CANADA
DEPARTMENT OF MINES
HON. W. A. GORDON, MINISTER; CHARLES CAMSELL, DEPUTY MINISTER

GEOLOGICAL SURVEY
W. H. COLLINS, DIRECTOR

MEMOIR 170

Studies of Geophysical Methods, 1930

OTTAWA
F. A. ACLAND
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Studies of Geophysical Methods, 1930

Part I

GEOPHYSICAL INVESTIGATIONS AT THE MAMMOTH CAVE, KENTUCKY, AND AT THE FALCONBRIDGE MINE, ONTARIO, UNDER THE JOINT AUSPICES OF THE GEOLOGICAL SURVEY, CANADA, AND THE UNITED STATES BUREAU OF MINES

By A. S. Eve and D. A. Keys[1]

CHAPTER I

ON THE ABSORPTION OF ELECTROMAGNETIC WAVES BY ROCK

INTRODUCTION

It is well known that in electrical prospecting the methods employed fall into three main groups, known as self-potential, resistivity, and induction methods.

It is with the third—the induction type—that the present investigation deals. In all cases there is a loop of insulated wire, of one or many turns, which may be horizontal, vertical, or inclined, and there is an alternating current of electricity flowing through the loop, which tends, as Faraday showed long ago, to excite an electromotive force around any conductors in its neighbourhood. If there is a conducting ore-body, of fair dimensions and not excessive depth, near the excited loop, then the electromotive force in this ore-body will cause a current to flow around it to an extent depending upon its resistance, or rather impedance. This secondary current will in turn stimulate in a receiving coil an induced current which may be amplified and then detected by an observer with head-phones.

It will be evident that the final effect, thus detected, must be extremely feeble, because the electromagnetic disturbance has to go from the loop to the ore-body, say 100 or 200 feet down in the earth, and through at least an equal distance from the ore to the receiving coil. The loss is in each case not inversely proportional to the distance, nor to the distance squared, but approximately to the distance *cubed*, for the loop behaves as a dipole or as a magnet, where an inverse cube law holds. Thus if a certain effect is observed for a conductor 100 feet down, the effect for 200 feet would be $\frac{1}{8} \times \frac{1}{8}$ or $\frac{1}{64}$ of that for 100 feet, and $\frac{1}{27} \times \frac{1}{27}$ or $\frac{1}{729}$ for 300 feet.

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[1] *Personnel.* Dr. A. S. Eve, Dr. D. A. Keys, Dr. F. W. Lee. Assistants, Mr. W. Joyce and Mr. H. Belloc.

An expression of gratitude is due to the Proprietors and Managers of the Mammoth Cave estate, and to Mr. Craig and his co-workers at the Falconbridge nickel mine, for their courtesy and assistance.

But even this double loss does not complete the story, for the earth surrounding the conducting ore-body is always itself at least a feeble conductor too. So that the question arises—to what extent are electromagnetic disturbances absorbed in their passage through such substances as sandstone, limestone, and various sedimentary and igneous rocks?

It will be admitted that this question is one of great practical importance in the exploration for ore-bodies, and of much scientific interest to both geologist and physicist. Moreover, it is closely related to the analogous problems of the penetration of radio (wireless) waves into the earth, and into seawater.

At first sight it would appear impossible to detect the effects due to an ore-body 200 feet below the ground, when stimulated by a loop on the earth above it. Experiment, however, shows that this can be done, and that detection of the effects produced in the ore-body can be made by a receiving coil and amplifier. Modern methods of detection, as applied in radio, permit of reception at great distances even of surprisingly feeble sources of power. A few watts are sometimes sufficient to project a message across the Atlantic.

SUMMARY OF PREVIOUS WORK

In June, 1926, experiments were made in Mount Royal tunnel, 3½ miles long, with a maximum overburden of 300 to 400 feet. Short waves, 40 metres, penetrated but a few hundred feet into the tunnel, whereas 411-metre waves could be detected throughout the tunnel, and longer waves, 1,300 metres, yet more readily. It was not known, however, whether these waves came through the openings, along rails and cables, or through the rocks constituting the mountain.[1]

In August, 1927, reception of speech and music was achieved in the Caribou mine, Colorado, at a depth of 550 feet, the source being KOA, Denver (326 metres), 50 miles away. It seemed probable that these signals came through the rock, but the shafts and cables may have acted as carriers.[2]

In April, 1928, a series of experiments were carried out in Mount Royal tunnel where measurements of the strength of carrier waves were made, confirming and extending the results obtained in June, 1926. Short waves (55 metres) fell in strength rapidly on entering the tunnel and could not be detected beyond 1,600 feet. But 411-metre, 1,400-metre, and 17,000-metre waves were measurable throughout the tunnel. There was evidence to sustain three modes of entrance: through the rock, through the mouths and a shaft, and along the track and various cables.[3]

In June, 1929, the Geological Survey, Canada, and the United States Bureau of Mines, worked at Mammoth cave, Kentucky, in a cave free from conductors with about 300 feet of overburden consisting of sandstone and limestone, with 100,000 to 200,000 ohm-centimetre resistivity. It was proved beyond question that broadcasting signals from Cincinnati, Louisville, and Nashville, 100 to 200 miles away, penetrated through 300 feet of overburden, and that these signals did not penetrate far inside the

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[1] "Nature", vcl. 120, No. 3009, p. 13 (July 2, 1927).

