	....	
150	6 W.	34 N.		150	17 W.	24 N.		150	15 W.	15 N.	
175	14 W.	36 N.		175	16 W.	24 N.		175	15 W.	16 N.	
200	17 W.	36 N.		200	22 W.	26 N.		200	15 W.	20 N.	
225	29 W.	37 N.	Possible that 14 W. is an error for 24 W.	225	24 W.	30 N.		225	25 W.	23 N.	
250	14 W.	38 N.		250	22 W.	36 N.		250	25 W.	25 N.	
275	25 W.	43 N.		275	30 W.	40 N.		275	28 W.	29 N.	
300	22 W.	45 N.		300	32 W.	46 N.		300	33 W.	34 N.	
325	25 W.	45 N.		325	28 W.	41 N.		325	38 W.	31 N.	
350	21 W.	37 N.		350	30 W.	29 N.		350	41 W.	22 N.	
375	23 W.	23 N.		375	35 W.	22 N.		375	34 W.	14 N.	
400	....	....	Pool room	400	35 W.	12 N.		400	31 W.	14 N.	
425	....	....		425	35 W.	0		425	34 W.	11 N.	
450	21 W.	2 N.		450	35 W.	7 S.		450	32 W.	6 N.	
475	....	....		475	....	....		475	....	....	
500	47 W.	36 S.	Pipe to pool room	500	35 W.	14 S.		500	29 W.	0	

The plans indicate the presence of the west body quite satisfactorily, but the east body (line 600 to 1,100) gives no positive indication other than might be expected from ground currents, especially since the overburden was swampy. As the body was known to contain chalcopyrite and pyrite of reasonable conductivity it should be capable of being detected electrically. A possible reason for its non-detection in this case is suggested in Figure 39 in which the two sides of the loop are represented (at X and Y), the lines of force are shown, and A, B, and C represent the conducting body in three possible positions. Let this body be thin. Then it will be noticed that the number of lines of force cutting the body in any of the three positions will be small, with the result that the induced E.M.F. and hence the induced current will be weak. Moreover, the two currents will be a short distance apart and will rapidly neutralize the effects of each other. The central, A, position is particularly catastrophic, since in this position it is not possible for the vein to serve even as a concentration path for ground currents, whereas in position B, and still more so in position C, the left hand ground currents will tend to concentrate in the veins and give the desired effect. To test out this theory the "X" side of the loop was extended 600 feet making a 1,200-foot square in all. The resulting case is illustrated in Figure 40.

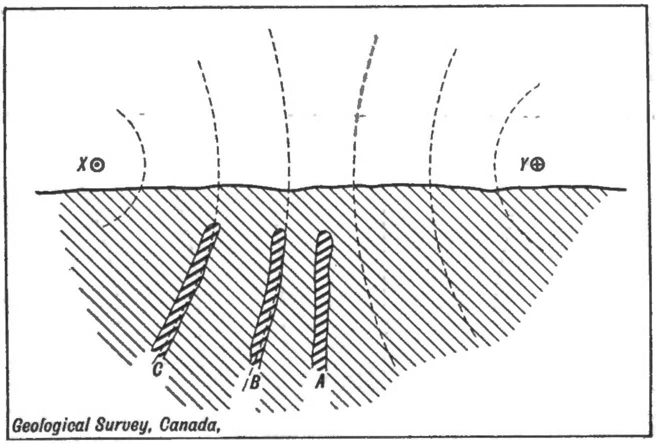


Figure 39. Illustrating general conditions possibly existing in the case of the eastern ore-body, Abana mine, Desmeloizes township, Quebec, using small loop, Bieler-Watson method.

In this case it will be observed that a considerable number of lines of force cut the body in any of the three positions, and do so in such a way as to have one current at the top of the body and the return current at the bottom, so that the neutralization of one field by the other is small. Moreover, all positions are favourable for the concentration of right hand ground currents.

Observations were made, using the enlarged loop, along three lines over the supposed location of the body. Lack of time prevented a more complete survey, but the three lines were sufficient to prove the point in question. These results show a distinct, though weak, indication verifying the above reasoning and showing that caution must be exercised before declaring ground barren.

Observations

Frequency check: L=12·7 millihenries C=7·46 microfarads
whence f=517 cycles /sec.

This value is sufficiently accurate for our purpose since the measuring device used was tuned to 510 cycles /sec.

Current in small loop about 2·5 amps.

Current in large loop about 2·3 amps.

These values varied depending on the temperature of the generator and transformer, but have no effect on the readings since a ratio and not an absolute value is measured. Their only effect lay in a varying sensitivity. The observations taken are given in the accompanying tables. From these readings the maps and figures were made. For the purpose of definitely fixing all points, the positions of No. 1 shaft and the pool room were determined. When this was done the angle of the base-line was found to be 26·20 degrees south of east. Certain points at which measurements were made were near pipes, rails, and so forth, which produced local disturbances that could not be allowed for conveniently. Hence all such measurements being doubtful their indications are dotted.

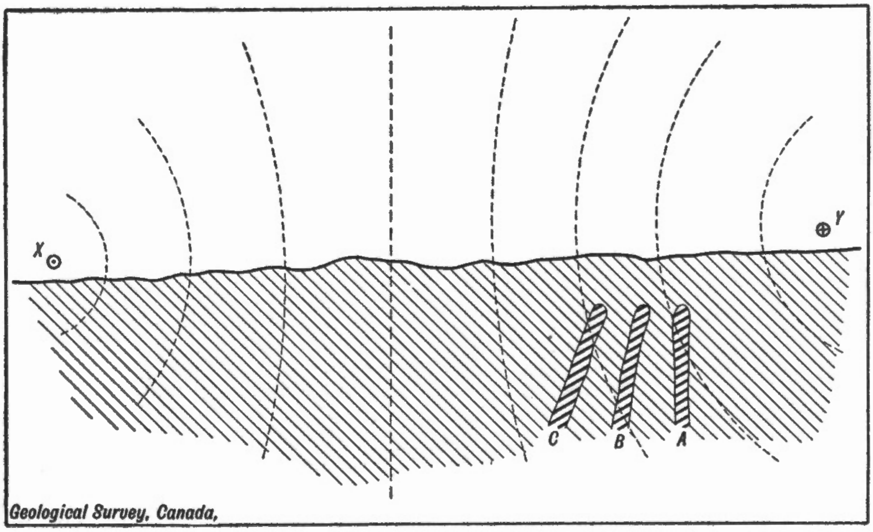


Figure 40. Illustrating general conditions possibly existing in the case of the eastern ore-body, Abana mine, Desmeloizes township, Quebec, using large loop, Bieler-Watson method.

Results

The arrow map Plan No. 9 shows a strong indication at about 200 feet north on the traverse lines 200, 300, 400, and 500 feet east. This corresponds to the ore-body west of the dyke. It will be noticed that there is no particularly convincing indication along the 600-foot and remaining traverse lines to the east in either the small or large loop indications.

The profile map (Plan No. 10) gives more information. The main indication shows one strong conductor and another weaker and shorter one to the south. The lack of continuity of the western indication into the eastern part shows that the ore-body stops at about 500 east. The indications show a slight dip towards the north. In the case of the eastern body there is no definite indication with the small loop, for all indications present can be attributed to ground currents. The large loop, however, gives another story, although the indications are weak. The weakness is due to poor conductivity and not depth, bearing out the contention that the conducting body is thin. The observations are not sufficiently complete to warrant any statement concerning the eastern and western extent of the body.

As mentioned in a previous paragraph, definite information of the depth cannot be given unless the refractive index of the rock and overburden for a 500-cycle wave is known. However, this index must be greater than 1, so that assuming a refractive index of unity the determined depth will represent a minimum depth. With this in mind, the following information is obtained:

Main Body Primary Conductor

—	Location	Depth	Remarks
		Feet	
Line E 200	North 180	25	Very uncertain
" E 300	" 190	20	Very good conductivity
" E 360	" 180	25	" "
" E 400	" 200	15	" "
" E 500	" 175	50	" "

Western limit uncertain due to local disturbances. Eastern limit about east 550.

Main Body Secondary Conductor

		Feet	
Line E 300	North 145	....	Uncertain
" E 360	" 155	30	Good conductivity
" E 400	" 155	....	Uncertain

Western limit about E 300, eastern limit about E 425.

Eastern Body

		Feet	
Line E 800	North 315	70–80	Poor conductivity
" E 900	" 310	55	" "
" E 1000	" 305	60	" "

Eastern and western limits unknown, due to incomplete results.

Results at Errington Mine

Here the rock is chiefly graphitic slates and tuffs having distressingly good conductivities. For this reason no success was expected with the method, but an attempt was made merely to ascertain the effects such conditions would produce.

A rectangular loop of one turn of wire, 900 feet by 600 feet, was laid with the length along the strike of the body. The power was supplied from a 500-cycle gasoline driven generator, the property of the United States Bureau of Mines. An attempt was made to get readings but without success, the values all being beyond the range of the instrument. By the slow modified method several readings were made at scattered points, all in the neighbourhood of 1,000 to 2,000, indicating the magnitude of the disturbance created by the graphitic rocks. Comparing these values with those obtained at Abana, it is easily seen that little hope exists for the detection of an ore response in such a background of ground current indications. This background would also prevent the use of any other of the usual inductive methods because it would be impossible to obtain sharp balance points.

General Remarks and Criticisms

The results with a massive ore-body seem in general to give much useful and fairly definite information as to the plan of the body and its conductivity. The depth indications are partly satisfactory, but it would be much better if the uncertainty due to refractive index were removed. No information is given as to the depth to which the body extends by this method. The chief difficulty in applying the method is the disturbances produced by ground currents. At Abana these were of slight consequence, but in localities where the overburden is made of boulder clays which contain a certain amount of mineral matter, the effects might be overshadowing, as in the extreme case at Errington mine. Such surface conductors are ideal for producing undesired disturbances, since they are near the surface and are of large extent, ensuring a large induced E.M.F. and low overall conductivity. The disturbances created by such parasitic bodies are, to some extent, distinguishable from ore-body indications since they give rise to distorted profiles. The difficulty lies in their possible "blanketing" of indications produced by ore-bodies beneath them.

The manipulation of the apparatus itself requires a skilled operator with good hearing, if speed and accuracy are to be obtained. Care must also be exercised in carrying out the work, otherwise bodies can be missed through lack of indication, as was the case with the eastern Abana body. For this reason only skilled men should carry out the method.

The method has yet to be tested over a disseminated ore-body before a final opinion can be passed on its usefulness.

PART III

EXPERIMENTS IN ELECTRICAL EXPLORATION MADE IN THE SUMMER OF 1929

By L. Gilchrist

INTRODUCTION

The following report is concerned largely with work carried out at the Abana mine in northwestern Quebec in collaboration with Mr. E. V. Potter of Baltimore, a member of the staff of the United States Bureau of Mines, and with Mr. H. G. I. Watson of McGill University, Montreal. Some work carried out at the Falconbridge and Errington mines, in Sudbury district, Ontario, is also discussed because of its relation to similar work at the Abana mine. The work at the Falconbridge and the Errington mines was done in collaboration with Professors A. S. Eve and D. A. Keys, and Mr. H. G. I. Watson, of McGill University, and Dr. F. W. Lee and Mr. W. Joyce of the United States Bureau of Mines.

The results of the following investigations are presented:

(I) Electrical investigations at the Abana mine.
  (*a*) Measurements of resistivity by the Wenner-Lee method with a megger.
  (*b*) Measurements of resistivity by the central electrode method (a central current electrode and two end current electrodes) with a megger.

(II) Electrical investigations at the Falconbridge mine.
  Measurements of resistivity by the central electrode method with: (1) a megger, (2) a milliammeter and potentiometer.

(III) Electrical investigations at the Errington or Treadwell-Yukon mine. Measurements of resistivity by the central electrode method with a milliammeter and potentiometer.

(IV) Magnetic investigations at the Falconbridge mine and the Errington mine. A magnetometer exploration with the Tiberg magnetometer.

Instruments

(1) THE MEGGER

This is an instrument which is used to measure directly the resistance of electrical conductors. It has been designed by Messrs. Evershed and Vignoles, Acton Lane Works, Chiswick, England. It has been in general use for some years for measuring the resistances of power-line conductors and insulators, and especially for measuring the resistances of earth plate contacts. More recently it has come into use for measuring resistances of parts of the earth. The connexions for measuring the resistance of an

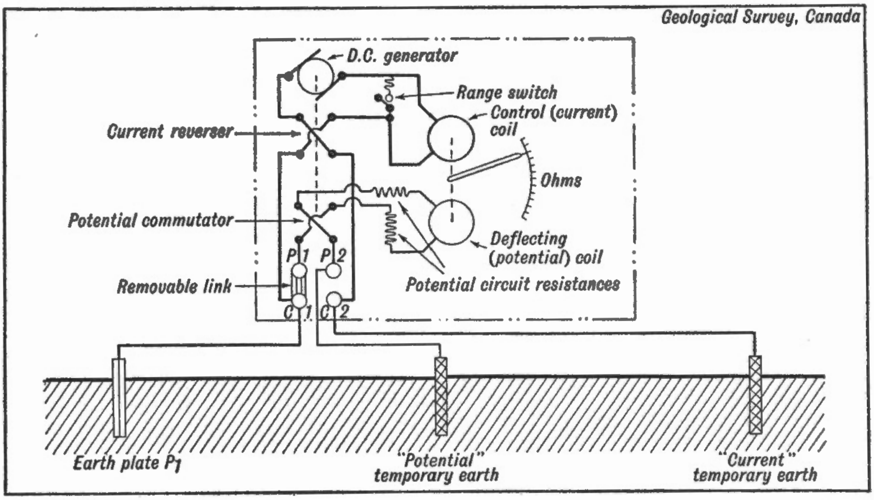


Figure 41. Arrangement of connexions to measure with a megger, the resistance of an earth contact plate.

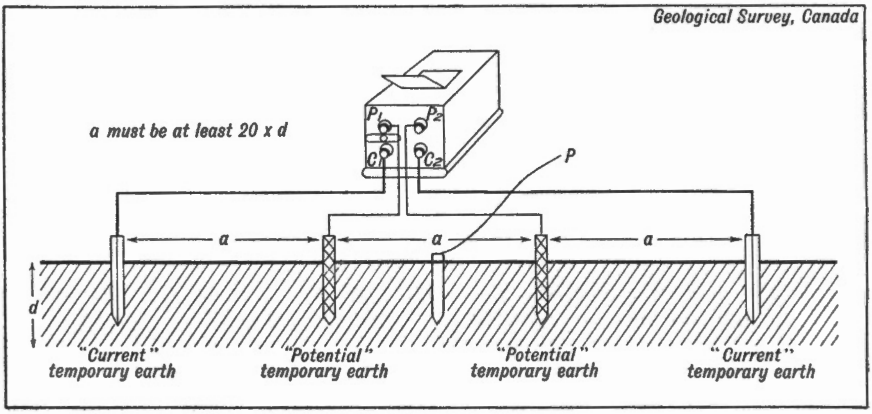


Figure 42. Arrangement of connexions to measure with a megger, by the Wenner-Lee method, the resistance of parts of the earth.

earth plate contact P_1 is shown in Figure 41 and the connexions which are used to measure the resistance of parts of the earth by the Wenner-Lee method are shown in Figure 42. The construction and theory of operation of the instrument are given in detail in the catalogues of the manufacturers and also by F. W. Lee[1].

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[1] Lee, F. W.: Tech. Paper 440, U.S. Bureau of Mines, 1928.

The megger is calibrated for use with definite external resistances of the connexions in the potential circuit (*See* Figures 41 and 42). In the case of the experiments made, the external resistances were largely associated with the stake contacts with the ground and were in general much higher than those permissible with the calibration. The readings on the instrument were, therefore, multiplied by a correction factor:

$$\frac{l + p_1 + p_2}{l_1}$$

where l is the internal resistance of the potential circuit, $l_1 = l +$ the resistance permitted in calibration and p_1 and p_2 are the resistances of the potential earths. This correction factor is approximately that which is given by the manufacturers of the instrument.

Calibration curves were made for the meggers experimentally. These curves were in general agreement with those obtained by means of the correction factor.

(2) THE MILLIAMMETER AND POTENTIOMETER

These are instruments in general use for measuring, respectively, the strength of a current passing through a conductor, and the potential difference between two points on the conductor. From these two measurements the resistance of the conductor may be calculated.

(3) THE TIBERG MAGNETOMETER

This is a simple magnetic needle so mounted that the directions of a magnetic field in a horizontal plane and in a vertical plane may be determined. With the assistance of an auxiliary magnet and a compensating weight the magnitude of the magnetic force may be determined. The instrument is in common use and its construction and theory are well known.

(I) ELECTRICAL INVESTIGATIONS AT THE ABANA MINE

(a) Resistivity by the Wenner-Lee Method

Four lines were marked out on the surface as shown on Plan No. 11. Two lines, A-A and B-B, were located so as to cross the western ore-body and one line, F-F, to cross the eastern ore-body. The fourth line, E-E, crosses lines A-A and B-B, follows the direction of the strike of the western ore-body, and is almost directly above it where it has been developed on the 300-foot level. Points were located on each line 50 feet apart. Measurements were made at the points on lines A-A, B-B, and F-F which are marked 4S, 3S, 2S, 1S, O, 1N, 2N, 3N, and 4N, and on line E-E at the points marked 4E, 3E, 2E, 1E, O, 1W, 2W, 3W, 4W. These measurements were made for depth ranges of 100 feet, 200 feet, 300 feet, and 400 feet, in accordance with the Wenner method.

The technical procedure was as follows:

(1) The potential stake resistances, i.e., the resistances of the contact of the leads to P_1 and to P_2 with the earth, were measured by the method indicated in Figure 41.

(2) On line F-F and for the 300-foot depth range on line E-E, the contact resistance at a point P half-way between the contact points in (1) was measured.

(3) Readings were made of the resistance of the ground intermediate between the earth contact points of the leads to P_1 and P_2 and of the ground between P_1 and P and of the ground between P and P_2 as indicated in Figure 42. These readings were corrected for potential stake resistances in order to obtain the true values of the resistances of the intermediate parts of the earth, i.e., of $P_2^R P_1$, $P_2^R P$, $P^R P_1$.

(4) The resistivity of $P_1^\rho P_2$ was calculated from the formula of Wenner, viz., $P_1^\rho P_2 = {}_2\pi a P_1^R P_2$ where a is the distance between the earth contact points of P_1 and P_2 as shown on Figure 42. The values of $P_2^R P$ and $P^R P_1$ served as a qualitative indication of the relative resistivities in the region between the earth contact points of P_2 and P and the region between the earth contact points of P and P_1.

Results of Measurements by the Wenner-Lee Method on Lines A, B, E, and F

The values of the inter-bowl resistances $P_2^R P_1$, $P_2^R P$, and $P^R P_1$ are given in Table I.

(1) On lines A-A, B-B, and F-F, P_2 is the potential stake on the south side and P_1 is the potential stake on the north side. On line E-E, P_2 is the potential stake on the east side and P_1 is the potential stake on the west side.

(2) Megger No. 1, which had three scale ranges, 0-3000 ohms, 0 to 300 ohms, and 0 to 30 ohms, was used to make the measurements of potential stake resistances and the resistances $P_2^R P_1$, $P_2^R P$, $P^R P_1$ on the lines A-A, B-B, and E-E except for the depth range of 300 feet on E-E. In the latter case megger No. 2, whose scale ranges were 0-300 ohms, 0-30 ohms, and 0-3 ohms, was used. It was also used to make the measurements on line F-F. This megger (No. 2) was not available for work on the other lines.

(3) The potential stake resistances for the contacts of P_2, P, and P_1 were measured on line E for the depth range of 300 feet and for all depth ranges on line F.

The potential stake resistances of P_2 and P_1 were measured for all ranges on lines A, B, and E, but the stake resistance of P was not measured on these profiles except for the depth range of 300 feet on line E.

The stake resistance of P on lines A, B, and E was calculated from the fact that $P_2^R P^1 = P_2^R P + P^R P_1$ (approximately), where these are the corrected resistances. The uncorrected readings of these resistances are known and also the stake resistances at P_2 and P_1.

TABLE I

P is in ohms per cm. cube. R is in ohms.

Line A

Station	100 feet depth			200 feet depth			300 feet depth			400 feet depth		
	$P_2^{\rho}P_1 \div 10^2$	$P_2^{R}P$	$P^{R}P_1$	$P_2^{\rho}P_1 \div 10^2$	$P_2^{R}P$	$P^{R}P_1$	$P_2^{\rho}P_1 \div 10^2$	$P_2^{R}P$	$P^{R}P_1$	$P_2^{\rho}P_1 \div 10^2$	$P_2^{R}P$	$P^{R}P_1$
4 S	574	1·9	0·6	1,148	2·3	0·7	1,608	1·9	0·9	1,171	0·63	0·5
3 S	421	......	......	1,148	1·9	1·1	1,895	2·7	1·3	1,761	1·2	1·1
2 S	670	1·2	2·3	1,187	1·2	1·9	1,608	1·6	1·2	1,302	1·6	0·1
1 S	1,091	2·4	3·3	1,416	1·5	2·2	1,838	0·3	2·9	2,200	1·8	1·1
0	1,493	2·7	5·1	1,378	1·3	2·3	2,699	0·9	3·8	1,990	0·7	1·9
1 N	1,148	2·9	3·1	1,608	1·4	2·8	2,067	0·7	2·9	2,297	1·1	1·9
2 N	1,512	2·6	5·3	1,952	1·3	3·8	1,723	0·4	2·6	1,838	0·6	1·8
3 N	1,742	4·1	5	2,297	2·3	3·7	1,838	0·4	2·8	2,297	1·1	1·9
4 N	1,818	3·1	6·4	1,914	1·7	3·3	1,895	1·1	2·2	1,914	1·3	1·2
Line B												
4 S	957	......	......	1,340	2·4	1·1	2,125	2·5	1·2	1,378	0·7	1·1
3 S	900	......	......	1,416	2·3	1·4	1,665	2·0	0·9	1,302	......	......
2 S	842	2·3	2·1	1,263	1·8	1·5	1,608	1·6	1·2	1,838	1·6	0·8
1 S	957	1·7	3·3	1,608	2·1	2·1	1,665	1·7	1·2	1,991	1·6	1
0	1,282	1·6	5·1	1,034	1	1·7	1,206	1·2	0·9	1,838	1·4	1
1 N	1,034	2·5	2·9	1,110	......	......	1,321	1	1·3	1,761	1·1	1·2
2 N	1,340	3·1	3·9	1,072	0·8	2	1,206	0·7	1·4	1,761	0·9	1·4
3 N	1,627	4	4·5	995	1·2	1·4	1,263	0·9	1·3	1,761	0·8	1·5
4 N	1,723	6·8	2·2	1,302	1·5	1·7	1,436	1·3	1·2	1,991	0·4	2·2
Line F												
4 S	427	1·1	1·1	593	0·66	0·75	1,028	0·8	1	1,225	0·93	0·97
3 S	415	1·17	0·97	628	......	......	1,022	0·68	1·1	1,340	0·77	1·01
2 S	389	1	1	766	1·1	1·2	1,103	0·91	1·26	1,246	1·31	0·95
1 S	400	1·04	1·04	1,011	0·5	2·3	1,068	0·45	1·14	1,309	0·98	1·10
0	613	1·42	1·77	1,164	1·26	1·93	1,108	1·18	1·2	942	0·76	0·95
1 N	605	1·58	1·58	961	1·4	1·3	1,016	0·89	1	1,118	1·01	0·73
2 N	668	1·45	2	846	1·12	1	1,039	1·05	0·68	1,355	1·05	0·78
3 N	804	1·62	2·61	662	0·96	0·91	752	0·82	0·56	1,233	0·95	0·77
4 N	....	2·64	6·6	632	0·85	1·1	930	0·66	1·2	1,378	0·735	1·09
Line E												
4 E	580	1·3	1·8	509	0·63	0·7	379	0·28	0·39	368	0·15	0·31
3 E	651	1·6	1·8	513	0·5	0·84	403	0·33	0·41	459	0·27	0·38
2 E	668	2·1	1·4	567	0·6	0·9	477	0·37	0·46	513	0·28	0·39
1 E	727	2·1	1·7	425	......	......	551	0·52	0·43	551	0·36	0·36
0	771	2	2	563	0·2	1·27	574	0·59	0·35	597	0·53	0·25
1 W	710	3·1	0·6	586	0·93	0·6	631	......	......	536	0·3	0
2 W	611	2·3	0·9	609	......	......	....	......	......	490	0·4	0
3 W	576	1	2	436	0·15	1	597	0·91	0·17	344	0·3	0
4 W	318	0·7	0·95	333	0·31	0·56	528	0·66	0·21	88	0·1	0

CONCLUSIONS

(1) With reference to line A.