[2] "Nature", vol. 120, No. 3020, p. 406 (Sept. 17, 1927).

[3] 'Reception Experiments in Mount Royal Tunnel', "Proc. Inst. Radio Eng.", vol. 17, No. 2, pp. 347-376 (Feb., 92 9).

cave through the entrance. It was further shown that a 500-cycle alternating current in a ten-turn coil placed on the ground above the cave gave electromagnetic waves that could be detected with a coil and head-phones through at least 900 feet of rock.[1]

The time became ripe for the far more difficult task of *measuring* the intensity of the received signals for different frequencies, and of ascertaining the law of absorption of such signals during their passage through rocks of known resistivity.

METHOD OF MEASUREMENT

It is always possible to amplify an alternating current until it is measurable by some form of alternating current galvanometer or ammeter. Unfortunately the process of amplification introduces great uncertainty in the final results even in the laboratory, and in the field this method has been found highly unreliable. It is unnecessary to enumerate here all the causes of fluctuating or variable output. Yet the next great forward step in prospecting by induction methods is to obtain definite measurements, which at present are wholly lacking because no reliable method has yet been invented. Dr. F. W. Lee suggested, therefore, the use of a copper oxide rectifier and a direct current galvanometer capable of measuring 10^{-8} amperes, and acting on this suggestion the task was attacked hopefully, with little realization of the many difficulties that were to crop up.

Copper Oxide Rectifiers

The Union Switch and Signal Company of Pittsburgh provided three sets of copper oxide rectifiers, $\frac{1}{8}$, 1, and $1\frac{1}{2}$ inches in diameter. Some tests at various distances from a horizontal loop, 100 feet in diameter, carrying 3 amperes of 500-cycle alternating current showed that the 1-inch diameter rectifier was the best suited for the purpose, giving at 100 feet from the centre of the loop about 15 cm. deflexion on the galvanometer.

If a sheet of copper is carefully oxidized and prepared it has three remarkable properties:

(1) It is photoelectric,

(2) It can rectify an alternating current; and there is a drawback, namely,

(3) It has a well-marked temperature coefficient.

It was, therefore, necessary to maintain the rectifier at a constant temperature in a thermostat, and to make sure that the same temperature was maintained when calibrating above ground, and when taking measurements in the cave. This was not easy, because above ground the temperature varied from 84° to 94° F., and in the cave from 54° to 56° F. However, with a good supply of iced and of hot water, regulation was satisfactorily achieved, not in the earlier, but in the final readings which will alone be quoted in this report.

It is further necessary to place the rectifier in a container that will prevent sunlight, or other strong light, from falling upon it, otherwise the photoelectric effect will produce variations that may greatly exceed the quantities under measurement.

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[1] Tech. Pub. No. 316, Class L, "Geophysical Prospecting", No. 19, Am. Inst. of Min. and Met. Eng. (Feb., 1930).

If a plate of copper with its surface oxidized is placed in contact with a plate of lead, then a current of electricity can pass from the lead to the copper, but not from the copper to the lead. This is the basis of rectification and it indicates that electrons can pass from the copper through the oxide to the lead, but not in the reverse direction. No satisfactory explanation of this fact seems to be known. The effect is over the whole surface and not confined to a point as with a crystal rectifier used in a simple radio detecting set.

Four such plates of copper–copper oxide–lead are compactly joined together with an arrangement as indicated in the diagram (Figure 1). Each rectifier is indicated by an arrow and a plate showing the direction in which direct current is able to flow. When the left conductor is positive the path is along p, and when the right is positive the path is along q passing to R and the galvanometer, and returning through S and thence through the two pairs of rectifiers in parallels.

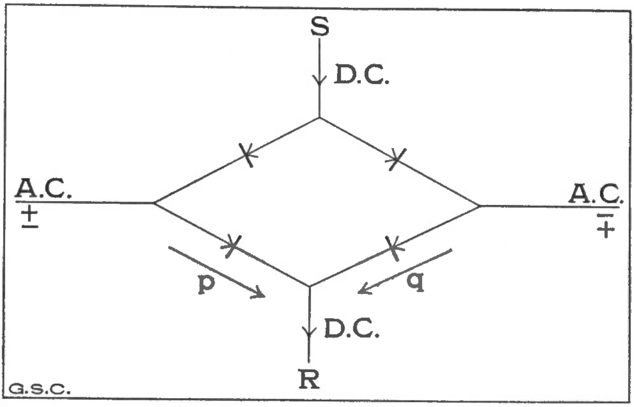

Figure 1. Copper oxide rectifier.

After the received current was duly rectified it was measured by a wall-type Leeds and Northrup galvanometer with a sensitivity such that 1 mm. scale deflexion corresponded to $6 \cdot 7 \times 10^{-9}$ ampere. This galvanometer was fastened to a wooden block which was clamped firmly to a tripod table, and this in turn was carefully levelled until the small galvanometer coil was free and vertical between the poles of the magnet. A higher degree of sensitivity would be troublesome in field work.

GENERAL ARRANGEMENT

A heavy but portable gasoline engine, described in previous reports, turned an induction type generator which gave 500-cycle alternating current. This current passed to a transformer and then through ten turns of heavily insulated wire forming a horizontal loop on the ground 50 feet in radius. Straight beneath the loop in the cave, at a point found by transit survey and checked by electrical survey, was a horizontal receiving coil mounted on a transit so that azimuth and dip could be read, or adjusted as required. This coil was placed in a horizontal plane and connected with a condenser, so that tuning was possible and resonance was obtained—a point of such importance that a special section will be devoted to it. The alternating current from the coil and condenser was taken to the copper oxide rectifier, and the resulting direct current was measured by the galvanometer.

The mutual inductance between loop and coil, both circular, was then calculated by formulæ as set forth in "Radio Instruments and Measurements," No. 74, Bureau of Standards Publication, Washington, D.C.

The electromotive force in the receiving coil will be proportional to:

(1) The mutual inductance between loop and coil;
(2) The current in the loop;
(3) The frequency employed.

On the other hand the deflexion in the galvanometer will depend on the electromotive force in the coil and upon a number of other factors, some of them known, some unknown; such as the impedance of the coil, the efficiency of the rectifier, and the galvanometer constant. How then could there be hope of dealing with these quantities that would be difficult to determine?

The solution was a simple one, and apparently not open to criticism. Another small coil B was taken, and placed at a measured distance from the main coil, A. A measured current was passed through the small coil B and that current was varied, or the distance between coils was changed, until the same deflexion was obtained as with coil A in the cave when the excited loop L on the ground was operating.

The mutual inductance between the two circular coils was then calculated and it is seen that the following relation holds, *if there were no absorption* of the electromagnetic effects in the rock.

When the galvanometer deflexion is the same both in the cave observation and the surface calibration then the currents in the primary must be inversely as the mutual inductances. If that is not the case then there must be absorption by the rocks between coil and loop, and the magnitude of the percentage loss can be determined.

MATHEMATICAL SUMMARY

Let capital letters refer to the large scale measurements between loop and coil, and small letters refer to calibration measurements between coil and coil. Let subscript 1 refer to transmission in the primary and subscript 2 to reception in the secondary,

$$\text{Then } E_2 = -M\frac{dI_1}{dt} = M2\pi fI_1$$

$$e_2 = -m\frac{di_1}{dt} = m2\pi fi_1$$

$$\therefore \frac{E_2}{e_2} = \frac{MI_1}{mi_1}$$

Also the electromotive forces E_2 and e_2 are proportional to the deflexions D and d

$$\therefore \frac{D}{d} = \frac{MI_1}{mi_1}$$

Hence it is necessary in practice to read two deflexions, to measure two currents, and to calculate two mutual inductances, and if the deflexions on the galvanometer are the same, then MI_1 should equal mi_1, and if not the percentage loss is a matter of simple arithmetic. So easy in theory, and so difficult in practice!

As to the mutual inductances—if loop and coil are sufficiently far apart—it can be stated that

$$M = \frac{2A_1n_1 A_2n_2}{z^3}$$

treating them as though they were two magnets. Here A_1, A_2 are the areas, n_1, n_2 are the number of turns, and z is the distance from centre to centre. This method is too crude if the distance between centres is comparable with the radii. In such a case it is necessary to determine the shortest and the longest distance from circumference to circumference, say r_2/r_1, then to look up Table 16, p. 286, "Radio Instruments and Measurements," and find F. Calculate $M_o = F\sqrt{Aa}$ where A and a are the areas, substitute in $M = M_o n_1 n_2$, where n_1, n_2 are the number of turns, and then you arrive at the mutual inductances in microhenries (μH).

ON THE NATURE AND RESISTIVITIES OF THE ROCKS TRAVERSED

At the place of observation there are 100 feet of nearly horizontal Cypress sandstone above 24 feet of Mammoth Cave limestone, between the loop on the ground and the coil in the cave.

The resistivities of typical blocks of these two materials were found as:

Limestone........................	480,000 ohm-cm.
Sandstone........................	650,000 ohm-cm.

The single, or electric, probe method gave right on the top of large exposed slabs of the two materials:

Limestone........................	78,000 ohm-cm.
Sandstone........................	300,000 ohm-cm.

On the other hand, several electrical surveys over the camping ground gave for the sand and sandstone beneath values for the resistivity of 10,000 to 40,000 ohm-cm.

Of course the differences between wet and dry limestone and sandstone are great.

A selection has been made of 10^5 ohm-cm. as the best average resistivity of the sandstone which forms 100 of the 124 feet of the rock traversed. Rooney and Gish find 10^4 as a good average value for the resistivity of limestone in the ground in Peru, and M. E. Dice considers 10^5 as too high a value for the resistivity of limestone.

The element of uncertainty in resistivity is undesirable as the formulæ used in all calculations are highly sensitive to the values assigned to the resistivities.

Thus for 500 cycles and 124 feet the absorption coefficient (*See* page 13)

$$e^{-\frac{2\pi f \kappa z}{c}}$$

gives values as follows:

Resistivity in ohm-cm.	Absorption coefficient per cent
10^4	16
10^5	5
10^6	$\frac{1}{1000}$

On the other hand with a resistivity of 10^5 ohm-cm. there is obtained:

Frequency	Absorption per cent per 124 feet	Thickness to half value in feet
500	5	1,600
21,400	32	250
43,200	39	170

It is clear that when these, or analogous experiments, are pushed to a final conclusion great care will be necessary to ascertain the resistivities of the rocks traversed, no less, indeed, than that devoted to measuring the absorption itself.