At the depth range of 100 feet a good conducting region exists at 4 S to 2 S. Fair conductivity exists in this region at the depth range of 200 feet. The conductivity of this region lowers at the depth range of 300 feet and improves again in the depth range of 400 feet.

(2) With reference to line B.

At the depth range of 100 feet a good conducting region existed in the region 4 S to 1 S and at 1 N. The conductivity in the region 4 S to 1 S is much lower in the depth ranges of 200 feet and 300 feet. In these ranges there is a region of fair conductivity from 0 to 3 N. In the depth range of 400 feet a fair conductivity exists at 4 S and 3 S and also at 1 N to 3 N.

(3) With reference to line F.

At the depth ranges of 100 feet good conductivity exists from 4 S to 1 S. On the 200-foot level the good conductivity region appears to be 4 S to 2 S and 2 N to 4 N, and on the depth range of 300 feet at the points 3 N and 4 N, but in the 400-foot depth range it exists at the points zero and 1 N.

(4) With reference to line E.

At all depth ranges the conductivity is in general much better than exists on the other lines, which suggests that this line is on the direction of strike of the good conductor.

At all depths it shows high conductivity at the extreme points 3 W and 4 W. At these points there was an extensive ore dump of good conductivity. However, it should be noted that the conductivity has increased greatly at the extreme west at a depth of 400 feet.

General Conclusions

(1) On lines A and B the good conducting region corresponded roughly with the position of the ore-body as deduced from its known position on the 300-foot level.

(2) It is difficult to discern definite correspondence between better conducting regions along profile F and the known position of the ore-body in the eastern zone. It is possible that this is accounted for by the fact that in general the ore-body contains a high percentage of sphalerite and also that the adjacent dyke was a body of low conductivity, and the overburden of comparatively good conductivity.

(3) Although high conductivity exists along the whole of profile E and corresponds with the general strike of the ore-body, it is difficult to discern correspondence between the conductivity and the broken or discontinuous character of the ore-body.

(4) Since the average reading for $P_2^R P_1$ on the megger was about 3 ohms it is evident that the readings on megger 1 (scale 30) must have an important margin of error. The readings with megger 2 (scale 3) are correspondingly more accurate.

(5) In all cases where the megger is used to measure resistances the external potential circuit resistances should be as small as possible. In order to obtain this condition multiple potential stake contacts should be used and if possible placed in moist ground.

(*b*) Measurements of Resistivity by the Central Electrode Method

In all the measurements by the Wenner-Lee method it is evident that the presence of two current electrodes creates a difficulty in interpreting the measurements of resistance in adjacent regions. Moreover, as the centre of measurements is moved along a profile a section at *one* side of the region of measurements is removed and a new section at the *other* side is brought into the region of measurement. This inevitably makes the interpretation of the measurements very difficult.

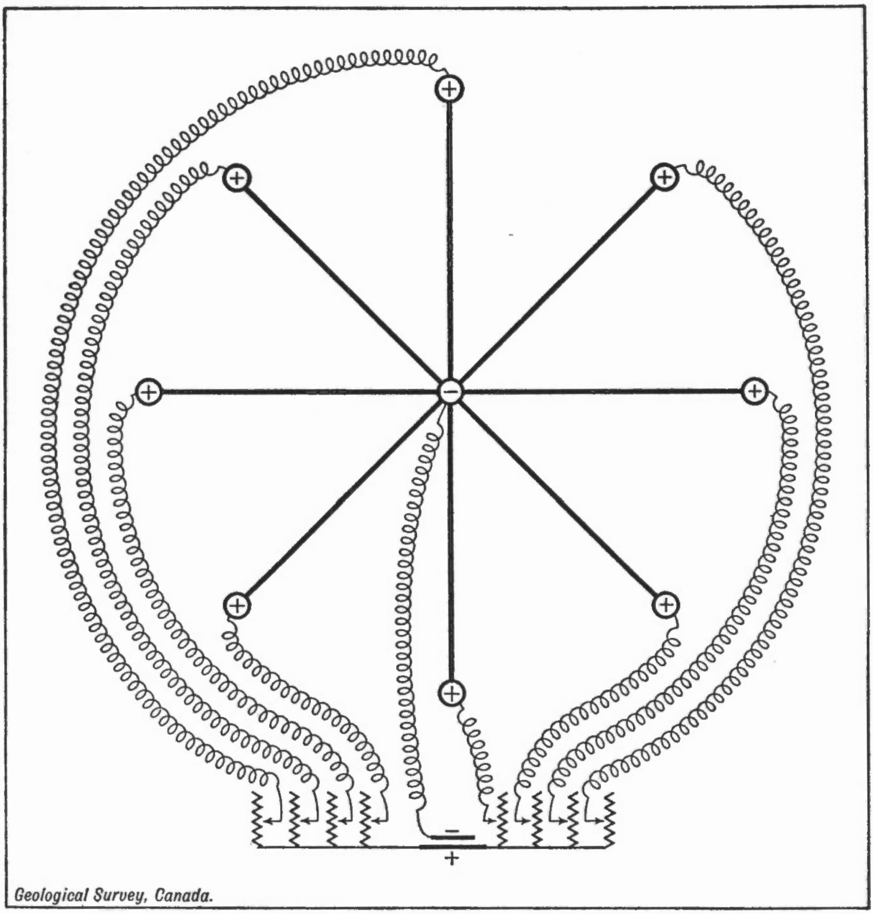


Figure 43. Arrangement for central electrode method.

In order to obtain a degree of symmetry that would simplify interpretation it appeared desirable to use a central current electrode and a set of distant current end electrodes symmetrically placed about the central electrode as shown in Figure 43 and to provide by means of auxiliary resistances that the currents passing into the earth at the distant electrodes should be equal. Circumstances did not permit the operation of this plan in complete detail, but a degree of symmetry was obtained by using a central current electrode and two distant collinear current electrodes and by taking measurements along a line almost at right angles to the line of the current electrodes.

It was hoped further that by making the measurements at points above the dyke, information would be obtained on: (*a*) the depth of the overburden on the dyke; (*b*) the location of good conducting bodies adjacent to the dyke.

Five lines D I, D II, D C, D III, and D IV, were run north and south on the surface above the dyke as shown on Plan No. 11. These lines crossed line E and the points of intersection are marked zero. Stations for the potential electrodes were located on the profiles at intervals of 50 feet and are indicated as 8 S, 7 S, 6 S, 5 S, 3 S, 2 S, 1 S, 1 N, 2 N, 3 N, 4 N, 5 N, 6 N, 7 N, and 8 N. The stations marked S are south of line E and those marked N are north of line E.

Two sets of measurements were made with the central current electrodes at D C 1 N and at D II O and the end current electrodes at distances of 1,068 feet and 1,032 feet respectively.

As the profiles D II and D C were not at right angles to the line of the current electrodes a preliminary experiment was carried out with the central current electrode at D C 1 N and resistances of the section D C 1½ N to D C 2 N were determined with the potential electrode along the line D C and along lines on each side of D C and at 45 degrees to D C. The results are given in Table II. The results show that the true line of symmetry is more nearly at right angles to the line of the current electrodes, but the direction of the lines is not sufficiently divergent from this to interfere with the interpretation of the results of the main experiment.

TABLE II

Results with the Central Electrode Method

Symmetry about line D C

Instrument—Milliammeter and Potentiometer

Station		R—ohms
Along line D C	1½ N—2 N (26 feet)	8·8 9·06 average=8·93
45° northwest of line D C	1½ N—2 N (26 feet)	7·96
45° northeast of line D C	1½ N—2 N (26 feet)	8·12

In the main experiment the values of the resistivity ρ are calculated from the formula $\rho = 2\pi R \frac{a\ b}{b-a}$

R = the resistance of a section of the region in ohms. This section is that enclosed by two bowls of radii a and b.

- a — distance from the central current electrode to the near potential electrode.
- b — distance from the central current electrode to the far potential electrode.

This formula would be more properly applicable in the case of one central electrode and several end current electrodes distributed symmetrically about the central one. In the present case it may be applied to show comparatively the values of ρ in adjoining sections of a region.

Circles are drawn on Plan 11 and on Figure 48 about D II O as centre to indicate the sections included in the measurements of R about this centre. Similar circles might be drawn about D C 1 N as centre, but to avoid confusion these are omitted. The sections included in the measurements about this centre are, however, easily made clear.

Megger 1 was used to measure the potential stake resistances and megger 2 (scales O-3 and O-30) was used to measure R. The values of R were corrected for the potential stake resistances.

The results of the experiment are shown in Table IV.

Measurements of R were also made on line D C north side with a milliammeter and potentiometer and were in general accord with those obtained with the megger. These were not so reliable or accurate as the results observed with the megger.

TABLE IV

Results with the Central Electrode Method

(Central current electrode and two end current electrodes)
Instrument—Megger No. 2

Line D C Central current stake at D C 1 N			Line D II Central current stake at D II O		
Station and distance	R ohms	$\rho \div 10^2$ ohms per cm. cube	Station and distance	R ohms	$\rho \div 10^2$ ohms per cm. cube
Feet			Feet		
6 S – 5 S (50)	0·23	917	7 S – 6 S (50)	0·42	1,688
5 S – 4 S (50)	0·57	1,639	6 S – 5 S (50)	0·33	948
4 S – 3 S (50)	0·54	1,030	5 S – 4 S (50)	0·24	459
3 S – 2 S (50)	1·04	1,194	4 S – 3 S (50)	0·67	770
2 S – 1 S (50)	1·65	948	3 S – 2 S (50)	1·45	833
1 S – 0 (50)	3·53	696	2 S – 1 S (50)	3·25	622
0 – ½N (26)	6·74	609	1 S – ½S (25)	3·87	370
1½N – 2 N (26)	6·54	614	½ N – 1 N (27)	5·08	468
2 N – 3 N (52)	3·73	721	1 N – 2 N (52)	2·94	585
3 N – 4 N (54·5)	2·83	1,612	2 N – 3 N (51)	1·62	980
4 N – 5 N (50)	0·96	1,201	3 N – 4 N (59)	1·76	1,894
5 N – 6 N (50)	0·54	1,108	4 N – 5 N (48)	0·34	762
6 N – 7 N (55)	0·48	1,353	5 N – 6 N (49)	0·16	497
7 N – 8 N (50)	0·36	1,561	6 N – 7 N (56)	0·60	2,348
Instrument—Milliameter and Potentiometer					
1½N – 2 N	8·95	....			
2 N – 2½N	1·77	....			
2 N – 3 N	3·19	....			
3 N – 4 N	2·26	....			
4 N – 5 N	0·68	....			
5 N – 6 N	0·45	....			

TABLE V (a)

Line D C

South side Central stake to ½ N=25 feet				North side Central stake to 1½ N=25 feet			
Station	Distance across section	R^1 (Experimental)	$\bar{R}^1$ (Calculated)	Station	Distance across section	R^1 (Experimental)	$\bar{R}^1$ (Calculated)
	Feet				Feet		
½ N − 0..........	26	6·74	6·74	1½ N − 2 N....	26	6·54	6·54
½ N − 1 S........	76	10·27	9·57	1½ N − 3 N....	78	10·27	9·72
½ N − 2 S........	126	11·92	10·62	1½ N − 4 N....	132·5	12·10	10·79
½ N − 3 S........	176	12·96	11·19	1½ N − 5 N....	182·5	13·06	11·28
½ N − 4 S........	226	13·50	11·46	1½ N − 6 N....	232·5	113·60	11·59
½ N − 5 S........	276	14·07	11·67	1½ N − 7 N....	287·5	14·08	11·80
½ N − 6 S........	326	14·30	11·82	1½ N − 8 N....	337·5	14·44	11·94

TABLE V (b)

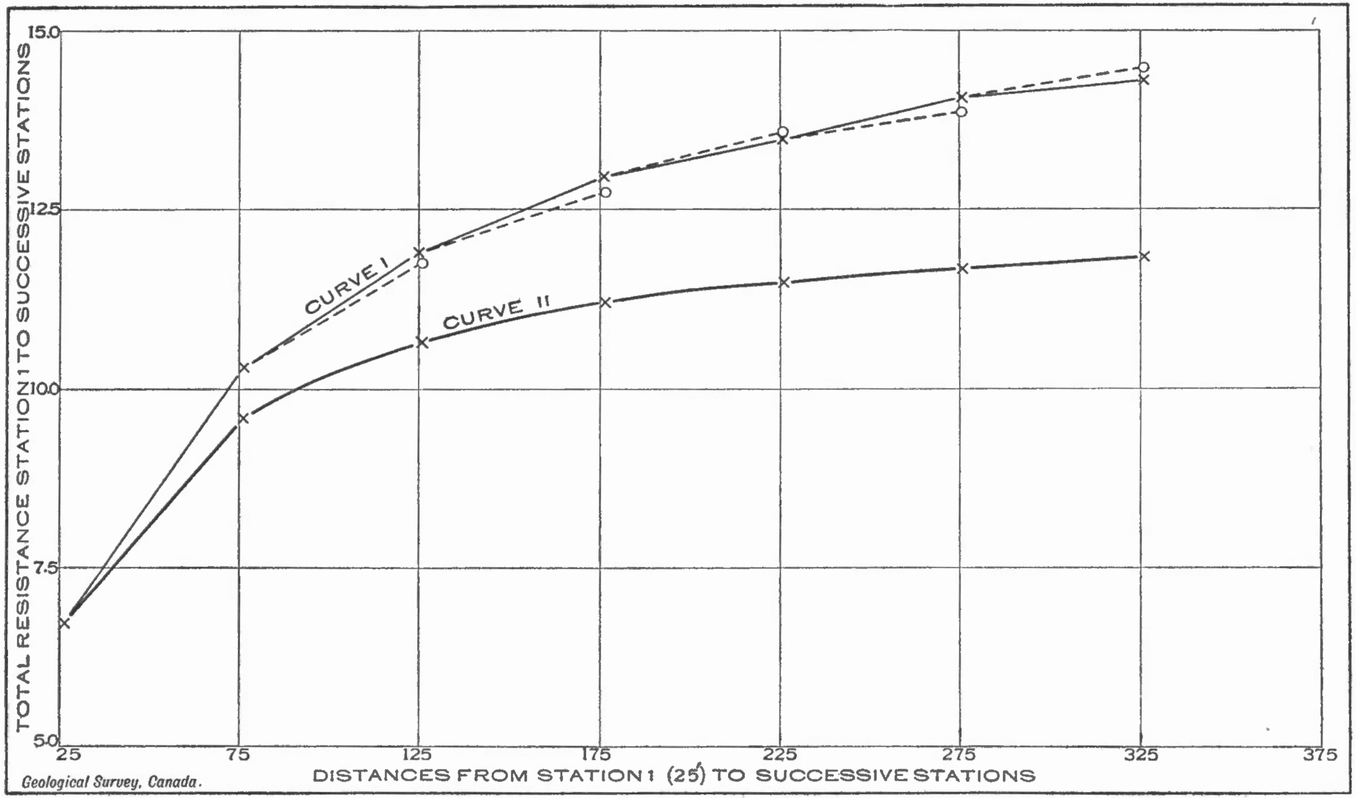
Line D II

South side Central stake to ½ S=25 feet				North side Central stake to ½ N=25 feet			
Station	Distance across section	R^1 (Experimental)	$\bar{R}^1$ (Calculated)	Station	Distance across section	R^1 (Experimental)	$\bar{R}^1$ (Calculated)
	Feet				Feet		
½ S − 1 S........	25	3·87	3·87	½ N − 1 N.....	27	5·08	5·08
½ S − 2 S........	75	7·12	5·79	½ N − 2 N.....	79	8·02	7·43
½ S − 3 S........	125	8·57	6·44	½ N − 3 N.....	130	9·64	8·22
½ S − 4 S........	175	9·24	6·79	½ N − 4 N.....	189	11·40	8·64
½ S − 5 S........	225	9·48	6·96	½ N − 5 N.....	237	11·74	8·84
½ S − 6 S........	275	9·81	7·09	½ N − 6 N.....	286	11·9	8·99
½ S − 7 S........	325	10·23	7·18	½ N − 7 N.....	342	12·5	9·11

In order to show the changes in resistance which take place with increasing depth range the total resistances R^1 of the sections included between the bowl of shortest radius and the successive bowls outward are calculated and are shown in Table V (a) and V (b) in column marked R^1—experimental. For comparison the total resistances are also calculated for a homogeneous medium of the resistivity of the section included between the two most shallow bowls. This section probably consists entirely of overburden. The results are shown in Table V (a) and V (b) in column marked $\bar{R}^1$—calculated. Both sets of results are also shown in Figures 44, 45, 46, and 47. In these figures curves I represent the experimental results and curves II the calculated results. The latter curves are, of course, smooth curves, whereas the slope of curves I if compared with the tangents to curves II at the same depth-points indicates the changes in average resistivity as successively deeper annular bowl sections are included.

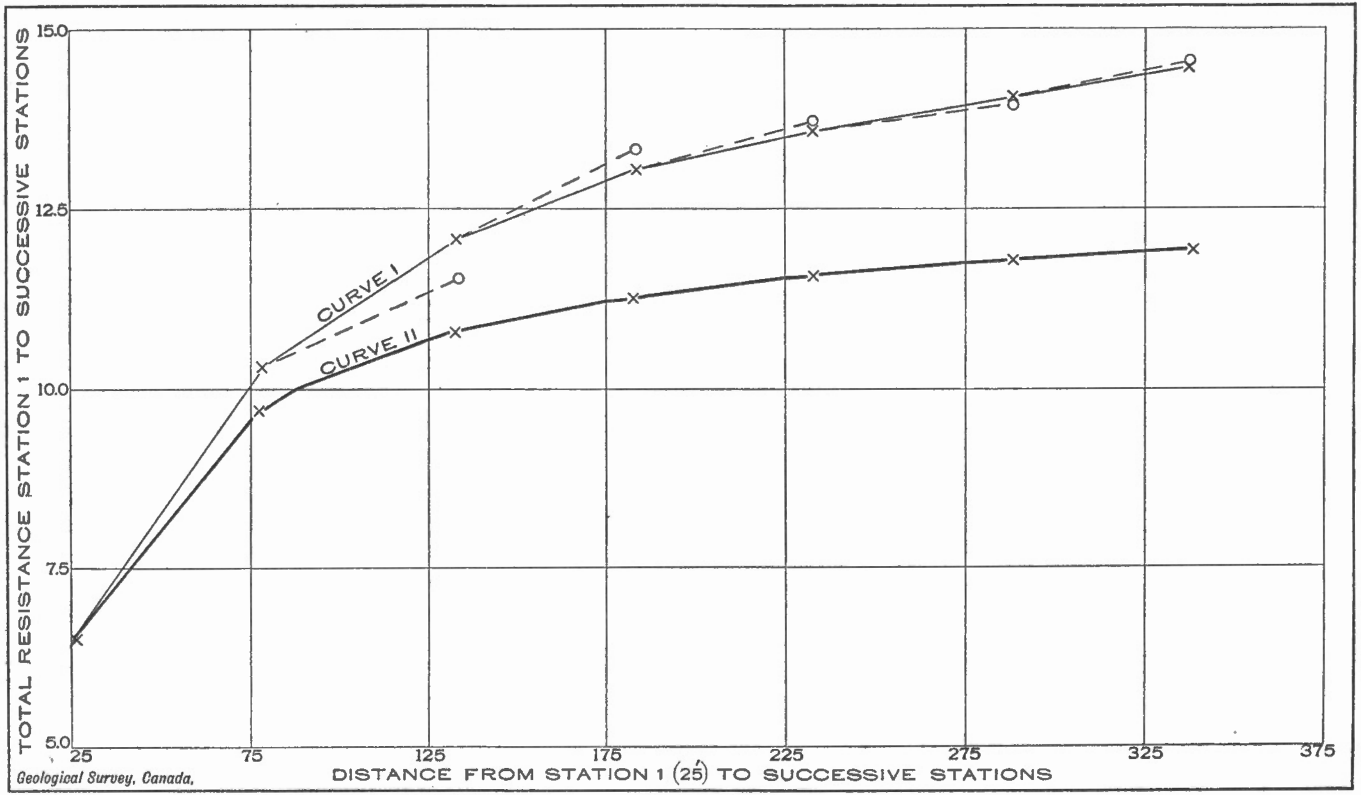
For example, in Figure 45, on which the results for line D C north side are shown, the total resistance of the annular bowl section included between bowls radius 25 feet and radius 103 feet (that is 25 feet+78 feet), viz., 10·27 ohms, is greater than it would be if the average resistivity of this section were the same as that of the annular bowl section of radii 25 feet and 51 feet (that is 25 feet+26 feet), viz., 9·72 ohms. This rate of increase persists into the section of radii 103 feet and 157·5 feet (that is 25 feet+132·5 feet), but is definitely less in the next section of radii 157·5 feet and 207·5 feet.