Coils

On previous occasions a large, rectangular coil, made in the United States Bureau of Mines workshop at Pittsburgh, had been used for induction experiments. For many reasons this was not suitable for the present series of experiments, so that Dr. F. W. Lee had two new circular coils wound on wooden frames which could be mounted on a tripod stand and revolved about a vertical or horizontal axis through measurable angles.

Coil A, for low frequency work, 500 cycles, had 841 turns of No. 24, double cotton covered wire.

Coil B, for higher frequencies, 10 to 100 kilocycles, had 124 turns of No. 14 double cotton covered wire.

Both coils were wound on frames 20 inches in diameter with grooves $\frac{15}{16}$-inch wide and $\frac{3}{4}$-inch deep.

ON RESONANCE, OR THE IMPORTANCE OF TUNING

When a direct uniform and continuous current is passed through a coil the relation between electromotive force, current, and resistance is given by Ohm's law

$$E = R\,I,$$

when an alternating current is used the corresponding relation is

$$E = Z\,I$$

when Z is called the impedance. The current lags behind the electromotive force by a phase angle φ whose cosine is R/Z. The impedance Z is a blend of three factors; the resistance R, the reactance due to inductance $X_L = 2\pi fL$, and the reactance due to capacitance $X_c = \frac{1}{2\pi fC}$, where f is the frequency, L the self inductance in henries, and C the capacitance in farads. If $X = X_L - X_c$ is written, then a right-angled triangle shows the connexion between resistance, reactance, impedance, and phase angle. It is desirable to make Z as small as possible, where $Z^2 = R^2 + (2\pi fL - \frac{1}{2\pi fC})^2$ and this can be done by making $2\pi fL = \frac{1}{2\pi fC}$, and then $Z = R$, or the impedance has the lowest possible value equal to the resistance alone. Hence in all measurements with coils, whether using head-phones, or rectifier and galvanometer, it is desirable to introduce a condenser with adjustable capacity so that the relation holds

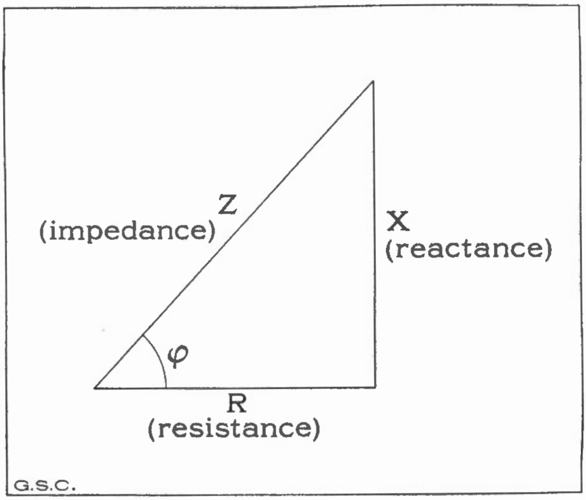

Figure 2. Showing connexion between resistance, reactance, impedance, and phase angle.

$$2\pi \text{ times the frequency} = \frac{1}{\sqrt{LC}}$$

Example

A five-turn loop, 50 feet in diameter, was excited with 1·52 amperes of 500-cycle frequency. A keen observer, with the 841 turns coil held horizontally and with good head-phones, walked away from the centre of the loop to 363 feet, when the signals became just inaudible. He then introduced the condenser, and rapidly tested for a maximum effect by altering the dials. He now walked to a further total distance of 944 feet from the centre of the loop before the signals again became just inaudible. This was done without the use of the amplifier. With amplification and a larger current in the loop, there is no doubt that signals could be read about a mile away. The main point, however, is the fact that the distance reached was nearly trebled by resonance. The inverse cube law of distance holds, so that in this case the effect was increased twenty-five fold.

For measurements with coil, and copper oxide rectifier, and galvanometer, a vernier condenser was sometimes used so that fine adjustments could be made, for it was necessary to find the very peak or maximum value of the resonated current.

It was also often useful, when using high frequency, to introduce capacitance into the large loop which had a formidable reactance due to inductance. In this way a larger current could be maintained in the loop.

When a receiving coil is in constant use in the field it is quite unnecessary to carry a dial condenser. A small, suitable condenser, as used in radio work, can be fixed to the frame of the coil, and resonance is then permanently secured. The head-phones are connected to terminals which lead to the coil and to the condenser in parallel.

EXPERIMENTAL WORK

500-Cycle Frequency

On June 10 the A coil (841 turns) was taken down in the cave to River Hall, 300 feet below the five-turn loop which was on the surface and immediately overhead.

The zero of the galvanometer was exceedingly steady, for the cave is free from vibrations and wind, and indeed is an admirable constant temperature laboratory throughout the year. When the loop above ground was traversed with an alternating current of about 5 amperes, and 500 frequency, the deflexion of the galvanometer was certainly visible, but it was less than the diameter of the cross hair of the eye-piece. Yet on connecting head-phones to the coil the note due to the loop current above ground was exceedingly clear without amplification. It was at once obvious that the apparatus, though sensitive, was not capable of measuring effects through 300 feet of earth.

The loop was, therefore, moved to a point above the "Top of Corkscrew" and the coil was set up 21 feet from the "pinnacle."

With $0{\cdot}24\ \mu$ F in series with the coil there was now obtained:

TABLE I

Current in loop	Galvanometer deflexion in cm.
Amp.	Cm.
4·56	10·4
4·08	8·65
3·15	5·6
2·83	4·6
1·89	2·1

These observations, with repetition according to a prearranged program, were taken in about two hours. The distance from horizontal loop to horizontal coil was 152 feet, but owing to the height of the chamber in the cave the thickness of the rock traversed only 124 feet.

The value of the mutual inductance between loop and coil was 1·25 microhenries.

It was then necessary to calibrate the receiving set by using the subsidiary coil B. The two coils A and B were, therefore, placed 15·2 feet apart so that their mutual inductance was 8·636 μH. The currents were then adjusted to give the same deflexions as in Table I and these currents were 0·50, 0·46, 0·37, 0·34, 0·23 ampere respectively.

Now, remembering that for the same deflexions there should be MI = mi, observation against calculation can be tested thus:

TABLE II

M = 1·25 μH, m = 8·636 μH

I	i	MI	mi	Loss per cent
1·89	0·23	2·36	1·99	15·6
2·83	0·34	3·54	2·94	16·8
3·15	0·37	3·94	3·20	18·7
4·08	0·46	5·10	3·98	22·0
4·56	0·50	5·70	4·32	24·2
			Mean..........	19·5

These figures indicate a loss by absorption of about 20 per cent when 500 cycle electromagnetic disturbances pass through 124 feet of rock whose resistivity is between 100,000 and 200,000 ohm-cm. This result was received with extreme mistrust, as the loss suggested is much greater than any theory could justify and larger than should have been expected from the fact that the loop could be readily detected by the large Pittsburgh coil, unresonated, and without amplifier, through 900 feet of rock. It became, therefore, necessary to run down every possible source of error, and it was quickly found that the effect of temperature on the copper-oxide rectifier was the chief source of error.

When the temperature of the thermostat was gradually raised from 74 to 84 degrees Fahrenheit, with the current steady in the loop above ground, the readings of the galvanometer increased as follows:

	Cm.		Cm.
74°F.....................	17·00	79° F.....................	18·1
75.......................	16·95	80.......................	18·18
76.......................	17·33	81.......................	18·43
77.......................	17·6	82.......................	18·55
78.......................	17·9	83.......................	18·6
		84.......................	18·68

While at 57 degrees F. the reading was 10·2 cm., so that the temperature coefficient was about 0·4 per 1 degree F., and these readings give a graph fairly linear from 76 degrees to 81 degrees F., so that in subsequent work the temperature was maintained within 1 degree of 80 degrees F. The rectifier was also screened from sun or lamp light to prevent radiation effects.

FINAL OBSERVATIONS WITH 500-CYCLE FREQUENCY

After several days work with results which it is not necessary to record, the final observations were as follows. Owing to some rearrangements of the loop the mutual inductance of loop and coil A was 1·16 μH. Fresh readings were taken in the cave with the copper-oxide rectifier in a thermostat maintained at 80 degrees F. and the observations were

Current in amperes I	Deflexions in cm.
4·2	17·8
3·01	9·2
2·29	5·4
1·62	2·7

These are the means of several repeated readings.

Coil B was now placed at distances varying from 20 to 25 feet from coil A and the deflexion of the galvanometer was read. The mutual inductance between the two coils was then calculated and the results were as follows:

Distances between coils in feet	Mutual inductances	Galvanometer deflexions in cm.
	m	
20	3·872	18·05
21	3·267	13·46
22	2·842	10·2
23	2·487	7·8
24	2·189	6·05
25	1·936	4·70

The current in coil B was 1·23 amperes and the thermostat was at 80 degrees F., coil A (841 turns) was resonated with 155 microfarads.

There is now obtained.

TABLE III

M	I	m	i	MI	mi	Loss per cent
1·167	4·20	3·77	1·23	4·90	4·64	5·3
1·167	3·01	2·70	1·23	3·51	3·32	5·4
1·167	2·29	2·07	1·23	2·67	2·546	4·6
					Mean	5·1

Here the mutual inductances are in microfarads and the currents are in amperes.

The conclusion thus reached is that in passing through 124 feet of rock, consisting of sandstone and limestone, whose resistivity, measured in situ, lies between 100,000 and 200,000 ohm-centimetre, the electromagnetic disturbance from a horizontal loop on the ground, excited with an A.C. current of 500 cycle frequency, suffers a 5 per cent loss by absorption before reaching a receiving coil 156 feet vertically beneath it underground. Hence reduction to half value would be effected, by absorption alone, in passing through 1,670 feet, or the equivalent 510 metres.