In Figure 47, for the results on D II north side these changes are more clearly portrayed. The inclusion of the poor conducting bodies in the section of radii 52 feet to 104 feet and of good conducting bodies in the adjacent more remote sections and then again of poor conducting bodies in the most remote section are definitely shown. In order to show the changes still more clearly the total resistances that would exist from the edge of the inner bowl to the remote rims of the successive bowls have been calculated as if the average resistivity of any annular bowl section persisted without change into its next remote neighbouring section. The results are shown on the figures by points joined by dotted lines to the next preceding points on the curves for the experimental total resistances. The slopes of these dotted lines may now be readily compared with the slopes of the corresponding lines on the experimental curve. The results are also given in Table VI.



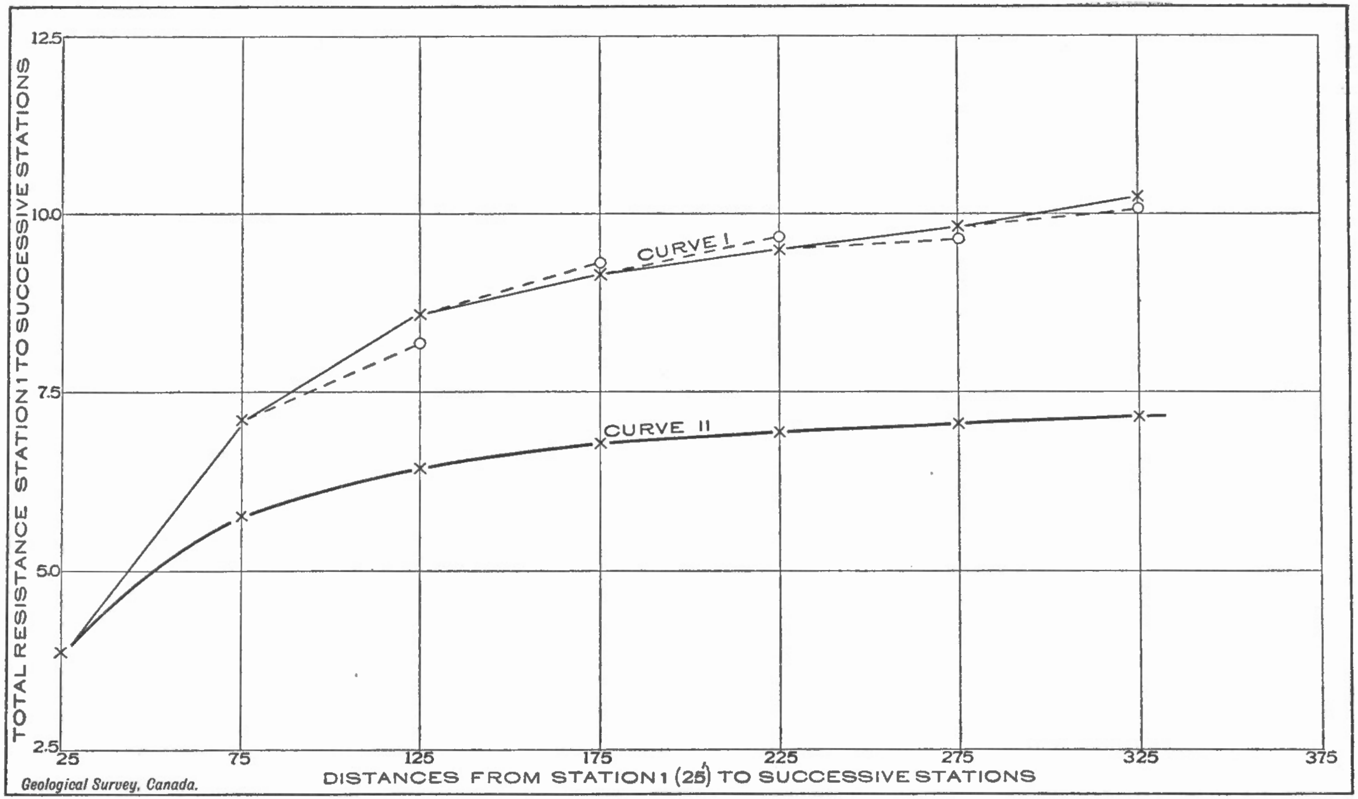
Geological Survey, Canada.

Figure 44. Results for line DC south side Abana mine. Curve I=Experimental values; curve II=calculated values as if the average resistivity of the innermost bowl section persisted throughout the region. Total resistances calculated as if average resistivity of any section persisted into next adjacent section, are indicated by the points joined by pecked lines to points on curve I.



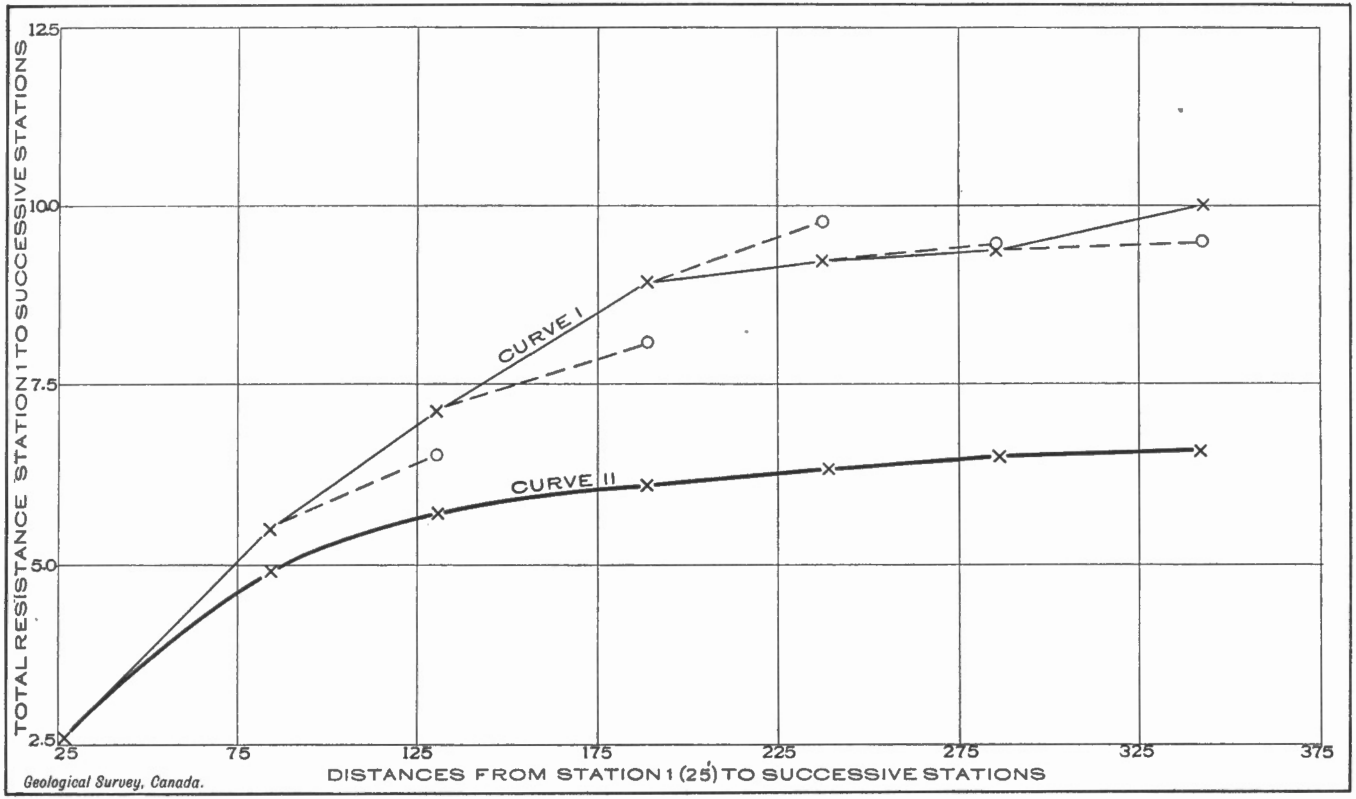
Geological Survey, Canada.

Figure 45. Results for line DC north side of Abana mine, Desmeloizes township, Quebec. Curve I=experimental values; curve II=calculated values as if the average resistivity of the innermost bowl section existed throughout the region. Total resistances calculated as if average resistivity of any section persisted into next adjacent section, are indicated by the points joined by pecked lines to points on curve I.



Geological Survey, Canada.

Figure 46. Results for line D II south side Abana mine. Curve I=experimental values; curve II=calculated values as if the average resistivity of the innermost bowl section existed throughout the region. Total resistances, calculated as if the average resistivity of any section persisted into the next adjacent section, are indicated by points joined by pecked lines to curve I.



Geological Survey, Canada.

Figure 47. Results for line D II north side Abana mine. Curve I=experimental values; curve II=calculated values as if the average resistivity of the innermost bowl section existed throughout the region. Total resistances, calculated as if the average resistivity of any section persisted into the next adjacent section, are indicated by the points joined by pecked lines to points on curve I.

TABLE VI

Line D II north side

Comparison of total resistances R^1 from the rim of the inner bowl to distant rims of successive bowls obtained experimentally with the total resistances R^1 calculated as if no change in conductivity existed in two adjacent annular bowl sections.

Annular bowl section	$\rho \div 10^2$	Resistance of annular bowl section experimental	Resistance of annular bowl section calculated[1]	R^1 experimental	R_1 calculated
Feet					
½ N – 1 N (25 to 52)..........	468	5·08	5·08	5·08	5·08
1 N – 2 N (52 to 104)..........	585	2·94	2·35	8·02	7·43
2 N – 3 N (104 to 155)..........	980	1·62	0·97	9·64	8·99
3 N – 4 N (155 to 214)..........	1,894	1·76	0·91	11·40	10·55
4 N – 5 N (214 to 262)..........	762	0·34	0·85	11·74	12·25
5 N – 6 N (262 to 311)..........	497	0·16	0·24	11·9	11·98
6 N – 7 N (311 to 367)..........	2,348	0·60	0·13	12·5	12·03

This method of presentation of curves has been adopted as the information presented in this way is well within the degree of precision of the experimental results. If the actual resistivities of the sections and depths were plotted, or if only the changes in resistances of sections and depths were plotted and the total resistances were omitted the results would be much more pronounced but the degree of precision less.

The changes in resistance correspond remarkably well with the known changes in the conducting medium as the depth ranges increase. Circles that are shown on Plan 11 indicate the portions that include ore-bodies. On Figure 48, which shows a vertical section through the ore-body and the dyke, circles have been drawn with the central current electrode point D C 1 N as centre. These show approximately the successive annular bowl sections, the position of the ore-body on the 300-foot level, and the probable depth of the overburden. The increases in resistance as shown in Table V and in Figures 44, 45, 46, and 47 correspond very well with the changes from overburden to dyke material and the decreases in resistance with the changes in the medium brought about by the inclusion of ore-bodies.

The following observations may be made from an inspection of the figures and plan:

(1) The changes in resistance which appear to correspond to changes from overburden to dyke are quite pronounced. On line D II it appears to be more pronounced on the north side than on the south side. This is probably due to the inclusion of ore-body on the southwest side which counteracts the effect of the dyke. The ore-body on the east side is also included with increasing depth ranges, but it is largely sphalerite and, as shown in an earlier section of this volume, it is comparatively a poor conductor.

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[1] The numbers in this column have been obtained on the supposition that the average resistivities of each annular bowl section persisted into the adjacent remote annular bowl section.

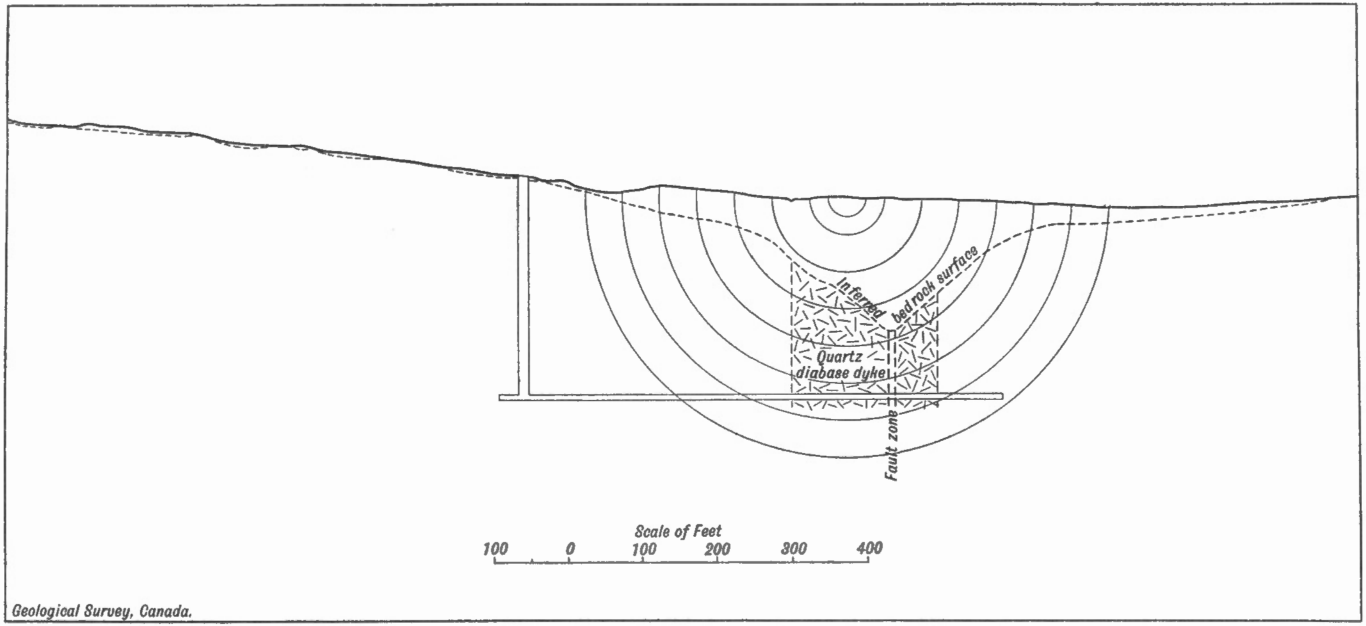

Figure 48. East-west vertical section through shaft and main drift at 300-foot level, Abana mine, Desmeloizes township, Quebec, showing approximately the successive annular bowl sections.

(2) The depth of the overburden in the neighbourhood of point D C O is 125 to 175 feet and near the point D II O the depth is about 100 feet to 125 feet. This corresponds very well with the probable condition as shown in Figure 48. It is also known that at a point about 50 feet to the east of D C O, where there is a fault in the dyke, the depth of the overburden is about 200 feet. These depths would, of course, be more precisely obtained by making measurements for smaller annular bowl sections. In determining the depth of the overburden, measurements every 10 feet should have been made between the points 25 feet and 250 feet.

(3) The inclusion of the same conducting bodies in the successive annular bowl sections is shown in both sets of results. This is more pronounced for the conducting bodies in the western ore zone than in the eastern ore zone. A comparative study of the curves for D C south side and for D II south side shows that a good conducting region is nearer the D II line than the D C line on the south side. For the ore-bodies in the western zone the distance to the point D II O is less than the distance to D C O. The former point is about 70 feet southwest of the latter point.

General suggestions and conclusions with reference to I (b).

(1) The apparent homogeneous character of the material of the dyke, together with a similar condition in the overburden but of lower resistivity than that of the dyke, made the location of the central current electrode above the dyke highly suitable for explorations in the surrounding territory.

As shown by the magnetic work, of which an account is presented in a preceding part of this volume, the general direction and extent of the dyke can be obtained by magnetic measurement (*See* Plan 11). In conjunction with other geological evidence its position may be readily located. It should then form a very useful base for electrical explorations in the district by the single electrode method.

(2) It is suggested that the accuracy of the measurements could be improved and the progress of the work expedited if one potential stake were fixed in position about 25 feet from the central current electrode and only the other potential stake moved to several successive distant positions along a line passing through the central current electrode and the adjacent fixed potential stake. The first potential stake should then be moved to suitable positions farther out and several sets of measurements made, the positions of the potential stakes for each set of measurements being governed by the results obtained in the preceding sets. By this method the readings on the megger would be larger and probably more accurate.

(3) This method of investigation with the megger as the measuring instrument will detect readily changes of conductivity such as existed at the Abana mine to a depth of at least 325 feet, the limit to which the measurements were made.

(II) ELECTRICAL INVESTIGATIONS AT FALCONBRIDGE MINE

Resistivity by the Central Electrode Method (central current electrode and two end current electrodes)

This method was used on July 10, 1929. The central current stake was placed at Station B, Figure 16. The end current stakes were placed 900 feet west and 900 feet east of this. This line was about 100 feet south of the ore-body. Two sets of measurements were made along a line through B in the north-south direction, one set with megger No. 2 and the other set with the milliammeter and potentiometer. The results obtained with the megger are given in Table VII and those obtained with the potentiometer in Table VIII.

With regard to these results the following observations may be made:

(1) Both sets of results show a rapid decrease in resistivity with increasing depths, a change that commences at very shallow depths.

(3) In the results with the milliammeter and potentiometer the diminution in resistivity is more rapid in the north side than in the south side, i.e., in the direction of the ore-body. This is not evident in the results obtained with the megger.

(4) It should be noted that in the measurements with the megger the total potential stake resistances were very high and the corrections correspondingly large.

In the measurements with the milliammeter and potentiometer many of the polarization voltages were high. They were not uniformly distributed about the central current stake nor did they have a simple relationship to the applied voltage. It is assumed that complete correction for these is made by reversing the current and averaging the two sets of potential readings.

(5) The results may be considered accurate to the second figure, at least in so far as they depend on the readings.

(6) In connexion with this work it is well to note that Dr. F. W. Lee on July 8 had made similar measurements at the same point B at the Falconbridge mine about one current electrode considered as a single electrode and a second current electrode being at a considerable distance in a similar way to that which had been used by the Schlumberger Electrical Prospecting Methods Company.[1]

These measurements were made with the milliammeter and potentiometer and are being published separately and are of interest in comparison with these results.

Dr. Lee also made measurements of the distribution of potential about the single electrode along a line passing through the two current electrodes, i.e. the east-west line as well as along the north-south line. These results are also of interest in view of measurements that were made later at the Errington mine on the distribution of potential about a central current electrode with which were used both single and multiple end current electrodes.

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[1] *See* "Geophysical Prospecting 1929"; Am. Inst. Min. Eng., p. 199. "Electrical Prospecting Applied to Foundation Problems" Irving B. Crosby and F. G. Leonardon.

TABLE VII

R=resistance of each annular bowl section in ohms
R^1=total resistance in ohms omitting sections 10 S – 20 S and 10 N – 20 N

Stations	Total potential stake resistances	R	R^1	$\rho \div 10^2$ ohms per cm. cube
10 S – 20 S	9,680	283	....	10,834
20 S – 40 S	11,580	149	149	11,408
40 S – 80 S	11,400	68	217	10,413
80 S – 160 S	8,940	15·6	232·6	4,778
160 S – 320 S	7,180	3·27	235·87	2,002
10 N – 20 N	8,900	326	....	12,480
20 N – 40 N	8,760	151	151	11,504
40 N – 80 N	10,360	67	218	10,260
80 N – 160 N	9,880	16·2	234·2	4,961
160 N – 320 N	8,120	3·96	238·16	2,425

TABLE VIII

Stations	Potential in millivolts	Current in milliamps	R	R^1	$\rho \div 10^2$ ohms per cm. cube
20 S – 40 S	759 760	4·3 4·4	175	175	13,399
40 S – 80 S	895 926	13·4 13·5	68	243·8	10,413
80 S – 160 S	217 270	13·4 13·5	18	261	5,513
160 S – 320 S	245 293	58 58	4·6	265·6	2,818
20 N – 40 N	849 846	4·6 4·7	182	182	13,935
40 N – 80 N	1,059 1,086	14·8 15	71·8	253·8	11,000
80 N – 160 N	232 276	14 14·1	18	271·8	5,513
160 N – 320 N	163 233	56·8 58	3·5	275·3	2,316

(III) ELECTRICAL INVESTIGATIONS AT THE ERRINGTON OR TREADWELL-YUKON MINE, JULY 29, 1929

Measurements of Resistivity by the Central Electrode Method

A central current electrode was set up at a station about 2,300 feet northward of No. 3 shaft in a region that had previously been explored by Dr. F. W. Lee. Four end current electrodes were placed at points 874 feet south, 1,200 feet west, 911 feet north, and 915 feet east of the central current electrode respectively. These were detachable so that one, two, or four end electrodes could be used at will. This arrangement was made in order to determine if the distribution of potential about the central electrode depended on the number of end electrodes that were used. If the experiments were made with a uniform conductor with a uniform distribution of potential about the central current electrode then the formula $\rho=2\pi R\frac{ab}{b-a}$ would be applicable for the determination of resistivity. The region in which the measurements were made was not a uniform conductor and the results can not be interpreted as a test of the applicability of this formula in determining resistivity. The experiments actually determined the distribution of resistance about the central electrode and in doing this the distribution of potential. The calculation of resistivities by means of the above formula is, however, of advantage as a guide to the magnitudes and the changes of the resistivities in the region. Consequently, the values of the resistivities as well as of the resistances are given in the tables of results.

A direct current was used and all measurements were made with a milliammeter and potentiometer.

The following experiments were carried out:

(1) A set of measurements was made to determine if the results were affected by the potential electrode contacts with the ground. A central current electrode and four end current electrodes were set up and the currents passing through the end electrodes were equalized. A set of measurements was made with four stakes at each of the potential electrode contacts and a set was made with one stake at each of the potential electrode contacts. The potential measurements were made along the west line. Measurements were made with the current in both directions. The results are given in Table IX. The actual measurements are given in order to show the degree of accuracy of the readings on the instruments and, therefore, of the results.

TABLE IX

Stations	Four stakes at contact			One stake at contact			ρ ohms per cm. cube	Total distances from edge of inner bowl	R^1 (Total resistance)
	Millivolts	Milliamperes	R	Millivolts	Milliamperes	R			
Feet								Feet	
25 W–50 W....	408 415	89 88	4·65	341 343	73 75	4·62	44,360	25	4·635
50 W–100 W...	57 56	89 90	0·632	44 48	73 75	0·622	12,002	75	5·262
100 W–150 W...	17 23	205 206	0·097	21 13	173 173	0·098	5,610	125	5·359
150 W–250 W...	5 10	252 254	0·0296	6 6	210 212	0·0284	1,249	225	5·388

In these experiments even the smallest readings are such that accuracy obtains in the second figure in the results and in the larger readings there is a correspondingly higher degree of accuracy. For consideration in connexion with the results of other experiments: the values of ρ and R^1 are also given in Table IX.