Mr. Joyce has correlated our calibration readings in a single diagram (Figure 3) which shows the relation between the galvanometer readings and the mutual inductances between coils A and B when the distances between them are varied, but kept, of course, face to face. The left straight line in the diagram indicates results taken at the surface temperature, which was not carefully observed at the time. The two straight lines close together on the right represent measurements when the thermostat was maintained at 80 degrees F., and the only difference for the two sets of reading is that in one case the primary coil was tuned, and in the other case it was untuned. The fact that the results are almost coincident is a matter

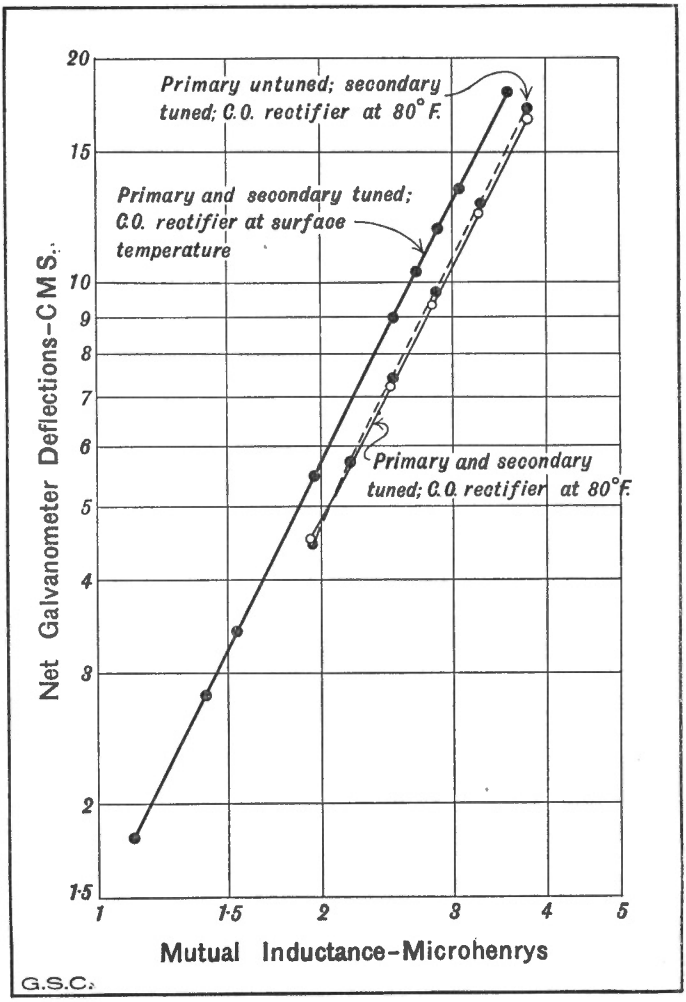

Figure 3. Coil calibration curve; primary current for all curves 1·20 amps.

of some importance, as it indicates that there were no prominent harmonics in the primary coil, and that the main effect under observation was truly of a single frequency.

COMPARISON OF RESULT WITH THEORY

There appear to be four theories worthy of consideration in connexion with the preceding result of the absorption of electromagnetic effects in rock. The first and most searching is that due to Sommerfeld[1] which indeed applies to the absorption of radio waves, and so far as the present writers have been able to apply this theory it does not appear to be usable in the case under consideration of the induction effects at a short distance from a loop excited with a current of 500-cycle frequency. The three other methods have been described in the 1929 report and already published[2] so that it will not be necessary to refer to them at great length.

If Maxwell's equation for a horizontal plane entering the ground vertically from above is written down then there will be no diminution simply due to the distance travelled into the earth, but there will be an absorption or attenuation factor

$$e^{-\frac{2\pi f \kappa z}{c}}$$

where e is the Napierian logarithmic base, f is the frequency, z is the distance traversed in centimetres, c has the value of the velocity of light, about 3×10^{10} cm. per second and κ is given by

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

and here again μ is the permeability equal to 1,

$$\epsilon = \frac{\text{dielectric constant}}{4\pi}$$

$$= \frac{10}{4\pi} = 0{\cdot}8 \text{ approximately, while } \sigma$$

is the conductivity expressed in electrostatic units, equal in the present case to $\frac{9 \times 10^{20}}{10^5 \times 10^9} = 9 \times 10^6$, so that ϵ can be ignored and the fact simply stated that

$$\kappa^2 = \frac{\sigma}{f} = \frac{9 \times 10^6}{500} = 1{\cdot}8 \times 10^4$$

$$\text{and } \kappa = 134$$

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[1] Ann. du Phys. 14, 28, p. 665 (1905).

[2] Tech. Pub. No. 316, Am. Inst. Min. Eng., Class L, Geophysical Prospecting, No. 19, "Absorption of Electromagnetic Induction and Radiation by Rocks". Herein, p. 6, $\sqrt{R}$ has been, in printing, omitted from the denominator of A.

Hence for a thickness of 124 feet or 3,782 cm. the absorption will be

$$e^{-\frac{2\pi \times 500 \times 134 \times 3782}{3 \times 10^{10}}}$$

$$\text{or } e^{-0 \cdot 053} = \frac{1}{1 \cdot 054} = 0 \cdot 958$$

so that 4·2 per cent should be lost by absorption. This agrees reasonably with the 5·1 per cent determined by experiment. The formula here used is quite sensitive to resistivity, and for 10^4, 10^5, 10^6 ohm-cm. the corresponding absorptions for 124 feet of rock are 16, 5, and 0·1 per cent by calculation.