(2) A set of measurements was made to determine if the number of end electrodes used affected the potential difference between two points on the east-west or north-south lines and to show the distribution of potential about the central electrode. For this purpose the potential electrodes were placed at two stations 50 feet to 150 feet and each of the end current electrodes used alone in succession, and then all of the end current electrodes used together. The results are shown in Table X. The potential and current readings are not given as in Table IX, but the values of R and ρ are given. In this table are also given the values of R and ρ in the region 50 feet to 150 feet which was calculated from the readings in experiment 1.

(3) A similar set of measurements was made as in 2, but with the potential electrodes at stations 100 feet to 400 feet. The results are shown in Table XI.

(4) The end current electrodes were each placed at a distance of 600 feet from the central electrode and the currents which passed through these electrodes were equalized and a set of measurements made for the stations 100 feet to 400 feet. The results are shown in Table XII.

TABLE X

End current electrodes used	Stations 50 feet N–150 feet N		Stations 50 feet W–150 feet W		Stations 50 feet W–150 feet W	
	R ohms	ρ ohms-cm.	R ohms	ρ ohms-cm.	R ohms	ρ ohms-cm.
North	0·863	1,240	0·798	1,146		
West	0·862	1,238	0·800	1,149		
South	0·868	1,246	0·798	1,146		
East	0·858	1,232	0·800	1,149		
North and south	0·863	1,240	0·800	1,149		
East and west	0·860	1,235	0·796	1,143		
North, south, east, and west	0·858	1,232	0·796	1,143	0·725 (Determined from the results in Table IX)	1,029

TABLE XI

End current electrodes used	Stations 100 feet N–400 feet N		Stations 100 feet S–400 feet S		Stations 100 feet E–400 feet E		Stations 100 feet W–400 feet W	
	R ohms	ρ ohms-cm.	R ohms	ρ ohms-cm.	R ohms	ρ ohms-cm.	R ohms	ρ ohms-cm.
North	0·107	273	0·199	508	0·129	332	0·189	487
West	0·118	301	0·201	513	0·136	347	0·196	500
South	0·110	281	0·198	505	0·115	294	0·199	508
East	0·114	291	0·206	526	0·112	286	0·201	512
North and south	0·114	291	0·206	526	0·120	306	0·190	489
East and west	0·115	294	0·197	503	0·125	319	0·195	497
North, south, east, and west	0·115	294	0·202	516	0·120	306	0·184	477

TABLE XII

End current	Stations 100 feet S-400 feet S	
Electrodes used	R ohms	ρ ohms-cm.
North	0·190	485
West	0·202	516
South	0·199	508
East	0·196	500
North and south	0·192	490
East and west	0·195	498
North, south, east, and west	0·187	477

Consideration of the Results Obtained in II and III

(1) From the results in Table IX it appears that the number of stake contacts of the potential electrodes did not affect the values of the regional resistances.

(2) From the results in Table X it appears that where the end current electrodes were at a considerable distance from the central current electrode the potential difference between two points 50 feet and 150 feet from the central electrode on either the north or west lines was unaffected by the number or position of the end current electrodes and that the potential differences between these points 50 feet and 150 feet from the central stake but in different directions did not differ more than 9 per cent. This seems to point to almost uniform distribution of potential about the central electrode to a distance of 150 feet independent of the number or position of the end current electrodes. Measurements were not made, however, along the east and south lines.

(3) From the results in Table XI it also appears the potential difference between two points 100 feet and 400 feet from the central electrode is independent of the number and position of the end electrodes which are used. There is, however, a much greater departure in the distribution of potential about the central electrode.

(4) From the results in Table XII it appears that even when the end current electrodes are only 600 feet from the central current electrode the potential difference between two points 100 feet and 400 feet from the central electrode on the south line is almost independent of the number and position of the end current electrodes, the maximum difference being about 7½ per cent.

These results are remarkable indeed, especially in the last case, and difficult of interpretation.

The following observations and suggestions may, however, be made and are put forward in an attempt to aid in a solution of the problem:

(1) The average value of the resistivity in the 100-foot to 400-foot section from the measurements on the south line are about 4 per cent less when the end current electrodes are at a distance of 600 feet, than the resistivity of the same section when the end current electrodes were at a distance of over 900 feet.

(2) From Table X it is seen that the resistance between the bowls given by the points 50 feet and 150 feet on the west line is 0·725 ohms when all the end current electrodes were used as determined from the results in Table IX. The subsequent set of measurements, the results of which are also given in Table X, gave a value for the resistance between these two points of the same section of 0·796 ohms with all of the end current electrodes in use, i.e. a difference of about 9 per cent. In fact the total resistance between 50 feet and 250 feet on the west line is only 0·753 ohms as given in Table IX, and the resistance between 50 feet and 150 feet on the west line is 0·796 ohms as given in Table X.

(3) The resistance between the bowls marked by the points 100 feet to 250 feet on the west line as given by Table IX is 0·126 ohms, whereas the resistance between the bowls marked by the points 100 feet and 400 feet on the west line as given by Table XI is 0·184 ohms. This leaves a resistance for the section 250 feet to 400 feet of 0·058 ohms. From this it is found that the resistivity in the bowl section 250 feet to 400 feet must be 7,401 ohms per cm. cube, whereas from Table IX the resistivity of the bowl section 100 feet to 150 feet is 5,610 ohms per cm. cube, and for the bowl section 150 feet to 250 feet the resistivity is 1,249 ohms per cm. cube as given by Table IX, i.e., the resistivity of the bowl section 150 feet to 250 feet is less than one-fourth of the resistivity of the adjacent inner bowl section 100 feet to 150 feet and about one-sixth of the resistivity of the adjacent outer bowl section 250 feet to 400 feet. These results are given in Table XIII. In this table the resistances and resistivities of the separate bowls are given. The distances from the edge of the inner bowl to the edges of the successive bowls is given in column 4 and the total resistances from the edge of the inner bowl to the edges of the successive bowls is given in column 5. From the data of columns 4 and 5 Figure 49 has been made. On this figure is also shown the direction the curve would have taken if the resistance of each bowl section persisted into the next adjacent deeper bowl section. It is evident from the figure, but especially from the resistivities, Table XIII, that it is not a good conductor suddenly intruding in the 150-foot to 250-foot section, but rather a poor conductor intruding in the 250-foot to 400-foot section, unless indeed a good conductor intrudes at much shallower depths—for from Table IX it is seen that there is a very rapid increase in conduc-

TABLE XIII

Potential stake stations	R ohms	ρ ohms-cm.	Distance from station 1 (25 feet)	R^1 ohms (Total resistance)
Feet			Feet	
25 W – 50 W	4·635	44,360	25	4·635
50 W – 100 W	0·627	12,002	75	5·262
100 W – 150 W	0·097	5,610	125	5·359
150 W – 250 W	0·029	1,249	225	5·388
250 W – 400 W	0·058	7,401	375	5·446

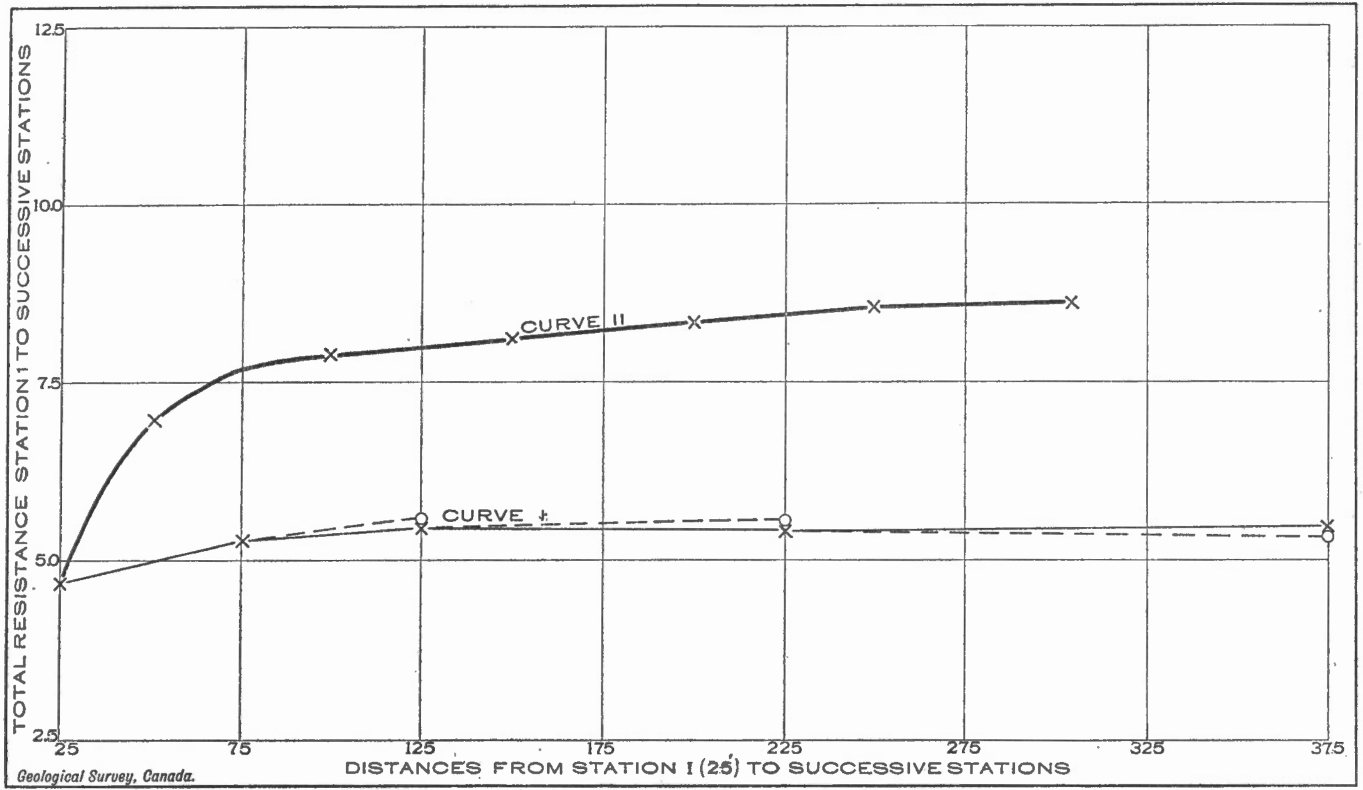

Figure 49. Results, Errington mine. Curve I=experimental values; curve II=calculated values as if the average resistivity of the innermost bowl section existed throughout the region. Total resistances, calculated as if the average resistivity of any section persisted into the next adjacent section, are indicated by points joined by pecked lines to curve I.

tivity with depth—and continues into the 150-foot to 250-foot section and is probably discontinued there, while a transition is made to an extensive, very poor, conducting material, probably rock, and the increase in resistivity becomes apparent in the 250-foot to 400-foot section.

It should be noted here that measurements made at station B, Falconbridge mine (*See* Tables VII and VIII), also show a very rapid decrease in resistivity with depth. Here, however, the resistivities at shallow depths are very high. In neither case is there much evidence of a change from a good conducting overburden to a poor conducting rock. Core specimens show that a poor conducting rock exists in the region. The results indicate rather an extensive good conducting material intruding at shallow depth (80 feet to 160 feet) into a very poor conducting material.

(4) Further, from the results of the measurements it appears from Table X that the resistivity as obtained from the measurements on the west line is lower than that for the north line for the bowl section 50 feet to 150 feet, whereas from Table XI for the bowl section 100 feet to 400 feet the resistivity for the west line is almost twice as great as for the north line, which may be understood if the good conducting material exists to greater depth on the north side than on the west side.

(5) It is of interest to compare these results with the results which were obtained by Dr. F. W. Lee for the same region at the Errington mine just prior to this time by a modification of the Gish-Rooney method. Dr. Lee obtained evidence of conducting material below 150 feet depth. The sensitivity of the two methods may also be compared readily from the results of the measurements.

(6) The conditions of resistivity at both the Falconbridge mine and at the Errington mine are different from that which exists at the Abana mine.

The resistivities at the station B region of the Falconbridge mine are very high to a depth of 80 feet and at greater depths become lower rapidly, but even at depths they are considerably higher than that at the Abana mine. The ore-body has a resistivity as low as 2 ohms per cm. cube and is embedded in a rock of very high resistivity which is covered with an overburden that is either shallow or of such high resistivity as not to counteract greatly the effect of the rock even at shallow depths.

The resistivities at the Errington mine in the region of the above investigation were very low indeed, except very close to the surface where they were as high as at the Abana mine. The decrease in resistivity with depth was much more rapid than at the Falconbridge mine. It was known that there were extensive graphitic deposits of very low resistivity at the Errington mine. The ore-body itself had a resistivity considerably higher than the graphite, and the problem was really to search for a conductor of resistivity higher than of the material closely associated with it, and in which the resultant resistivity of the combination was still low but not greatly different from that of the graphite itself, especially along the strike of the graphitic deposits. These resistivities were about $\frac{1}{10}$ to $\frac{1}{100}$ of that of wet clays and must have contributed largely to the necessity of the extensive inclusion of rock to increase greatly the resistivity with depth.

(7) It has been shown that the degree of accuracy of the readings precludes the possibility of error in readings, accounting for the apparent uniformity of distribution of potential in all directions within some distance from a current electrode, even when there is only one other current electrode used, and also for the remarkable constancy of the potential difference between two points 100 feet and 400 feet from the central electrode, with any number of current electrodes symmetrical about the central one and distant 600 feet from it. In this connexion the following suggestions are presented.

(*a*) Direct current was used in the experiments and there was a voltage polarization which increased with distance from the central electrode. In the region 100 to 400 it was varied in magnitude and was as much as 500 millivolts, while at the same two points in this region the actual net applied voltage readings were as low as 18 volts. It was assumed that the true applied voltage was obtained and the voltage polarization was eliminated by obtaining the voltage readings with the current in one direction and then reversed. It was not provided in general that the strength and duration of the current in both directions should be the same.

If this method does not eliminate voltage polarization then the errors in results may be of considerable magnitude.

At the Abana mine it was found difficult to get constancy of readings in repetition by this method. There the megger was used and consequently an alternating current was passed through the region in order to avoid polarization voltages. At the Errington mine the meggers were not used and no comparison is possible. At the Falconbridge mine where there were also voltage polarizations relatively much smaller considerable differences exist between the megger results and the milliammeter and potentiometer results—*See* Tables VII and VIII.

(*b*) The results that have been obtained would not hold for a uniform homogeneous conductor and are, therefore, probably due to the character of the conductor, e.g. a conducting medium in which the electrical current is dispersed by embedded non-conducting particles or to the effect of the applied current on the conductor.

It is known that where solid particles are embedded in an electrolyte and are not perfect non-conductors, that products of decomposition are deposited on the surface of the particles with a distribution that depends directly on the current density. If the products of decomposition, e.g. gases, are of high resistivity the denser currents are quickly weakened and dispersed and the current distribution becomes more nearly uniform over a considerable area about the electrodes. The overburden was much of the nature of an electrolyte with embedded particles.

From the results that have been obtained in the experiments at the Falconbridge mine and at the Errington mine the relative merits of a central current electrode with multiple end current electrodes and of a central current electrode with one end current electrode can hardly be appraised fairly in any respect.

The two meggers and a potentiometer which were used in the above experiments, together with auxiliary instruments, were the property of McGill University, Department of Physics, Montreal. A potentiometer, milliammeter, and resistance boxes and other auxiliary apparatus, which were used at the Abana mine, were the property of the University of Toronto, Department of Physics, Toronto.

MAGNETIC INVESTIGATIONS AT FALCONBRIDGE AND ERRINGTON MINES

On July 9 the Tiberg magnetometer of the Department of Physics, University of Toronto, was used to make measurements of the angle of dip in a plane at right angles to the direction of the magnetic field at points 200 feet south, 100 feet south, 50 feet south, 0, 50 feet north, 100 feet north, 150 feet north, 200 feet north, 300 feet north, and 400 feet north of station B, which is located on Figure 16. The results are plotted on Figure 50. The ore-body 100 feet north of station B is magnetic.

Along the same line at the same time similar measurements were made by Professor A. S. Eve and Professor D. A. Keys with an Askania Vertical Magnetometer. The results which were obtained with the Tiberg instrument were in fair accord with those obtained by the Askania instrument.

Some measurements were also carried out with another Tiberg magnetometer on another line at the same time as measurements were made with the Askania instrument on the same line. The results did not accord nearly as well.

Measurements were also made with the former magnetometer at the Errington mine from a point a little to the east of the bridge north of No. 3 shaft to a point 3,400 feet east of the first point. Readings were made at points 100 feet apart. Some differences in the magnitude of the dip were found. The ore-body conditions in the region are not known.

It is evident that changes in bearings or in the magnetic needles in these instruments take place which impair their usefulness and, therefore, the instrument should be tested and corrected frequently. If these precautions are carefully observed it is apparent that the Tiberg instrument will delineate very well magnetic conditions such as exist at the Falconbridge mine.

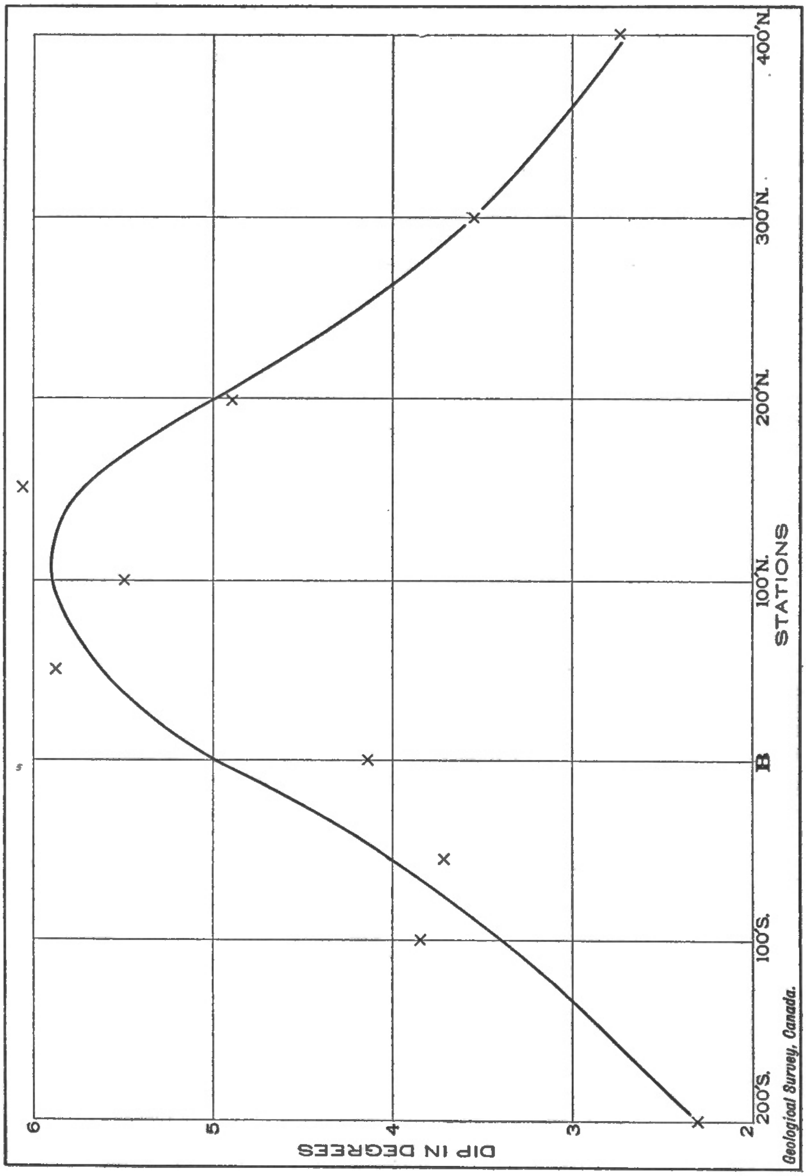

Figure 50. Results of magnetic exploration, at station B, Falconbridge mines.

PART IV

GEOPHYSICAL SURVEYS OF THE HULL-GLOUCESTER AND HAZELDEAN FAULTS

By A. H. Miller, C. A. French, and M. E. Wilson

CHAPTER I

INTRODUCTION

In connexion with the general problem of methods of geophysical prospecting it was desired to make some investigations of the applicability of the torsion balance to Canadian problems and conditions. When this matter came up, during the winter of 1927-28, no one in the Government service had had actual experience in the use of the torsion balance in the field for such purposes. However, the Dominion Observatory of the Department of the Interior, in connexion with its gravity work, had some experimental knowledge of the instrument and some acquaintance with the theoretical aspects of the case. After a consultation between the Directors of the Geological Survey and the Observatory, together with several of their colleagues, it was decided that it would be well to make at least some tentative investigations.

During the season of 1928 A. H. Miller, physicist in charge of the gravity division at the Observatory, was sent to Europe for the purpose of gaining first-hand information on the use of the torsion balance and field methods of investigation, as well as to compare and report on the various types of instruments available. Through the courtesy of the Director of the Geological Survey of Great Britain considerable time was spent with officials of that survey, with the object of becoming familiar with the theory and use of the torsion balance. Visits were made to several other British institutions; to the Geodetic Institute, Potsdam; the Geological Survey of Prussia, Berlin; the Baron Roland Eötvös Institute, Budapest; the Dutch Shell Oil Company, The Hague; and to field parties operating in Germany, Hungary, and Scotland.

Following this investigation it was decided in the early part of 1929 to undertake an investigation in this country to ascertain what application the torsion balance might have to geological problems in Canada.

It was agreed between the Department of Mines and the Department of the Interior that the work should be carried on under the joint direction of the Directors of the Dominion Observatory and the Geological Survey, that the Observatory should devote to the undertaking the services of the physicist in charge of the gravity division, and, when required, those of a field assistant, and that the Geological Survey was to furnish a geologist to co-operate in the field and office work as required, to pay the expenses of the field parties, and to furnish such additional field assistance as might be necessary.

Two instruments were ordered, one of these being an Askania Z balance, a photographically recording instrument made by the Askania Company of Berlin, the other the latest visual type of apparatus made by Ferdinand Süss of Budapest. The Askania balance was purchased by the Geological Survey and the Süss balance by the Observatory.

In order to acquire experience in using the instruments in the field, in making the necessary reductions, and in the interpretation of results, it was decided to begin the investigation with the survey of simple, well known, geological structures that are likely to be associated with mineral deposits.

The Askania balance became available for use towards the end of the summer of 1929. It was decided to spend the remaining part of the season, about two months, in a preliminary survey of sections of two faults in the immediate vicinity of Ottawa, near Leitrim and Hazeldean respectively. The geological structures associated with these faults were already fairly well known. An additional survey on the ground was made by M. E. Wilson of the Geological Survey. The gravitational work was under the charge of A. H. Miller of the Dominion Observatory. An experimental survey with standard magnetic instruments was also made over the same area by C. A. French of the Observatory, with a view to deciding whether for future work it would be worth while to provide magnetic instruments of the usual geophysical type. Reports on these three phases of the investigation will be found in the following pages.