But it will at once be realized that the writers were not really dealing with a horizontal plane wave at all, and that there was loss with distance, varying as the inverse cube power, below the centre of the loop. This loss with distance is already allowed for in the calculations for mutual inductance. As to the further loss due to actual absorption it may well be that, below the very centre of the loop, the successive waves pass downwards in a manner resembling closely horizontal plane waves. It is concluded then that the absorption coefficient $e^{-\frac{2\pi f \kappa z}{c}}$ may be safely used as an approximation for the attenuation below the loop.

The formula given by Dr. L. V. King, set forth in the report and paper last quoted, gives a result much smaller than the writer's observations warrant. King's reduction factor is $(1 + x)(1 + x^2)e^{-x}$ where

$$x = \frac{\text{depth}}{C\sqrt{2}}$$

$$\text{and } C = \sqrt{\frac{\text{resistivity in E.M.U.}}{8\pi^2 \text{ frequency}}}$$

This gives an absorption of only one or two parts in a thousand.

Finally there is the method due to Zenneck set forth in Fleming's "Principles of Electric Wave Telegraphy and Telephony," 2nd edition, pages 623, 730-744, New York, 1919 (Longmans, Green and Company).

It is doubtful, or more than doubtful, if this method can be applied at all in the present case. For the authors are largely ignorant of the dielectric constant of the rocks in situ, and indeed the whole scheme is worked out for waves in a *vertical* plane passing over many hundreds of miles across the surface of land or sea, and, as it were, soaking into the earth during their advance horizontally. Nevertheless the calculations have been made and the absorption arrived at by this theory is 2·1 per cent.

ON THE ABSORPTION OF ELECTROMAGNETIC EFFECTS AT HIGH FREQUENCY

It was the original intention to proceed upwards step by step from 500 cycles through a large range of frequencies, but delay in the manufacture of the necessary apparatus prevented this undertaking, and the authors were compelled to use the same apparatus as that fully described in their 1929 report and to concentrate on three high frequencies, 21·4, 29·7, 41·7 kilocycles.

It may be stated at the outset that a large crop of difficulties was run into, both expected and unexpected, and a review of the work and general situation is placed on record with a view to further investigations. It is well known that with high frequency work resistance becomes overshadowed by inductance and by capacitance, which, when multiplied by $2\pi f$ (in the present case at least 120,000), even if small, give rise to large reactance. By careful tuning, making $2\pi fL = \frac{1}{2\pi fC}$, whether generating a current in the loop, or measuring the induced current in the coil, it was hoped to eliminate reactance entirely.

The investigation may be summarized thus:

(a) The 500 cycles of the generator were combined with the 21,700 cycles of the oscillating valves and condenser and inductance coils, so that there were probably two peaks to the curves, namely, of combination frequencies 22,200 and 21,200 cycles; but the generator itself was not steady and oscillated slightly about the 500 cycles, so that the two peaks were working in-and-out, and repeatable values could not be got of a double peak which was varying in its altitude. In fact, just as it is difficult to get accurate measurements with an amplifier in the field, or indeed in the laboratory, so it was difficult to obtain reliable currents, steady both in magnitude and frequency, into the surface loop.

(b) Calibrating was begun on the receiving coil B (124 turns) by putting high frequency current through coil A (841 turns), but it was quickly realized that the hot wire ammeter, in series with A, indicated a much higher current than that passing round the turns of the coil. For the current largely passed from one turn to another as a capacity current, and but little went the longer journey round the 841 turns. A 5-turn coil was, therefore, made to use as the primary coil in calibration; and then, running again into the same trouble, a single circular turn for calibration had to be used.

(c) Owing to the inductance of the loop on the ground it was difficult to get sufficient current into the loop. Therefore, stakes 10 feet high were erected all round the circumference of the circle, 50 feet in radius, and "helix-winding" was adopted for the ten turns successively beginning at heights of 10, 9, 8—1 foot from the ground. These turns could be used in parallel, or in series, as required. Moreover, this elevation of the turns of the loop diminished the reactance due to capacitance with the ground. The problem of calculating anew the mutual inductance between loop and coil presented no difficulty.

(d) The behaviour of the copper-oxide rectifier at these high frequencies involves considerable uncertainties as there may be capacity currents which pass from plate to plate. This risk was probably obviated by taking precisely the same reading of the galvanometer when calibrating as had previously been obtained underground.

(e) A good many defects were naturally attributed to temperature variations, and working after midnight was, therefore, tried when the temperature was more steady and lower than by day, still using, however, a thermostat. Finally the calibrations were done at the steady temperature inside the mouth of the cave, and it was then realized that the task undertaken was really hopeless, owing to the causes set forth in *(a)*.

Perhaps the most reliable set of observations obtained were as follows:

M, the mutual inductance between 5 turns of the helical loop on the surface and the 124 turn coil B underground, equal to 0·0369 μH.

m, the mutual inductance between the 1 turn and 124 turn coils, 8·84 feet apart equal to 0·1015 μH.

I, the current in the loop, equal to 3·35 amperes.

i, the current in the 1 turn calibrating coil, equal to 1·04 amperes.

whence $MI = 0 \cdot 123$
and $mi = 0 \cdot 106$

indicating an absorption of about 14 per cent, for 21·7 kilocycle frequency and 124 feet of rock, 10^5 ohm-cm. resistance. But indeed, results for the absorption through 124 feet of rock of the 21 kc. frequency, had a wide range between 14 and 32 per cent, with a mean value of the order of 23 per cent, not out of keeping with a theoretical value of 30 per cent, as calculated from the absorption factor $e^{-\frac{2\pi f \kappa z}{c}}$. The values of 29 and 41 kc. are yet more unreliable, and need not here be quoted.