CHAPTER II

GEOLOGY OF THE OTTAWA DISTRICT

By M. E. Wilson (Geological Survey)

GENERAL GEOLOGY

The Ottawa district includes part of the border that separates the region in St. Lawrence valley underlain by flat Palæozoic strata and known as the St. Lawrence lowland, from the great Precambrian upland that occupies the greater part of northeastern North America, the Canadian Shield. The city of Ottawa is on Palæozoic strata and hence lies in the St. Lawrence lowland, but Precambrian rocks outcrop in the province of Quebec only 3 miles to the north and in South March township, 10 miles to the west. If only the bedrock formations be considered, the rocks of Ottawa district belong to two great groups, the Precambrian and the early Palæozoic.

The Precambrian includes a great variety of rocks belonging chiefly to an early Precambrian basal complex consisting of: (1) a group of highly metamorphosed sediments—white crystalline limestone, quartzite, and sillimanite-garnet paragneiss—the Grenville series; (2) a group of related igneous rocks—anorthosite, gabbro, pyroxene diorite, pyroxene syenite, etc.—that intrude the Grenville series, known as the Buckingham or anorthosite series; and (3) batholithic massives of granite and syenite that intrude both the Grenville and Buckingham series. The batholithic rocks evidently were intruded as an accompaniment of a mountain building uplift and have since been laid bare by prolonged erosion. Through this basal complex east-west-trending diabase dykes have been intruded. These have suffered no deformation and are, therefore, classed as late Precambrian.

The Palæozoic strata of the Ottawa map-area range from the Upper Cambrian (Potsdam) to the base of the Silurian (Richmond). The names of the various formations, their lithological character, and estimated thickness up to the top of the Gloucester (Upper Utica) are indicated in the following table:

	Group	Formation	Lithological character	Thickness feet
Ordovician	Utica	Gloucester	Shale	50–75
		Collingwood	Shale and limestone	25–30
	Trenton	Cobourg	Limestone with a little shale	680
		Trenton	Limestone	
	Black River	Leray	Limestone	
		Lowville	Limestone	
		Pamelia	Limestone and shale	
	Unconformity			
		Chazy (Aylmer)	Limestone	
		Chazy (Aylmer)	Shale and sandstone	200
	Unconformity			
Cambrian	Beekmantown		Dolomite and limestone	235
		Theresa (Transition beds)	Dolomite and sandstone	
		Potsdam	Sandstone and basal conglomerate	200

This tabulation follows closely the succession as outlined by P. E. Raymond[1] and Miss A. E. Wilson.[2] The thicknesses for the Gloucester and Collingwood are those estimated by Raymond, those for the other formations were obtained from an examination of samples from well-borings supplied to the writer by D. C. Maddox, Acting Chief of the Borings Division. The determination of the average thickness of many of the formations of the Palæozoic succession of Ottawa district is difficult because of the presence of unconformities. Thus the Potsdam formation of sandstones and conglomerates fills the inequalities of the Precambrian surface on which it rests and hence its thickness varies exceedingly according to whether it is measured over a hill or a valley in the pre-Palæozoic erosion plain. The only bore-hole in Ottawa map-area that has intersected the whole of the Potsdam is that at Somerset and Bay streets where it is 290 feet thick. On the other hand, sandstone exposed in Buckingham and Templeton townships to the north of Ottawa river, the only Potsdam in the Ottawa sheet that has been studied by the writer, has a thickness of only a fraction of this amount. The estimate of 200 feet[3] as the average thickness of the Potsdam is, therefore, only a rough approximation and

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[1] Raymond, Percy E.: Geol. Surv., Canada, Sum. Rept. 1911, pp. 35-6; Geol. Surv., Canada, Mus. Bull. 31, 1921; Bull. of the Mus. of Comp. Zool. at Harvard College, vol. 56, pp. 254-56 (1916).

[2] Wilson, A. E.: Geol. Surv., Canada, Mus. Bull. 33, pp. 19-57.

[3] Ami, H. M.: Trans., Roy. Soc. Canada, vol. 16, p. 167 (1900).

may be too high. In the same way the presence of erosion intervals between the Beekmantown and the Chazy and between the Chazy and the Black River group renders the thickness of these formations variable in different localities within the map-area. The thickness of 235 feet for the Beekmantown is the average of seven bore-holes. The thickness of 200 feet for the Chazy shale and sandstone is the average of six bore-holes. Since the strata from the base of the Chazy limestone up to the top of the Cobourg are practically all limestone there is no lithological variation by which these formations can be distinguished from one another in the samples from bore-holes. For this reason they have been measured together. The total average thickness for the entire succession from the bottom of the Chazy limestone to the top of the Trenton group as determined from three bore-holes, is 680 feet.

Faulting

The Palæozoic strata of Ottawa valley are intersected by numerous faults along which the formations on one side have been dropped down various distances up to 1,000 feet or more with respect to their continuation on the other side. In places along the border of the Laurentian highlands, the relatively soft Palæozoic strata on the downthrown side of faults have been eroded away leaving rugged scarps up to 700 feet high. The Eardley escarpment that extends northwesterly from Kings mountain for over 30 miles[1] is a typical example of these escarpments. The tests of the torsion balance at Leitrim and in Nepean township southeast of Hazeldean, by Mr. Miller, were made over two of these faults, that

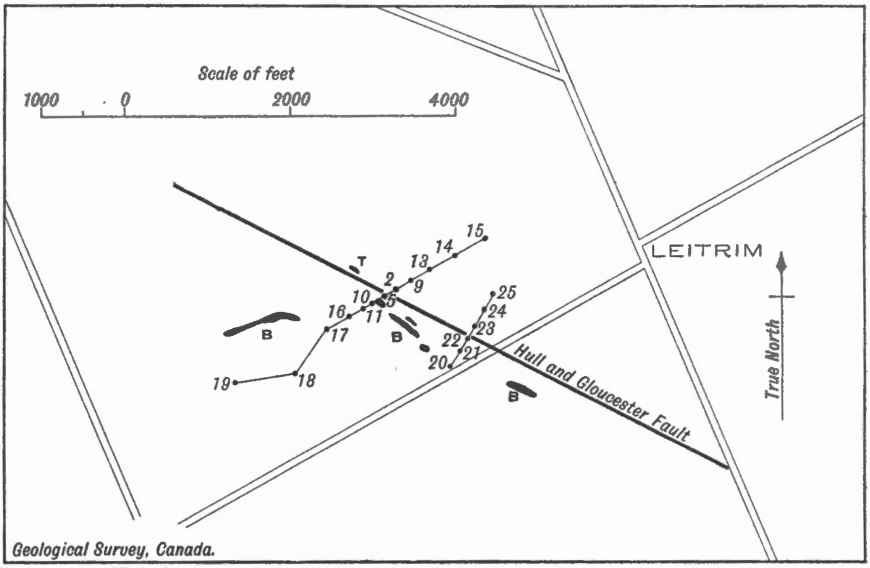

Figure 51. Hull-Gloucester fault at Leitrim, Ontario. Rock outcrops are shown in solid black; the outcrop of Trenton is labelled T, those of Beekmantown are labelled B. Lines of traverse and some of the stations occupied in torsion balance surveys are indicated.

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[1] Geol. Surv., Canada, Mem. 136, Plate I.

at Leitrim on the Hull and Gloucester fault and that near Hazeldean on a fault shown in the geological map of Ottawa and vicinity as the "Nepean and Gloucester fault and anticline", but designated in this report the Hazeldean fault.

The rocks exposed near the Hull and Gloucester fault at Leitrim (*See* Figure 51) consist chiefly of flat-lying Beekmantown dolomite lying to the southwest, on the upthrown side of the fault. At one point, north of the dolomite, there is a ridge about 150 feet long and 30 feet wide of fossiliferous grey limestone that dips 60 degrees northeast. Fossils collected from this ridge by the writer were identified by Miss A. E. Wilson as characteristic of upper Trenton. This outcrop, since it consists of strata normally several hundred feet higher than the Beekmantown, is presumably on the downthrown side of the fault. According to the geological map of Ottawa and vicinity prepared by R. W. Ells[1] the strata on the downthrown side of the fault at this point is Utica (Collingwood and Gloucester). The writer has had no opportunity to examine any rock outcrops that may be present in this region, but Miss A. E. Wilson states that excavations show that at least the summit of the hill at Leitrim is underlain by Lorraine. The total thickness of the Utica in Ottawa district according to Raymond is between 75 and 105 feet and Mr. Miller in mak-

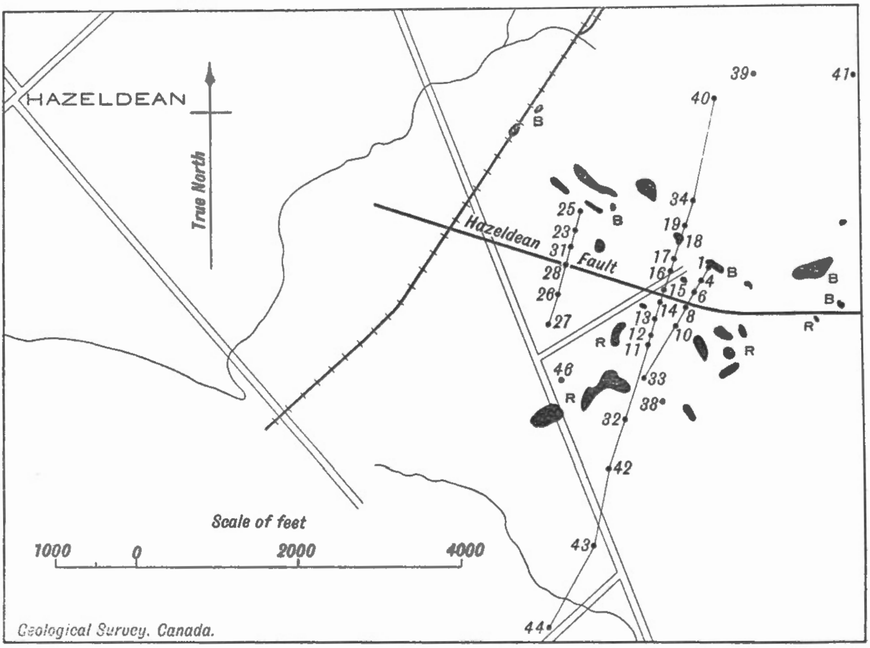

Figure 52. Hazeldean fault at Hazeldean, Ontario. Rock outcrops are shown in solid black; the outcrops of Black River are labelled R; those of Beekmantown are labelled B. Lines of traverse and some of the stations occupied in torsion balance surveys are indicated.

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[1] Geol. Surv., Canada, Ann. Rept., vol. XII (1902), Map. No. 714.

ing his calculations has assumed 66 feet of these strata to be present along the fault at Leitrim, but there is some doubt as to whether the Utica is actually present along the downthrown side of the fault in this locality, since the only downfaulted rock exposed along the fault belongs to the top of the Trenton group. The Beekmantown strata on the upthrown side of the fault, according to the geological map, are close to the contact with the Chazy shale and sandstone. The displacement on the Hull and Gloucester fault at Leitrim, therefore, as nearly as can be determined, is equal to the thickness of the Chazy, Black River, and, at least, almost all the Trenton, that is about 900 feet.

The rocks exposed along the Hazeldean fault in Nepean township southeast of Hazeldean (Figure 52), on the north or downthrown side of the fault consist of interstratified sandstone and dolomite belonging to the transition (Theresa) beds between the Potsdam and Beekmantown; on the south or downthrown side the rock is fossiliferous grey limestone. The fossils collected by the writer and by Miss Wilson from this limestone were identified by Miss A. E. Wilson as *Columnaria halli, Strophomena filitexta* Hall, *Bumastus?* sp., and a bryozoan epitheca. She states " that these fossils signify the very top of the Black River ".

The displacement along the Hazeldean fault in the locality where the tests were made corresponds, therefore, to the thickness of the Beekmantown (235 feet), Chazy (220 feet), and Black River (about 60 feet), or a total 515 feet.[1]

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[1] Wilson, A. E.: Geol. Surv., Canada, Mus. Bull. 33, pp. 19-29 (1921), and personal communication.
Raymond, Percy E.: Geol. Surv., Canada, Sum. Rept. 1911, pp. 352-354.
Wilson, M. E.: Geol. Surv., Canada, Mem. 136, pp. 47-53.

CHAPTER III

TORSION BALANCE SURVEYS OF THE HULL-GLOUCESTER AND HAZELDEAN FAULTS

By A. H. Miller (Dominion Observatory)

It is not proposed in this report to give a detailed account of the underlying theory of the Eötvös torsion balance. Although most of the literature on the instrument is in foreign languages a statement of the elementary principles involved will be found in the text book "Applied Geophysics", by Eve and Keys, and also in Ambronn's "Elements of Geophysics". A very good non-mathematical account appears in the Summary of Progress of the Geological Survey of Great Britain for 1926, by McLintock and Phemister. This report contains a bibliography which may be profitably consulted by those desiring further information in this respect.

For the purpose of explaining the results obtained in connexion with the present surveys it may be pointed out that the ordinary torsion balance is essentially a beam weighted at the ends and suspended from a support by a delicate fibre, the torsion constant of which has been accurately determined. In the original form, one of the weights is fixed on one end of the beam and the other is suspended from the other end by a fine wire about 18 inches long. This arrangement is somewhat modified in the case of the Askania Z balance (*See* Plate I) for the sake of compactness, the beam and hanging weight being replaced by a very light but rigid Z-shaped tube of aluminium, to which the weights are attached above and below the beam box. To protect it from air currents and disturbances caused by changes in temperature it is set up in a triple housing of metal (usually aluminium) and during observations is further protected by placing it in a small portable hut. In order to reduce the time of observation two beams are suspended parallel to one another in the same instrument, but differing 180 degrees in azimuth. In order to obtain the quantities which the instrument measures, the deflexions of the beams in three azimuths 120 degrees apart are required. As about an hour is required for the beams to reach their positions of equilibrium, it follows that about three hours are necessary for the determinations at any particular point. As it is highly desirable to check the observations by repetitions in the original azimuths, from five to six hours may be regarded as the minimum length of an observation.

As far as the application of the instrument to work in connexion with the location of geological structure is concerned, the torsion balance measures two quantities, the horizontal directing tendency (H.D.T.) and the gradient of gravity. For the determination of the H.D.T. the lower hanging weight could just as well be placed at the end of the beam. The purpose of suspending one of the weights below the beam is to enable the instrument to measure the gravity gradient.

The H.D.T. is a quantity which for any particular place depends upon the form of the equipotential or level surface at that point. Having regard to the small quantities which the instrument measures, the level surface is in practice always a curved surface. The magnitude of the H.D.T. depends upon the difference between the greatest and the least curvature of the surface in two vertical planes at right angles to each other. The direction of the H.D.T. is the direction of least algebraic curvature, a convex surface being considered positive. If the two curvatures are equal, as in the case of a spherical surface, then the H.D.T. is zero. If the curvatures are unequal and the surface convex and anticlinal, the direction is along the axis of the anticline. If, on the other hand, the surface is synclinal, the direction is at right angles to the axis of the syncline. In all cases the direction may be obtained by a consideration of the position in which the particles of the beam as a whole come nearest the level surface. In this position their potential energy is a minimum and, in accordance with a universal principle of nature, the beam tends, as it were, to fall into this position.

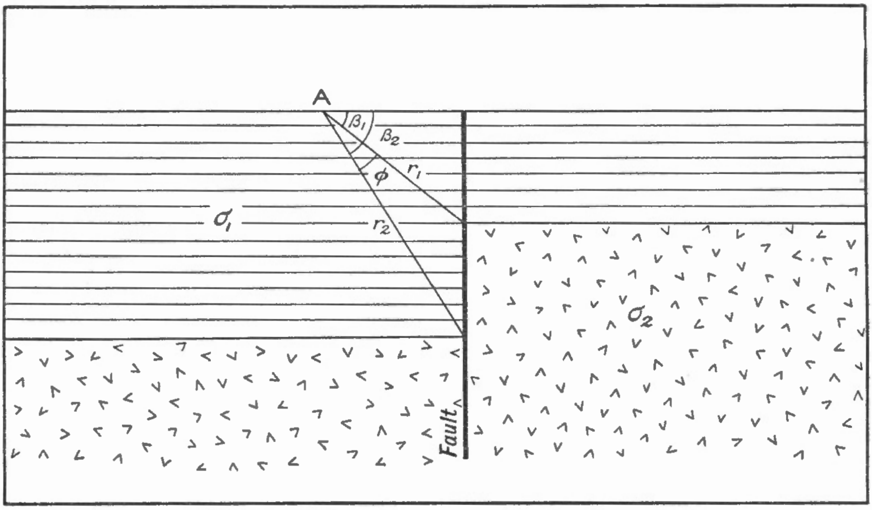


Figure 53. Illustrating a simple fault.

The gradient of gravity at any point is the rate of change of gravity in the horizontal direction in which its positive rate of change is greatest. Gravity itself is the force exerted in the direction of the vertical on unit quantity of matter at the particular point in question. It is the resultant arising from the combination of the gravitational attraction due to all matter composing the earth with the centrifugal force due to the earth's rotation. It is affected by the general distribution of material in the earth's crust. In gravitational prospecting, on the other hand, we are concerned with the comparatively local disturbances produced by the various geological features, accompanied by changes in density, such as faults, anticlines, etc., and by deposits of abnormally heavy or light material. As a heavy body or structure beneath the surface increases gravity, there is a tendency for the gradient to point in the direction of the heavy body.

THE GRADIENT AND THE H.D.T. IN THE CASE OF A FAULT

In order that a fault should produce a measurable effect on the instrument, it is necessary that it should bring strata of different densities in contact with one another. Referring to Figure 53, which may be taken to represent an ideal simple vertical fault, it can be shown that the gradient and H.D.T., produced by the structure at any point A, are respectively:

$$\text{Gradient} = 2\,\gamma\sigma \log_e \frac{\gamma_2}{\gamma_1}$$

$$\text{H.D.T.} = 2\,\gamma\sigma\,(\beta_2 - \beta_1) = 2\,\gamma\,\sigma\,\phi$$

where γ is the gravitational constant, equal to $66{\cdot}7 \times 10^{-9}$ c.g.s. unit, and $\sigma = \sigma_2 - \sigma_1$, the difference in density between the strata.

RESULTS AT LEITRIM AND HAZELDEAN

The results of the surveys over the Hull-Gloucester fault at Leitrim and the Hazeldean fault at Hazeldean are tabulated in tables I and II respectively. They are also shown graphically in the accompanying plans and graphs (*See* Figures 54 to 60, inclusive). The magnitudes are expressed in Eötvös units and the directions are magnetic bearings. One Eötvös unit is equal to 10^{-9} c.g.s. unit and is commonly designated by the letter E. To give an idea of its magnitude it may be stated that a round boulder about one foot in diameter placed about one yard from the instrument would produce a gradient of between one and two Eötvös units at the instrument.

The results have been corrected for the unevenness of the ground in the vicinity of the stations where the instrument was set up. For this purpose it was found necessary, for the gradient, to extend the corrections and the levelling necessary to obtain these corrections to a distance of about 50 yards from the station, and for the H.D.T. to about 400 yards. For the zone extending from 50 to 400 yards, contour sketches were made from levels taken in the field at the time the surveys were made. For certain stations in each locality, the corrections to be applied to the curvature or H.D.T. were determined to a distance of 5 miles. It was found that this outer correction did not exceed three Eötvös units. However, as the sketch maps for the zone 50 to 400 yards are based on levels that are rather incomplete, it is doubtful if the final H.D.T. values are correct to within less than five Eötvös units. The gradient values may be regarded as quite accurate. Both quantities are corrected for the normal effects produced by the shape and rotation of the earth. The final effects tabulated are, therefore, with the limitations mentioned, due to the gravitational effects produced by material beneath the surface.

DISCUSSION OF THE RESULTS

The Hull-Gloucester Fault at Leitrim. The plan (Figure 54) of the gravity gradient shows, in accordance with theory, gradients directed on both sides of the fault in the same sense and in general at right angles to the strike of the fault, with the maxima reached over the fault. On the side of lower density (*See* Figure 55) the H.D.T. is also, in accordance with theory, directed at right angles to the strike and, in the case of tra-

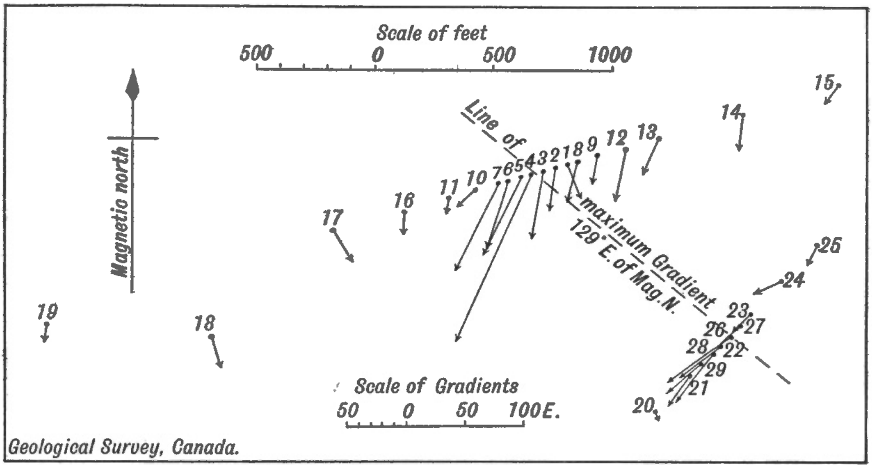


Figure 54. Plan of subterranean gradients, Hull-Gloucester fault at Leitrim, Ontario. For positions of stations, etc., relative to geological features, *See* Figure 51; arrows express direction and magnitude in Eötvös units.

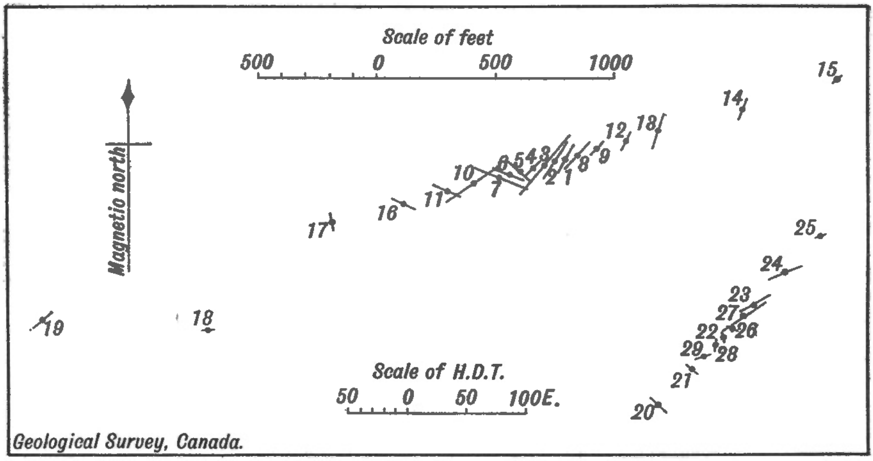


Figure 55. Plan of subterranean curvature values (H.D.T.), Hull-Gloucester fault at Leitrim, Ontario. For positions of stations, etc., relative to geological features, *See* Figure 51; lines express direction and magnitude in Eötvös units.

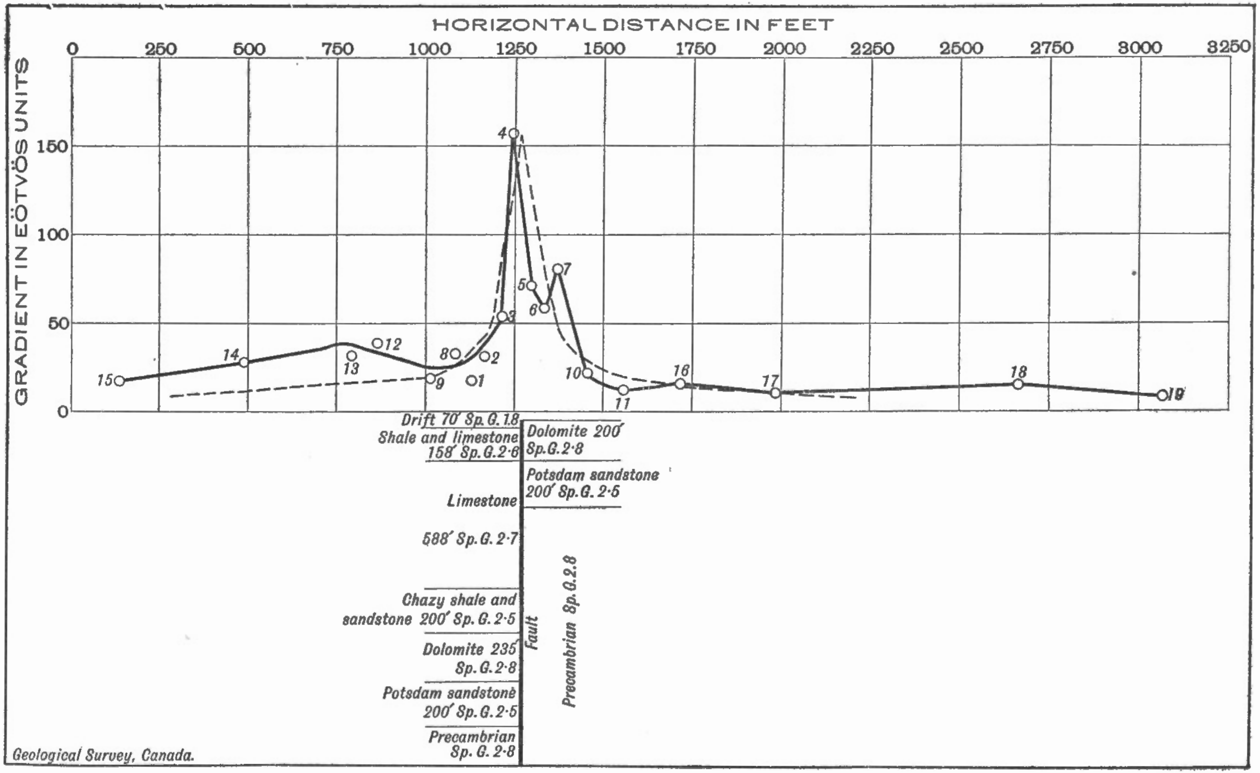
verse No. 1 (table I) at least, suddenly changes on crossing the fault to a direction parallel to the strike of the fault. There is a marked exception at station 10. Owing to the fact that it was found later that the instrument was repeating exposures in one or other of the azimuths it is probable that the anomalous result at this station may be due to an error of observation having the effect of turning the observed uncorrected results through an angle of 120 degrees..

TABLE I

Summary of Results at Leitrim

Station No.	Gradient		Horizontal directing tendency		Remarks
	Magnitude in Eötvös units	Direction	Magnitude in Eötvös units	Direction	
		° ′		° ′	
15	18·1	215 48	3·9	55 38	Traverse 1
14	31·9	189 36	20·5	16 57	
13	34·0	203 33	31·6	18 15	
12	44·0	191 48	15·5	30 03	
9	21·7	190 20	18·5	42 03	
8	37·1	193 24	32·7	39 48	
1	32·4	160 20	31·3	30 21	
2	37·0	186 03	41·1	35 03	
3	61·6	191 08	65·4	39 54	
4	162·0	205 20	17·1	47 31	
5	73·8	205 27	25·2	129 31	
6	62·4	199 39	24·3	113 00	
7	82·9	207 17	54·5	113 00	
10	21·3	224 49	51·3	56 42	
11	15·3	186 23	22·3	115 30	
16	19·4	183 32	20·6	116 50	
17	31·5	147 50	12·3	167 33	
18	29·0	161 41	9·2	82 46	
19	11·7	186 24	18·7	49 18	
25	20·2	209 21	7·2	65 30	Traverse 2
24	28·1	241 14	30·1	63 15	
23	25·2	221 09	28·1	55 18	
27	40·9	224 40	44·2	48 03	
26	70·5	229 58	5·9	116 56	
22	47·3	229 33	5·4	163 54	
28	55·6	217 10	7·4	28 16	
29	42·3	227 54	12·8	66 04	
21	32·9	215 52	13·2	126 52	
20	7·6	159 11	17·0	133 09	

In the case of the gradient graph (Figure 56) the ordinates represent the component of the gradient at right angles to the fault; in the case of the curvature graph (Figure 57) positive ordinates represent components perpendicular to the strike, and negative ordinates represent components parallel to the strike. In both cases the continuous lines represent the observed values, and the broken lines are the theoretical values computed for the section indicated. Also, in both cases, the distances as given are not actual distances along the transverse line but the components of these distances measured perpendicular to the fault, which are the quantities with which we are really concerned. The geological section, in so far as the thicknesses of the rock strata are concerned, was constructed from information supplied by M. E. Wilson. It is apparent, from the shape of the curves, that the sharp, large maxima are due to conditions near the surface. It can be shown that, in the case of an ideal vertical fault, half the distance between the maximum and minimum of the curvature is equal to the square root of the product of the depth of cover and the depth to the bottom of the block. As the distance between the maximum and minimum



Geological Survey, Canada.

Figure 56. Gradient-graph, Hull-Gloucester fault at Leitrim, Ontario. Ordinates represent components of gradients at right angles to the fault, at stations on traverse No. 1; stations are represented at their perpendicular distances from the fault plane; the broken line represents theoretical values computed on the basis of the assumed geological section along the plane of the fault as represented in the lower part of the figure.

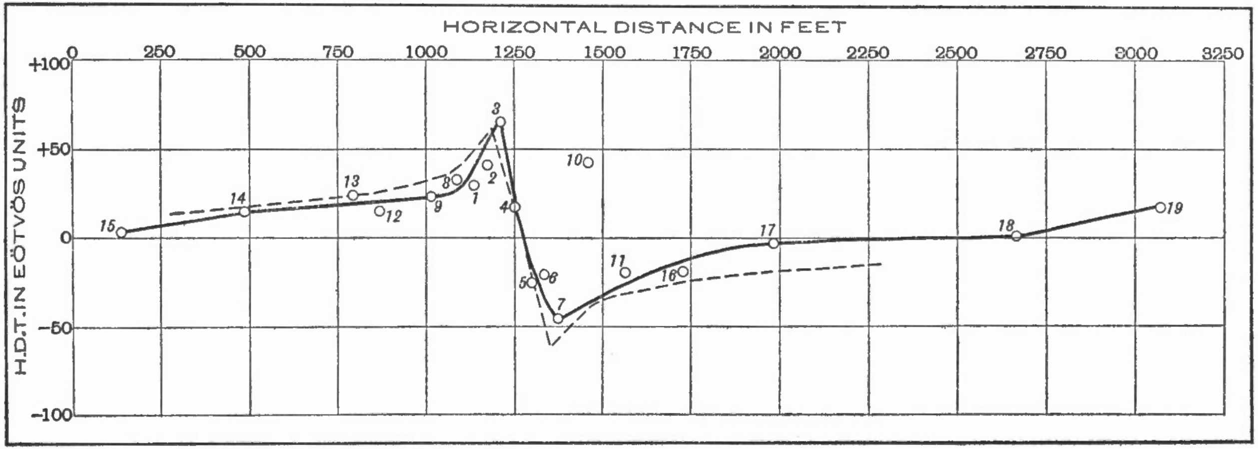


Figure 57. Curvature (H.D.T.)-graph, Hull-Gloucester fault at Leitrim, Ontario. Positive ordinates represent components of curvature (H.D.T.) at right angles to the fault and negative ordinates represent those parallel to the fault, at stations on traverse No. 1; stations are represented at their perpendicular distances from the fault plane; the broken line represents theoretical values computed on the basis of the assumed geological section along the plane of the fault (*See* Figure 56).

of the H.D.T. is about 160 feet, if we take the thickness of the Beekmantown dolomite on the upthrow side of the fault to be 200 feet the depth of cover over this block comes out to be 28 feet.

The depth of drift over the Beekmantown dolomite was adjusted to best fit the two curves and was found to be 42 feet. The densities of the sedimentary formations were taken from measurements made by the writer. The density of the Precambrian is unknown but was adjusted to fit the curves. Although the theoretical curves fit the observed data sufficiently well to show that the general conditions are explained, it is apparent that they do not represent the complete solution. This is most apparent in the case of the gradient on the downthrow side of the fault on traverse 1. It is possible that the disturbance in the gradient here may be due to the topographic form of the bedrock surface immediately beneath the drift, although no computations have been made to verify this supposition.

The lack of agreement between the theoretical and observed curvatures on the upthrow side of the fault is probably due to a hill in the vicinity for which the levelling is incomplete.

An estimate may be obtained of the thickness of the sedimentary rocks on the downthrow side of the fault by computing from the observed gradient curve the total change in gravity (the so-called gravity anomaly) produced by the fault, and by taking in conjunction with this the average weighted density difference of the several blocks comprising the fault. Theoretically the gradient curve should be integrated to infinity to obtain the complete effect, which is equal to $2\pi\gamma\sigma t$, where γ is the gravitation constant, σ the mean density difference, and t the thickness of the strata. The gravity anomaly obtained from the gradient curve in the present case is $2\cdot54 \times 10^{-3}$ c.g.s. unit. If this is taken, for the time being, as representing the total gravity anomaly and $0\cdot14$ the average excess of density on the upthrow side of the fault, the thickness of the sedimentary rocks on the other side of the fault, resulting from these assumptions, can be shown to be 1,420 feet. It can be shown from theoretical curves published by Shaw[1] that the above anomaly ($2\cdot54 \times 10^{-3}$ c.g.s. unit) must represent in this case at least 80 per cent of the anomaly if the integration were exact. So that our corrected depth can be shown to be not greater than 1,775 feet, a depth somewhat in excesss of that shown in the diagram, 1,423 feet, but in accordance with what might be expected from the disturbance in the curve to the north of the fault.

It, therefore, appears that, in the case of the Hull-Gloucester fault, the position and strike of the fault have been located from the torsion balance results with considerable accuracy, and that assuming an average density it has been possible to make a reasonable estimate of the sedimentary strata involved.

The Hazeldean Fault. In the case of this fault, the plotted results (*See* Figures 58, 59, and 60) show greater irregularities than in the previous survey. This is particularly true to the south of the fault. However, this was to be expected. The uppermost rock surface beneath the drift is,

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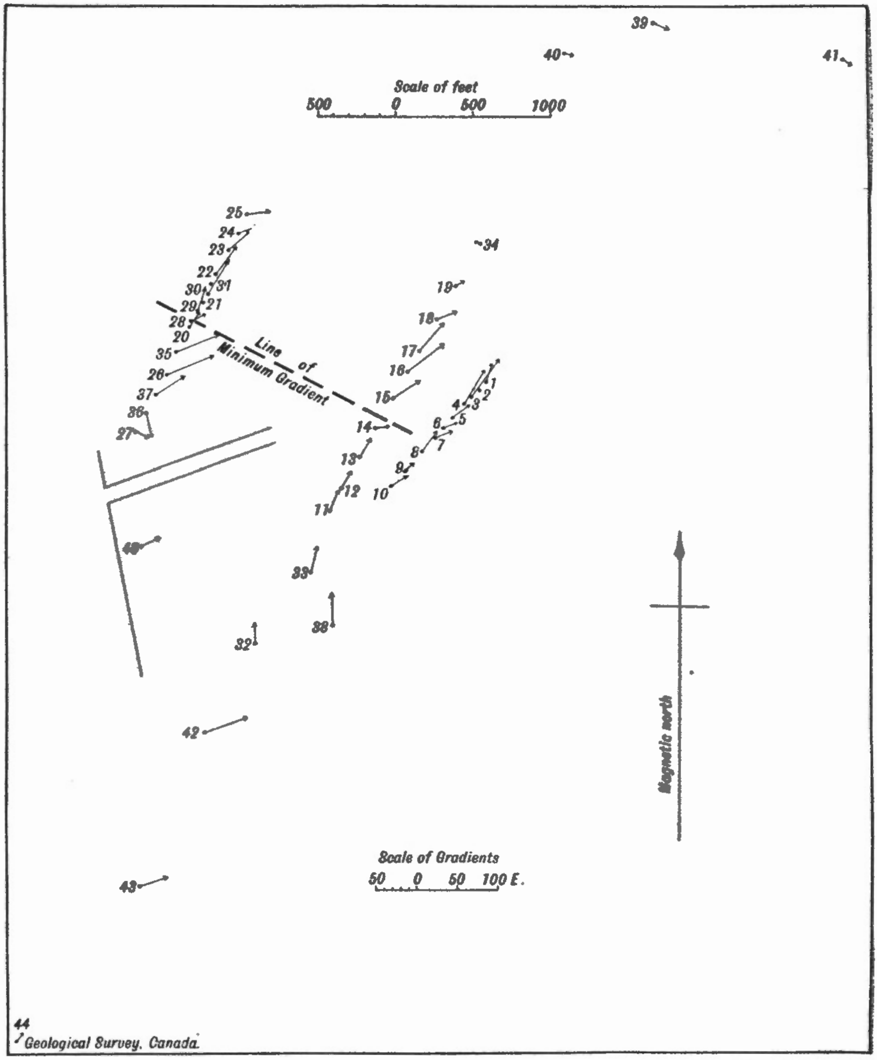
[1] "Interpretation of Gravitational Anomalies," by H. Shaw. Tech. Pub. No. 178, Am. Inst. Min. and Met. Eng., p. 63.

judging from the outcrops that occur, quite an irregular surface. In addition to this, the variable character of the Beekmantown strata and the probably irregular subterranean surfaces of both the Beekmantown and Precambrian no doubt combine to produce irregularities in the observed results.



Geological Survey, Canada.

Figure 58. Plan of subterranean gradients, Hazeldean fault at Hazeldean, Ontario. For positions of stations, etc., relative to geological features, *See* Figure 52; arrows express direction and magnitude in Eötvös units.

The disturbed directions of the curvature on traverses 1 and 2 in the vicinity of the fault on the south can be accounted for partly, and possibly entirely, by a depression in the rock surface covered by drift and

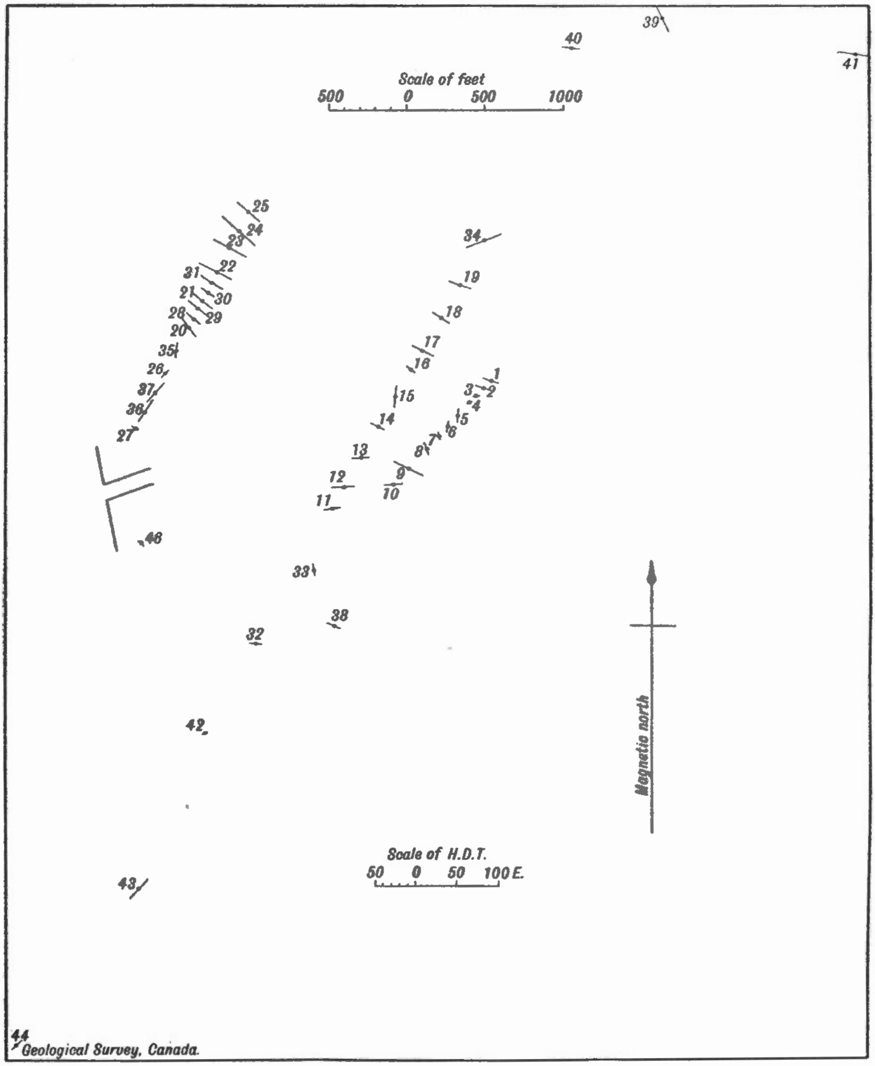


Figure 59. Plan of subterranean curvature values (H.D.T.), Hazeldean fault at Hazeldean, Ontario. For positions of stations, etc., relative to geological features, *See* Figure 52; lines express direction and magnitude in Eötvös units.

running at a magnetic bearing of about 130 degrees. In spite of these facts the gradients are generally directed in a direction at right angles to the strike of the fault and it is also clear that the position of the fault is located fairly closely by the minima of the gradients.

TABLE II

Summary of Results at Hazeldean

Station No.	Gradient			Horizontal directing tendency			Remarks
	Magnitude in Eötvös units	Direction		Magnitude in Eötvös units	Direction		
		°	′		°	′	
1	26·1	28	38	24·4	108	21	Traverse 1
2	47·3	39	57	19·5	112	43	
3	61·4	37	33	6·9	91	24	
4	49·5	20	58	8·7	53	22	
5	30·1	54	44	22·6	11	58	
6	20·6	68	40	13·9	10	30	
7	31·3	70	00	7·4	120	32	
8	30·5	38	29	16·6	158	00	
9	12·6	56	56	42·8	118	25	
10	29·2	55	23	23·8	85	24	
33	35·2	15	49	13·7	5	30	
40	12·9	107	09	26·8	104	09	Traverse 2
34	4·1	302	54	48·7	71	25	
19	15·8	60	31	32·5	111	26	
18	27·7	68	21	25·6	125	40	
17	48·2	43	19	34·4	119	30	
16	60·9	54	26	14·2	124	42	
15	41·7	58	49	26·7	10	38	
14	15·4	87	46	19·6	113	37	
13	26·3	36	57	24·5	84	07	
12	22·6	36	22	30·6	84	44	
11	29·4	28	30	21·7	81	51	
32	26·3	2	24	21·4	93	14	
42	60·1	71	23	4·6	66	16	
43	36·2	32	50	33·8	41	06	
44	10·6	109	58	22·1	44	29	
45	17·5	165	06	18·4	72	02	
25	31·9	83	42	37·1	133	46	Traverse 3
24	28·1	66	16	55·3	128	09	
23	38·5	49	44	48·4	119	07	
22	40·5	34	14	47·7	115	50	
31	44·0	32	11	33·2	120	48	
30	52·5	31	03	21·3	128	13	
21	43·6	28	13	34·5	126	06	
29	32·2	26	00	27·8	128	21	
28	17·4	55	18	25·8	128	23	
20	25·5	37	11	31·5	141	20	
35	61·0	67	46	19·6	5	28	
26	66·0	67	29	8·8	41	46	
37	43·2	58	00	33·8	40	19	
36	29·1	168	28	38·1	32	04	
27	18·3	117	22	5·2	116	22	
39	23·0	114	26	39·2	150	46	
41	13·8	128	00	40·0	95	50	
46	25·3	64	26	6·4	125	22	
38	41·3	2	38	23·8	110	02	

The general tendency of the fault at depth is to produce northerly gradients. Nearest to the surface, however, we have limestone in contact with sandstone, which tends to direct the gradient in the opposite sense. Over the fault the latter effect, although local, is quite large. Consequently at the edge of the fault we have a minimum gradient in contrast with the maximum over the fault at Leitrim. The gradient-graph (Figure 60), besides showing an approximate agreement of the observed and theoretical values, is interesting because it shows that a fault similar to this could be detected at a depth of over 200 feet. If no density differences existed until the Precambrian was reached, the gradients at the fault would be much larger than those actually found. To the south of station 28 the observed and theoretical curves differ considerably. The large variation between stations 27 and 35 is probably due to a basin in the limestone surface, the centre of which is in the vicinity of station 37.

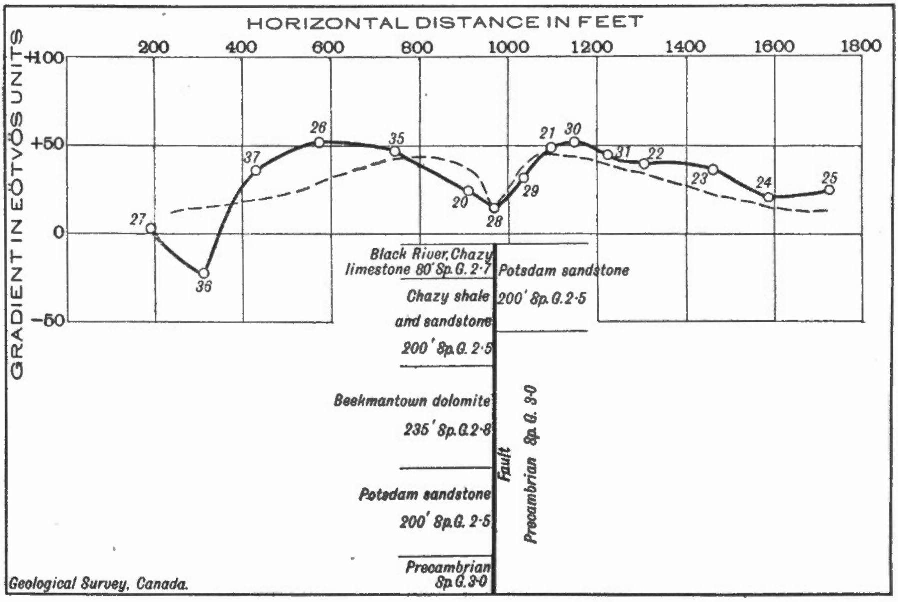


Figure 60. Gradient-graph, Hazeldean fault at Hazeldean, Ontario. Ordinates represent components of gradients at right angles to the fault, at stations on traverse No. 3; stations are represented at their perpendicular distance from the fault plane; the broken line represents theoretical values computed on the basis of the assumed geological section along the plane of the fault as represented in lower part of the figure.

BEHAVIOUR OF THE INSTRUMENT

Judged from the agreement obtained from repeated sets at the same station the accuracy of the instrument is quite satisfactory. Except for one or two minor troubles with the clockwork, of the sort likely to be encountered with any new instrument, but which are now apparently permanently rectified, the instrument performed very well. Usually two stations a day were completed, one during the day and one at night. As a rule more satisfactory results are obtained at night. For strictly accurate work during the day it is not advisable to make the period of observation too short. The writer made it a general rule not to accept a determination unless at least three complete sets had been recorded on the plate.

Although it would be more satisfactory to take a definite series of observations for the purpose, the results shown in table III, which are for stations at which both day and night observations were made, give some idea of the reliability of the day observations.

TABLE III

Comparison of Day and Night Observations

Date and time of observation	Number of sets	Station No. (Hazeldean)	Magnitude of gradient	Direction		Magnitude of H.D.T.	Direction	
			E	°	′	E	°	′
Oct. 11-12, 6 p.m.-8 a.m.	4	3	61·7	33	45	6·3	85	52
Oct. 14, 8.30 a.m.-4.10 p.m.	4	3	61·1	41	21	7·5	96	56
Oct. 18, 9 a.m.-4 p.m.	3	11	28·9	33	52	20·5	84	14
Nov. 16-17, 6 p.m.-8 a.m.	7	11	29·9	23	03	22·9	79	28
Oct. 31, 8 a.m.-4 p.m.	2	27	17·9	118	17	6·9	119	40
Oct. 31-Nov. 1, 5 p.m.-8 a.m.	6	27	18·7	116	27	3·5	113	04
Oct. 30, 9 a.m.-4 p.m.	3	31	43·4	32	07	33·6	120	11
Oct. 30-31, 4 p.m.-8 a.m.	7	31	44·6	32	15	32·8	121	26

CHAPTER IV

MAGNETIC SURVEYS OF THE HULL-GLOUCESTER AND HAZELDEAN FAULTS

By C. A. French (Dominion Observatory)

Magnetic methods are recognized as being useful in the location of various ore-bodies. They are applicable not only to iron ore deposits but also to non-magnetic ores which are associated with rocks possessing magnetic properties. The nature of the underground structure is inferred from the changes detected in the magnetic elements in the vicinity of the ore-body.

The magnetic surveys in the vicinity of the Gloucester and Hazeldean faults were carried out in conjunction with torsion balance surveys. From the known geological structure of these localities it seemed not unlikely that magnetic anomalies might be found. This appeared, therefore, a favourable opportunity to test the method and acquire experience in the interpretation of results.

GEOLOGICAL STRUCTURE

An idea of the geology of both the Hull-Gloucester and Hazeldean faults may be obtained from the preceding chapters. The Hull-Gloucester fault strikes approximately 130 degrees east of magnetic north. The upthrow is on the southwest. Though no values are available for the susceptibilities of the rocks it was assumed that if magnetic anomalies were found they would be due to magnetite in the Precambrian. The upper surface of this formation on the upthrow side of the fault is at a depth of 400 feet and the throw is approximately 1,000 feet.

The Hazeldean fault strikes approximately 120 degrees east of magnetic north. The upthrow is, in this case, on the northeast. The upper surface of the Precambrian is at a depth approximating 200 feet and the throw is about 550 feet.

THEORETICAL RESULTS

The application of magnetic methods to the location of underground structure is explained in textbooks on geophysics. The following are only a few of the many publications that may be consulted with regard to the methods and principles involved: " On the Location and Examination of Magnetic Ore Deposits by Magnetometric Methods ", by Haanel; Ambronn's " Elements of Geophysics "; " Geophysical Methods of Prospecting ", by C. A. Heiland; " Applied Geophysics ", by Eve and Keys; and Haalck's " Die Magnetischen Verfahren der Angewandten Geophysik ".

The usual method of illustrating the field of force around a magnet is by lines of force. If a magnetizable body, such as magnetite or soft iron, is introduced in a field the direction of the lines is changed due to the tendency of the lines to crowd into the iron. The field is altered both in direction and intensity. The body behaves like a magnet and is said to be magnetized by induction.

A deposit with which is associated magnetite or other magnetizable substance in the earth's field becomes in the same way magnetized by induction. Figure 61 represents a section of a magnetic formation with vertical face to the north. The block will have on its upper face the equivalent of a south magnetic pole and on its vertical face, owing to the direction of the earth's field, opposite polarity. For points above the deposit the effect due to the upper face, or south pole, will for the most part predominate. The lines of force arising from the magnetism induced in the formation are represented in the figure. This conception is introduced as an aid in predicting the results likely to be obtained in crossing a magnetic formation. The illustration represents the conditions, approximately, as they exist at Leitrim. The formation, which is assumed to be the source of disturbance, is the upthrown Precambrian on the south of the fault. The results to be expected as the fault is approached and crossed from the south, or upthrow side, are briefly summarized:

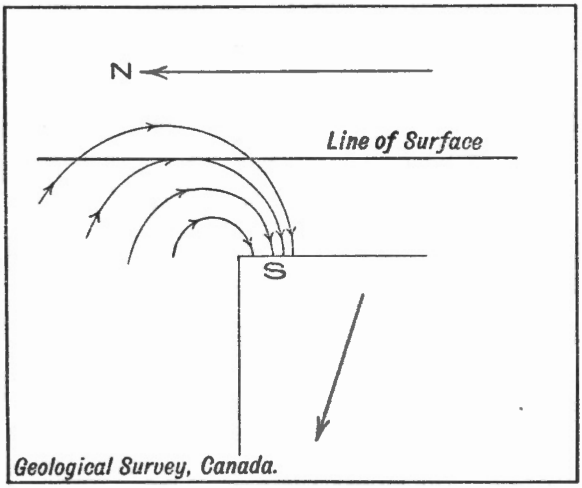


Figure 61. Section to illustrate lines of force arising from upper surface, at north side, of formation magnetized by earth induction.

(1) A decrease in the horizontal force as the edge of the fault is approached, until a minimum is reached approximately over the edge of the formation, after which an increase will occur.

(2) The vertical intensity will have a maximum value over the upthrow; as the fault is approached it will decrease, have a normal value over the edge of the formation and a minimum beyond.

(3) Over the upthrow the inclination will be greater than normal, a maximum near the fault and a minimum beyond.

(4) The declination would show no change if the fault were at right angles to the magnetic meridian. With the upthrow to the west and parallel to the magnetic meridian there would be an increase in westerly declination; over the edge the disturbance effect would be a maximum. At Leitrim the effect is likely to be small owing to the strike of the fault combined with the fact that the upthrow is on the south side.

The disturbance force over the south edge of a magnetic formation will probably differ somewhat in magnitude from that over the north edge; in direction, however, it will be quite different. Figure 62 represents the lines of force at the south edge of a formation magnetized by earth induction, and is intended to represent conditions as they are supposed to exist at Hazeldean. The results to be expected as the fault is approached from the south or downthrow side, are briefly summarized:

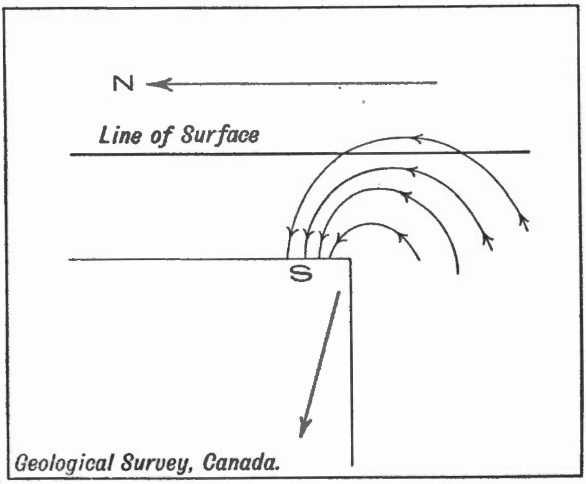


Figure 62. Section to illustrate lines of force arising from upper surface, at south side, of formation magnetized by earth induction.

(1) The horizontal force will increase, have a maximum value over the fault, then decrease.

(2) The vertical intensity will be normal over the downthrow, decrease near the fault, have a normal value over the edge and a maximum beyond.

(3) The inclination will change from a normal to a minimum near the fault, then gradually increase to a maximum beyond.

(4) On account of the strike of the fault the change in declination will be intermediate between zero, the value when the strike of the fault is at right angles to the magnetic meridian, and a maximum, which would occur if the strike were parallel to the meridian. With the upthrow on the north and east the disturbance force will deflect the north end of the needle to the east, that is to say there will be a minimum of westerly declination.

INSTRUMENTS

Various types of instruments[1] have been designed for magnetic measurements. For geophysical prospecting instruments are recommended which give relative values of the elements. As these were not available the investigations were made with instruments which are used for the accurate determination of the absolute values of the elements over the entire country. These included a combined magnetometer-earth inductor[2], which is one of the types designed by the Carnegie Institution of Washington, and a Dover dip circle. The former was used at practically all of the torsion balance stations to determine declination, inclination, and horizontal intensity. The dip circle[3] was also used at many of these stations, as well as at a number of additional stations which were not included in the torsion balance survey, for inclination and total force by what is known as Lloyd's method.[4]

TABLE IV

Magnetic Results at Leitrim (Traverse 1)

Station	Date	D	I	H	Z
		West ° ′	° ′	γ	γ
19	Oct. 7	13 46·3	75 40·8	14596	57144
18	" 7	33·9	42·1	591	251
17	" 7	39·2	38·0	654	212
16	" 5	55·8	38·6	614	097
11	" 2	55·1	38·7	597	037
10	" 2	55·2	38·5	614	090
7	" 5	52·6	37·5	629	079
6	" 5	45·0	39·3	617	157
5	" 8	54·6	37·5	606	56990
4	" 8	50·4	35·5	682	57151
3	" 8	14 08·9	41·4	578	150
2	" 8	13 54·6	38·4	618	099
1	" 8	57·0	38·5	599	031
8	" 9	52·9	38·7	603	060
9	" 9	57·0	39·8	570	040
12	" 9	52·2	40·0	612	182
13	" 9	50·9	37·1	626	040
14	" 9	49·2	37·4	642	123
15	" 10	42·4	39·4	588	051

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[1] *See* Ambronn: "Elements of Geophysics" (Translation), 1928, pp. 75-87.

[2] "Land Magnetic Observations", 1911-1913, vol. II, No. 175, Washington, D.C., pp. 9-12 (1912).

[3] "Directions for Magnetic Measurements", by Daniel L. Hazard, Washington, 1930, pp. 73-76.

[4] Ibid., p. 93.

TABLE V

Magnetic Results at Leitrim (Traverse 2)

Station	Date	D	I	H	Z
		West ° ′	° ′	γ	γ
20	Oct. 12	13 51·4	75 37·2	14642	57110
21	" 12	14 00·6	38·3	619	095
29	" 11	13 53·8	36·9	621	007
28	" 11	50·2	36·1	645	045
22	" 11	54·0	38·3	610	060
26	" 11	46·4	36·5	626	000
27	" 10	51·4	39·0	604	085
23	" 10	53·1	39·4	602	104
24	" 10	48·7	37·1	634	069
25	" 10	46·8	37·7	624	074

MAGNETIC RESULTS

The magnetic results obtained at Leitrim in the vicinity of the Gloucester fault are given in tables IV and V. The stations correspond to those occupied in the course of the torsion balance survey. Their positions will be found on Figures 51 and 54. At each of the stations the three magnetic elements, declination, D, inclination, I, and horizontal force, H, were determined. From the inclination and horizontal force the vertical intensity, Z, was deduced from the relation, $Z = H \tan I$.

Declinations have been corrected for diurnal variation and disturbance from data furnished by Mr. J. Patterson, Director of the Meteorological Service of Canada, from the Agincourt Magnetic Observatory. At some of the stations the corrections, when applied, did not produce satisfactory agreement among the observations. This applies to four stations in particular, namely, 19, 18, 17, and 6. A magnetic disturbance was in evidence on October 7 while observing at 19, 18, and 17. The results indicate that there is discontinuity in passing from these to adjacent stations, though it may be less marked than the results indicate.

The values of inclination and horizontal intensity were corrected for diurnal variation, but no attempt was made to correct for disturbance. The observations may, therefore, be in error by amounts exceeding the errors incidental to observing.

According to theory, assuming the source of the disturbance to be due to the Precambrian rocks south of the fault, certain general results are to be expected from observations of the magnetic elements in the vicinity of the fault. According to the summary already made there should be a minimum value of H over the fault, a gradual decrease of Z in crossing the edge from south to north, and a maximum value of westerly declination over the edge. According to torsion balance results (*See* Figure 54) the fault is along a line joining stations 4 and 26. From table IV it will be seen that at 4 there is a low value of D, minimum of I, maximum of H, and a value of Z somewhat above normal. At 26 there occurs a minimum of D, low of I, high of H, and low of Z. The results of D, I, and H are, at both stations, the reverse of what is expected from theory; at 4 there is a high value of Z and at 26 occurs, with one exception, the lowest. Considering the fact that the results at 19, 18, and 17 were taken during a magnetic storm, the discrepancies in the values of Z may, for the most part at least, be accounted for by errors incidental to observing. Errors of 1 minute in inclination and 10 gammas in horizontal intensity are quite possible. These will produce errors in the vertical intensity amounting to 70 and 40 gammas, respectively.

The general effect, apart altogether from the change at or near the fault, would be a greater value of the vertical force over the upthrow than over the downthrow. From table IV, which contains the results along traverse 1, the average value of the vertical force at nine stations south of the fault, or over the upthrow, is 57117γ, and the corresponding value at nine stations north of the fault is 57086γ. Leaving out of consideration three stations, 17, 18, and 19, having doubtful values, the mean over the upthrow is 57075γ. Along traverse 2, the results of which are given in table V, the average value of the force at four stations south of the fault is 57083γ, and the value at five stations north of the fault is 57063γ. From these there is, therefore, very slight, if any, evidence of an effect at the surface from this formation.

Although the evidence of a fault at 4 and 26 is lacking, the results indicate the existence of a disturbing body near the fault. In fact, the results at 3 correspond to what might be expected from a fault. This is not the case, however, when considered in relation to values at adjacent stations. The disturbing body may be associated in some way with the fault. Something in the nature of a highly magnetic rock parallel to the fault and located between stations 3 and 4 could produce the effects observed at stations near the fault. This would have the effect of counteracting the normal disturbance at the fault, if such existed, due to the material on the upthrow side. There may, on the other hand, be something associated with the sedimentary deposits to produce the disturbance.

RESULTS AT HAZELDEAN

The magnetic results at Hazeldean are given in tables VI, VII, and VIII, and are represented graphically in Figures 63, 64, and 65. Observations were taken at nearly all of the torsion balance stations. In addition, a number of stations were occupied for inclination and total force on traverse 3. The latter are indicated by letters following numbers. The relative positions of these will be obtained from Figure 65. These, it may be pointed out, have no place in the discussion relating to the fault.

The tables include, in addition to the absolute values of the elements, the corresponding anomalies. As far as the interpretation of the results is concerned there is not much advantage in deriving the latter except for plotting. The selection of data to represent the normal field was rather arbitrary. It will be noticed that there is not much change in the values of H and Z for stations 27-h to 27-l, table VIII. The mean of these was taken to represent the normal field. The value of D was derived from a

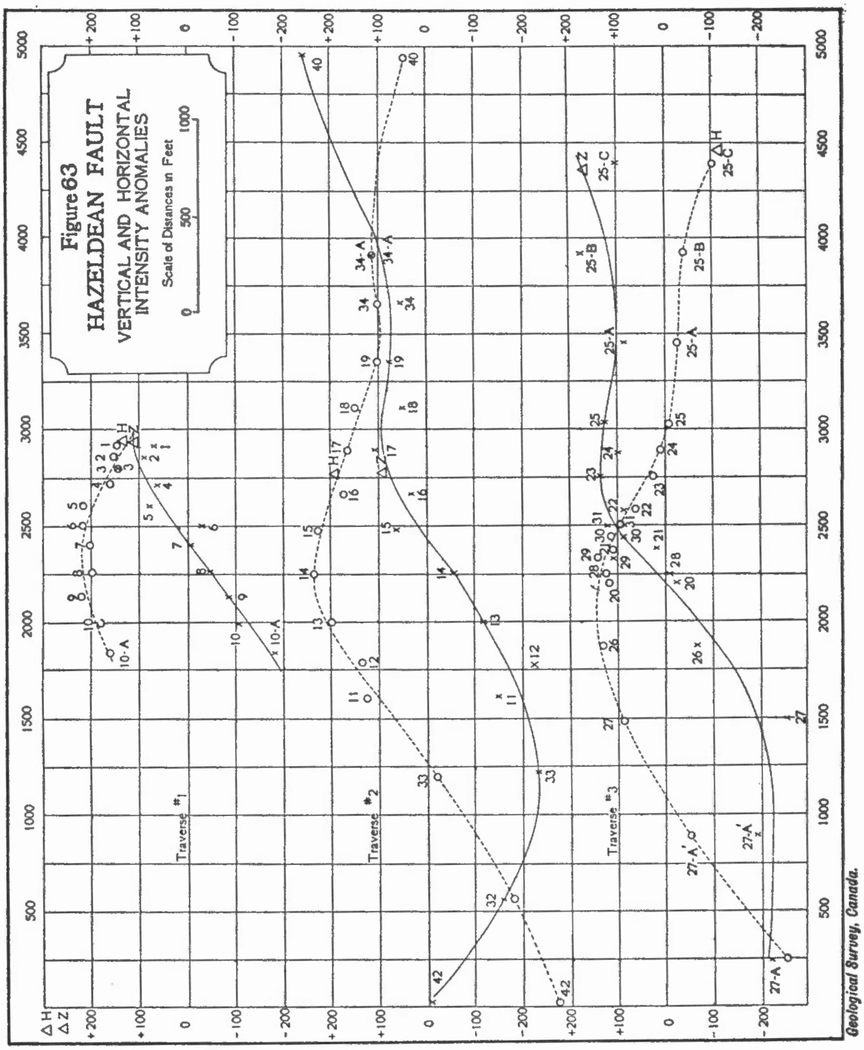


Figure 63
HAZELDEAN FAULT
VERTICAL AND HORIZONTAL INTENSITY ANOMALIES

Geological Survey, Canada.

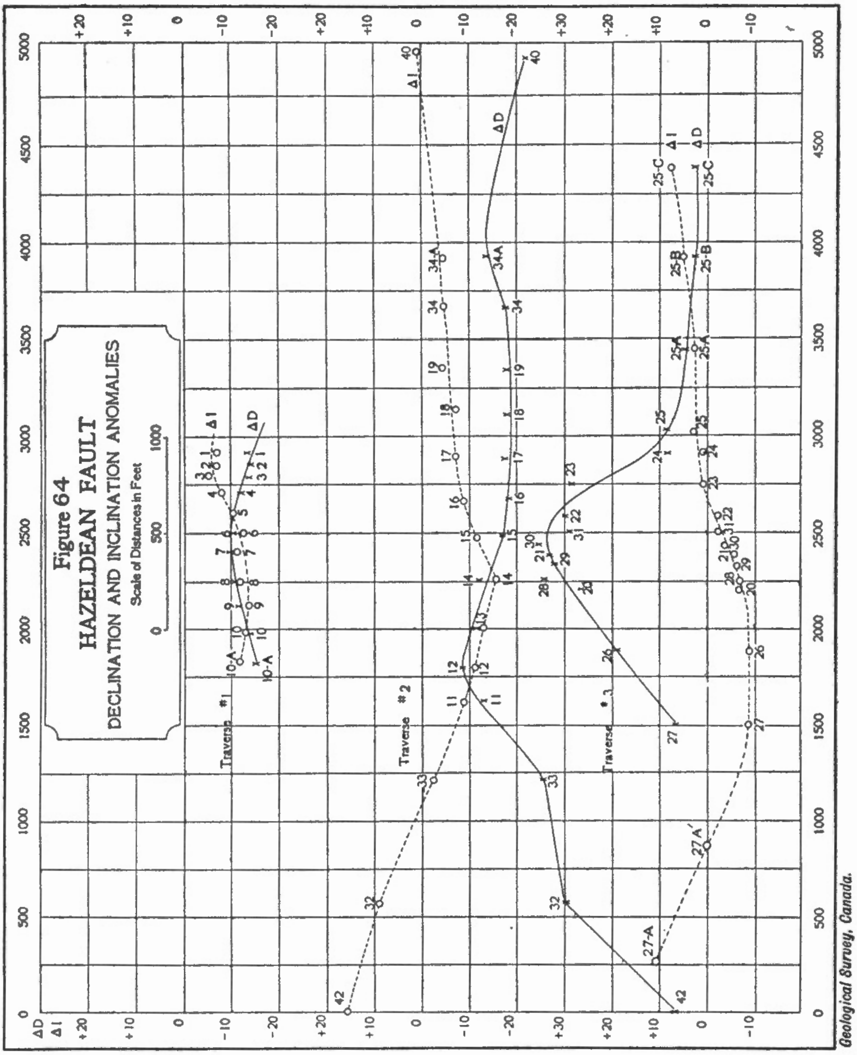


Figure 64
HAZELDEAN FAULT
DECLINATION AND INCLINATION ANOMALIES

Geological Survey, Canada.

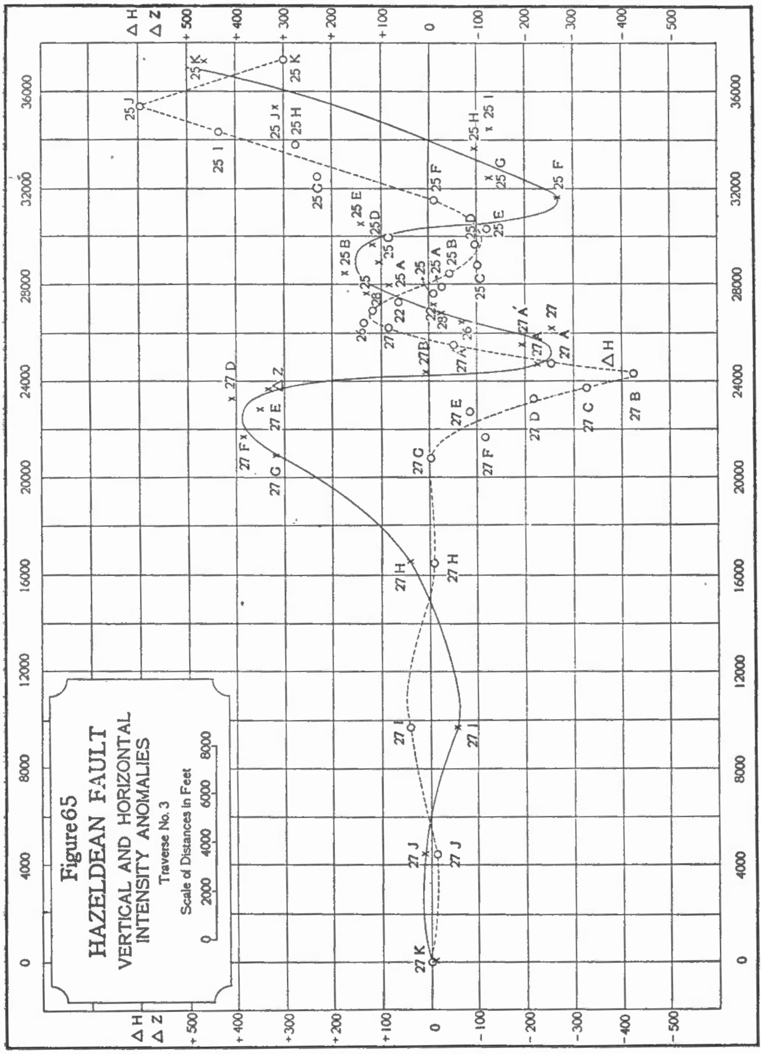


Figure 65

HAZELDEAN FAULT

VERTICAL AND HORIZONTAL INTENSITY ANOMALIES

Traverse No. 3

Scale of Distances in Feet

Geological Survey, Canada.

consideration of the values observed in the vicinity of the fault. The assumed normal values are: D=12° 47′; I=75° 31·7′; H=14756γ; and Z=57180γ. In deriving D it was assumed, in accordance with the usual convention, that westerly declination is negative. A positive value of D indicates, therefore, that the observed value is less than the computed.

According to theory, as was pointed out, when the upthrow is on the north, as at Hazeldean, there should be a minimum westerly declination and maximum H approximately at the fault, minimum value of I near the fault and maximum beyond, and a change in Z from a minimum, as the fault is approached from the south, to a maximum after it is passed. According to torsion balance results (*See* Figure 58), the fault passes approximately through station 28, midway between 14 and 15, and through 7. The results on traverse 1, which are given in table VI, indicate that there is that which corresponds to a fault very close to 7. The minimum declination is at 7, the mean curve of H, Figure 63, indicates a maximum approximately at 7, and Z changes from a negative to positive anomaly in passing along the traverse. On traverse 2 the minimum declination is at 12, which is some distance from the supposed location, maximum H at 14 as shown in Figure 63, and mean Z approximately over the fault. The minimum value of I also occurs at 14. On traverse 2, therefore, all elements, with the exception of D, are in accord with the results expected from a fault close to 14 and near the point indicated by torsion balance observations. On traverse 3 the minimum declination is at 28, maximum H at 29, and Z changes from a minimum to a maximum. The general characteristic exhibited by the inclination is in accordance with theory, a minimum south of the fault and a gradual change until a maximum is reached after it is passed.

The H and Z results at all stations along traverse 3 are not only given in table VIII, but are represented graphically in Figure 65.

The object in view in extending the traverse beyond what was covered by the torsion balance was to obtain, if possible, a series of uniform values which might be taken to represent the normal, undisturbed field. It was thought that over the downthrow and away from the fault local disturbance would probably be small. The traverse was extended also to the north to include stations between 25-a and 25-k.

The results indicate that the underground formation is probably very irregular. The results over the upthrow are not very surprising in view of the proximity of the Precambrian to the surface. The anomalies may, however, be due, partly at least, to gabbro, the presence of which may be suspected from the fact that it constitutes a part of the Precambrian exposures a few miles to the west. The pronounced changes over the downthrow between 28 and 27-g indicate the presence of a disturbance formation.

TABLE VI

Magnetic Results at Hazeldean (Traverse 1)

Station	Date	D	I	H	Z	ΔD	ΔI	ΔH	ΔZ
	1929	West ° '	° '	γ	γ	'	'	γ	γ
10-a	Oct. 26	13 01·8	75 20·0	14917	56996	− 14·8	− 11·7	161	− 184
10	" 22	00·6	18·8	938	57070	− 13·6	− 12·9	182	− 110
9	" 22	12 58·4	18·2	972	094	− 11·4	− 13·5	216	− 86
8	" 21	58·3	19·9	954	131	− 11·3	− 11·8	198	− 49
7	" 21	56·9	20·7	960	173	− 9·9	− 11·0	204	− 7
6	Nov. 14. Oct. 21	57·2	19·4	969	153	− 10·2	− 12·3	213	− 27
5	" 21	57·0	21·4	968	258	− 10·0	− 10·3	212	+ 78
4	" 19	58·9	23·8	915	244	− 11·9	− 7·9	159	+ 64
3	" 19	13 00·6	25·4	900	325	− 13·6	− 6·3	144	+ 145
2	" 19. Nov. 14.	00·7	24·9	908	268	− 13·7	− 6·8	152	+ 88
1	Oct. 19. Nov. 14.	00·4	24·6	899	247	− 13·4	− 7·1	143	+ 67

TABLE VII

Magnetic Results at Hazeldean (Traverse 2)

Station	Date	D	I	H	Z	ΔD	ΔI	ΔH	ΔZ
		West ° '	° '	γ	γ	'	'	γ	γ
42-a	Nov. 8	....	75 43·9	14591	57378	....	+ 12·2	− 165	+ 198
42	" 13	13 36·3	47·6	475	177	− 56·3	+ 15·9	− 281	− 3
32	Oct. 31	17·1	40·7	572	020	− 30·1	+ 9·0	− 184	− 160
33	Nov. 1. " 12.	12·6	29·5	736	56947	− 25·6	− 2·2	− 20	− 233
11	Oct. 23	12 59·8	22·7	881	57030	− 12·8	− 9·0	+ 125	− 150
12	" 23	55·4	20·6	889	56967	− 8·4	− 11·1	+ 133	− 213
13	" 23	58·8	18·6	957	57062	− 11·8	− 13·1	+ 201	− 118
14	" 23	59·4	17·9	988	124	− 12·4	− 15·8	+ 232	− 56
15	" 24	13 04·3	20·4	981	242	− 17·3	− 11·3	+ 225	+ 62
16	" 24	05·3	22·6	928	209	− 18·3	− 9·1	+ 172	+ 29
17	" 24	04·4	24·4	920	286	− 17·4	− 7·3	+ 164	+ 106
18	" 24	05·4	24·3	902	230	− 18·4	− 7·4	+ 146	+ 50
19	" 25	05·1	27·1	858	260	− 18·1	− 4·6	+ 102	+ 80
34	" 30	04·7	26·8	856	224	− 17·7	− 4·9	+ 100	+ 44
34-a	" 31	00·8	27·1	868	290	− 13·8	− 4·6	+ 112	+ 110
40	Nov. 15	08·8	32·6	807	434	− 21·8	+ 0·9	+ 51	+ 254
39	" 16	13·2	32·3	836	576	− 26·2	+ 0·7	+ 80	+ 396

TABLE VIII

Magnetic Results at Hazeldean (Traverse 3)

Station	Date	D	I	H	Z	ΔD	ΔI	ΔH	ΔZ
		West ° ′	° ′	γ	γ	′	′	γ	γ
27-l	Nov. 14		75 32·8	14741	57193		+ 1·1	− 15	+ 13
27-k	“ 14		31·8	756	178		+ 0·1		− 2
27-j	“ 14		32·7	743	192		+ 1·0	− 13	+ 12
27-i	“ 12		28·6	795	118		− 3·1	+ 39	− 62
27-h	“ 8		33·0	746	221		+ 1·3	− 10	+ 41
27-g	“ 8		36·7	752	497		+ 5·0	− 4	+ 317
27-f	“ 7		43·9	641	568		+ 12·2	− 115	+ 388
27-e	“ 7		41·2	676	521		+ 9·5	− 80	+ 341
27-d	“ 7		49·8	542	594		+ 18·1	− 214	+ 414
27-c	“ 7		55·0	428	512		+ 23·3	− 328	+ 332
27-b	“ 7		55·9	333	192		+ 24·2	− 423	+ 12
27-a	“ 4		42·9	503	56956		+ 11·2	− 253	− 224
27-a′	“ 14		31·8	707	986		+ 0·1	− 49	− 194
27	Oct. 29	12 40·4	23·2	841	921	6·6	− 8·5	+ 85	− 259
26	“ 29	28·0	22·7	889	57110	19·0	− 9·0	+ 133	− 70
20	“ 25	20·6	24·9	872	156	26·4	− 6·8	+ 116	− 24
28	“ 29	12·6	24·8	878	172	34·4	− 6·9	+ 122	− 8
29	“ 30	14·8	25·5	896	289	32·2	− 6·2	+ 140	+ 109
21	“ 25	14·0	25·9	864	194	33·0	− 5·8	+ 108	+ 14
30	“ 29	12·0	26·9	866	265	35·0	− 4·8	+ 110	+ 85
31	“ 29	17·8	28·2	851	301	29·2	− 3·5	+ 95	+ 121
22	“ 25	17·4	29·7	815	265	29·6	− 2·0	+ 59	+ 85
23	“ 26	18·6	32·4	780	314	28·4	+ 0·7	+ 24	+ 134
24	“ 26	28·6	32·6	767	278	18·4	+ 0·9	+ 11	+ 98
25	“ 26	28·6	34·1	748	307	18·4	+ 2·4	− 8	+ 127
25-a	“ 31	32·7	34·5	730	265	14·3	+ 2·8	− 26	+ 85
25-b	“ 31	44·7	36·6	716	356	2·3	+ 4·9	− 40	+ 176
25-c	“ 31	44·7	39·0	654	281	2·3	+ 7·3	− 102	+ 101
25-d	Nov. 2		39·0	660	296		+ 7·3	− 96	+ 116
25-e	“ 2		40·4	637	310		+ 8·7	− 119	+ 130
25-f	“ 5		28·5	749	56931		− 3·2	− 7	− 249
25-g	“ 5		16·9	988	57057		− 14·8	+ 232	− 123
25-h	“ 5		15·0	15027	077		− 16·7	+ 271	− 103
25-i	“ 4		05·2	194	052		− 26·5	+ 438	− 128
25-j	“ 20		02·9	354	496		− 28·8	+ 598	+ 316
25-k	“ 20		21·5	061	647		− 10·2	+ 305	+ 467

LOCAL DISTURBANCE FORCES

If a comparison of the absolute values of the elements on the three traverses at Hazeldean is made, it will be seen that there is a marked difference between traverse 3 and either 1 or 2, the latter two differing only slightly. At the fault on 3 the declination is 12° 12′ west and on 2 and 1 the values are 12° 59′ and 12° 57′ west, respectively. The corresponding values of H are 14878γ, 14988γ, and 14969γ, and of Z, 57172γ, 57124γ, and 57173γ. From the values of D it is evident that there is the equivalent of a south pole located between traverses 3 and 2. A south pole situated southerly from 3 would have the effect of diminishing the horizontal force—it acts in opposition to the earth's normal field—and increasing it in the case of 2 and 1.

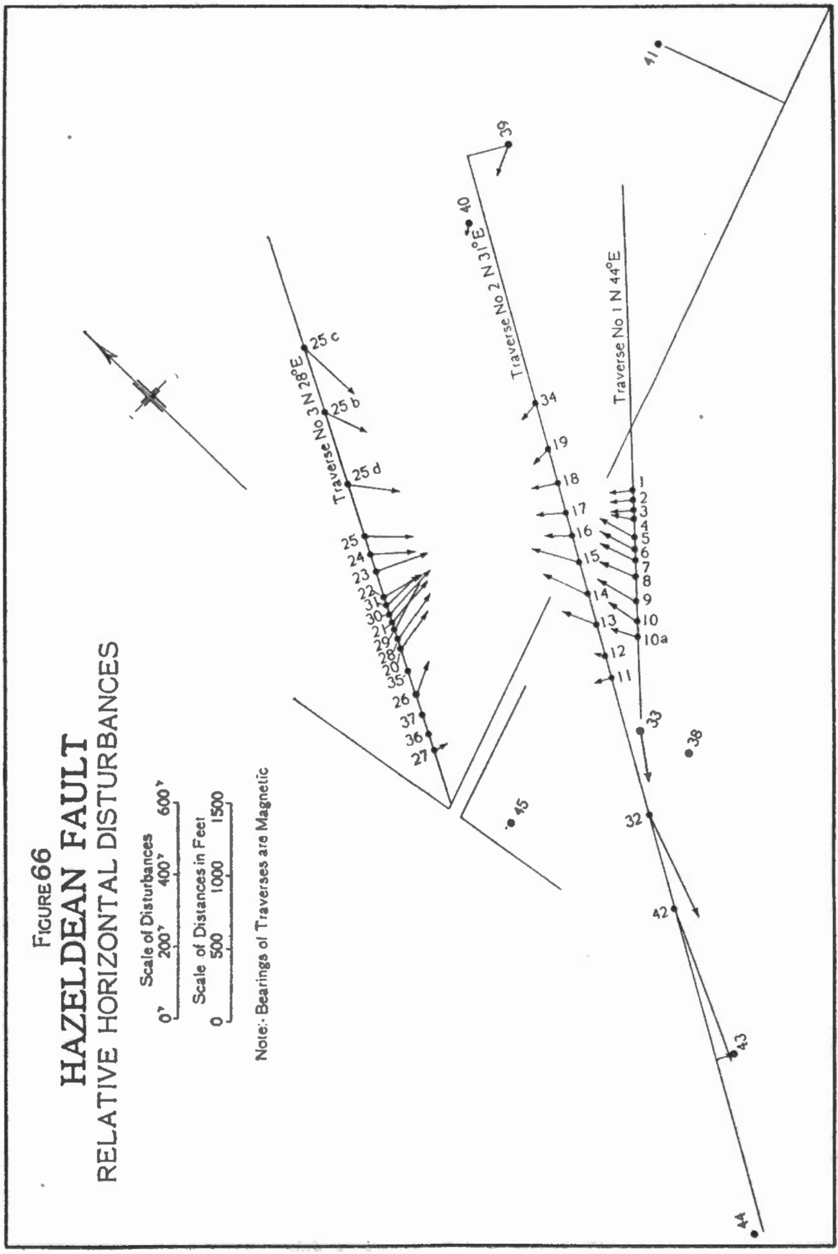


FIGURE 66

HAZELDEAN FAULT

RELATIVE HORIZONTAL DISTURBANCES

Geological Survey, Canada.

The relative horizontal forces were determined for stations at which declinations were available. These are given in table IX. The values of the disturbance force, F, and the angle, ϕ, positive when reckoned from the north through the west, were determined from the expressions,

$$F = \left[(\Delta N)^2 + (\Delta W)^2\right]^{\frac{1}{2}}$$

$$\text{and } \phi = \tan^{-1} \frac{\Delta W}{\Delta N}$$

where ΔN is the difference between the observed and computed north components of the horizontal force

and ΔW is the difference between the corresponding west components.

These horizontal forces are represented in direction and magnitude by the arrows in Figure 66. The results indicate that the attracting body is between traverses 2 and 3, and somewhat away from the fault. The results would be more satisfactory, however, if the stations had been more uniformly distributed. This would alter the datum plane and affect, to some extent at least, the values of both the force and the direction.

TABLE IX

Relative Disturbance Forces at Hazeldean

a—*Traverse* 1

Station	ΔN	ΔW	ΔZ	F	ϕ
	γ	γ	γ	γ	°
10-a	+ 49	+ 64	− 207	81	+ 52·7
10	+ 71	+ 64	− 133	96	+ 42·0
9	+ 106	+ 62	− 109	123	+ 30·3
8	+ 88	+ 58	− 72	105	+ 33·4
7	+ 95	+ 53	− 30	109	+ 29·1
6	+ 104	+ 56	− 50	118	+ 28·3
5	+ 103	+ 55	+ 55	117	+ 28·1
4	+ 50	+ 52	+ 41	72	+ 46·1
3	+ 34	+ 55	+ 122	65	+ 58·3
2	+ 41	+ 58	+ 65	71	+ 54·7
1	+ 33	+ 54	+ 44	63	+ 58·6

TABLE IX (Continued)

Relative Disturbance Forces at Hazeldean (Continued)

b—*Traverse 2*

Station	ΔN	ΔW	ΔZ	F	φ
	γ	γ	γ	γ	°
42	− 415	+ 106	− 26	430	+ 165·7
32	− 302	+ 50	− 183	306	+ 170·6
33	− 138	+ 68	− 256	154	+ 153·6
11	+ 15	+ 48	− 173	50	+ 72·6
12	+ 28	+ 31	− 236	42	+ 47·9
13	+ 91	+ 61	− 141	110	+ 33·9
14	+ 120	+ 70	− 79	139	+ 30·2
15	+ 109	+ 89	+ 39	141	+ 39·3
16	+ 56	+ 82	+ 6	99	+ 55·7
17	+ 50	+ 76	+ 83	91	+ 56·7
18	+ 31	+ 76	+ 27	82	+ 67·8
19	− 12	+ 65	+ 57	66	+ 100·5
34	− 14	+ 63	+ 21	65	+ 102·5
34-a	+ 2	+ 49	+ 87	49	+ 87·7
40	− 65	+ 69	+ 231	95	+ 133·3
39	− 41	+ 94	+ 373	103	+ 113·7

c—*Traverse 3*

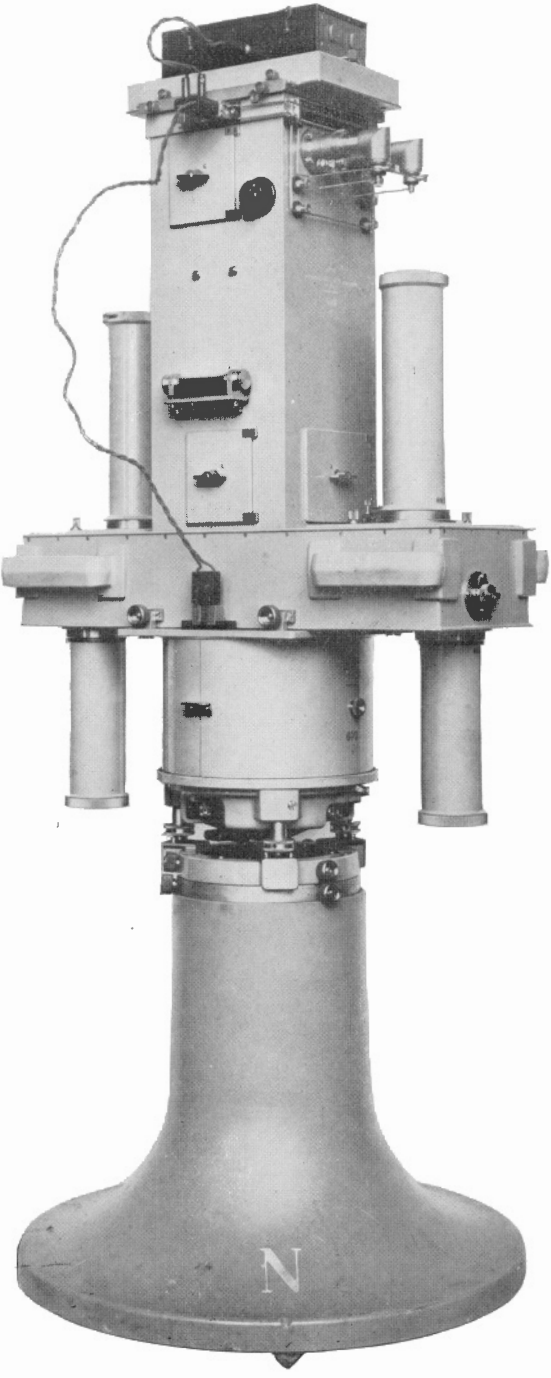
Station	ΔN	ΔW	ΔZ	F	φ
	γ	γ	γ	γ	°
27	− 5	− 43	− 282	43	− 96·6
26	+ 54	− 85	− 93	101	− 57·6
20	+ 44	− 120	− 47	128	− 69·5
28	+ 57	− 152	− 31	162	− 69·4
29	+ 73	− 139	+ 86	157	− 62·3
21	+ 43	− 149	− 9	155	− 73·9
30	+ 46	− 157	+ 62	164	− 73·7
31	+ 26	− 136	+ 98	138	− 79·2
22	− 9	− 146	+ 52	146	− 93·5
23	− 44	− 148	+ 111	154	− 106·6
24	− 66	− 109	+ 75	127	− 121·2
25	− 84	− 113	+ 104	141	− 126·6
25-a	− 106	− 100	+ 65	146	− 136·7
25-b	− 130	− 52	+ 153	140	− 158·2
25-c	− 191	− 66	+ 78	202	− 160·9

CONCLUSION

From the magnetic results at Leitrim it was concluded that there was no positive evidence of a fault at the points indicated by the torsion balance, though there were indications of a discontinuity in the vicinity of the fault and probably associated in some way with it. At Hazeldean, on the other hand, there were definite indications of the existence of a fault. Considering the fact that the interpretation of magnetic anomalies is admittedly a question of some considerable difficulty, it is doubtful if a more definite response could be expected.

Although the success of the magnetic method in locating underground structures depends upon the interpretation of results it is necessary that the observations be as accurate as possible. Sensitive instruments are not necessary when the magnetized body has a high permeability, but in investigations such as the two under consideration they are essential. The elimination of both the periodic and irregular changes in the elements also is important. The results at both Leitrim and Hazeldean would be more satisfactory if disturbance corrections had been applied to inclination and force as well as to declination. For the determination of these changes a duplicate set of instruments, one of which would be located at a base station, would be of advantage. This would make it possible to determine final values of the elements as the work is progressing, which is very desirable in investigations of this nature.

The instruments used for determining D, I, and H, although not the types recommended for this class of work, probably give as accurate values of the elements as any designed for field use. The relative values of vertical intensity would probably be more satisfactory, however, if they had been obtained with one of the improved types of variometer designed for work of this nature.



The Askania torsion balance (Schweydar Z type)