It must be remembered that this is the first attempt to achieve measurements of this kind, and it is clear that research work must be done in the laboratory on the use of a copper oxide rectifier with high frequency, and an alternator must be so designed and controlled that a single frequency will be maintained in the loop. The use of the gasoline engine will be avoided and an electric motor used to drive a direct current generator which will in turn give a current between filament and plate of a valve, and the grid-filament voltage can be controlled with a radio oscillator of adjustable frequency.

There appears to be no reason why success should not finally be achieved, and it is doubtful if there is any more important problem in geophysics than precise knowledge of the passage of electromagnetic waves of various frequency through rocks of known resistivity.

The further problem of finding the dielectric constant of rocks in situ awaits solution also.

SUMMARY

(1) A method has been devised using coil, with resonated circuit, copper oxide rectifier, and direct current galvanometer of measuring underground, at a depth of 152 feet, the electromagnetic effects of an alternating current in a large, circular loop laid horizontally on the earth's surface.

(2) In the case of currents of 500-cycle frequency the measured absorption, due to the conductivity of the rocks 124 feet thick, was 5 per cent, so that the thickness to reduce the effects to half value, by absorption alone, would be 1,670 feet or 510 metres.

(3) The resistivities of the sandstone and limestone have been measured in situ and found to be between 100,000 and 200,000 ohm-centimetre.

(4) A theoretical value of the absorption for 124 feet of rock, with 500 cycles, and 100,000 ohm-cm. resistivity can be calculated from Maxwell's equation for a horizontal plane wave moving vertically into the earth and it equals 4·1 per cent, showing reasonable agreement.

(5) Preliminary measurements have also been made with currents of 21 kilocycles in the loop, and with further experiments in the laboratory with copper oxide rectifiers and with further improvements in the regulation of frequency of the current in the loop, it appears probable that measurements can be made of the laws of absorption of currents from 500 to 100,000 cycles a second.

(6) Experiments were also made on the joint use of resonated circuits and amplifiers.

CHAPTER II

ON THE USE OF VERTICAL AND HORIZONTAL MAGNETIC VARIOMETERS IN THE LOCATION OF MINERALS

INTRODUCTION

In the present section a number of experiments will be described illustrating the various applications of the magnetic variometers in finding the position and extent of mineralized veins, and in the interpretation of the depth and dip of the mineralized zones located. The magnetic dip needle was the earliest method of geophysical prospecting,[1] and it has been definitely accepted by mining men as of practical value in the location of such magnetic ores as magnetite and pyrrhotite. Since Thalén first published his work on the "Examination of Iron Ore Deposits by Magnetic Measurements" in 1879, many forms of dip needle have been designed for use in the field. The latest type of such instrument is a form of sensitive magnetic balance called a magnetic variometer, because with it the variations in the strength of the horizontal or vertical component of the earth's magnetic field from place to place are measured instead of the absolute values of the fields. There are two such types of balance, the one called a vertical variometer which measures the variations in the vertical components of the earth's magnetic field, as the instrument is moved from place to place, and the other, the horizontal magnetic variometer, by means of which variations in the horizontal component of the earth's magnetic field are measured. The instruments used in the present investigations were of the Askania type.[2]

In order to illustrate the practical value of the magnetic variometers, and the method of using them in the field to locate veins of magnetic ore, a number of examples will be described under appropriate headings, in which the results of surveys and experiments will be given, and the interpretation to be assigned to the curves obtained will be explained. These experiments will indicate to the reader the possibilities of the instruments and their limitations. They will also give some idea of the general procedure of applying magnetic methods to survey a region and of the interpretation of the meaning of the curves obtained.

The region chosen for the experiments was the Falconbridge nickel mines, located in Sudbury basin, Ontario, and the authors are indebted to Mr. E. Craig, Mr. Alex. Campbell, and Mr. D. Kerney for the valuable assistance they rendered. Much help was also received from Mr. H. Belloc who assisted. The known ore deposit of the Falconbridge mine occurs along the contact of the norite and quartzite, with an east-west strike and a slight dip to the north in some places, and to the south in others. The ore contains pyrrhotite by which it is detected magnetically,

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[1] Haanel, E.: "On the Location and Examination of Magnetic Ore Deposits by Magnetometer Measurements". Eve and Keys: "Applied Geophysics", Chap. II.

[2] *See* Eve and Keys: "Applied Geophysics", pp. 29-44.

and is covered with an overburden of glacial drift which varies from about 97 feet to 112 feet in thickness. The deposit has been drilled at various points along its length, and the records of the drilling are known. This body is, therefore, a useful one to illustrate the various applications of the two types of magnetic variometers. The different phases of the work will now be described in each of the following experiments.

EXPERIMENT No. I

Magnetic Surveys with the Askania Vertical Variometer over the Known Pyrrhotite Deposit at the Falconbridge Mine

The location of a magnetic dyke is a comparatively simple matter with a vertical magnetometer. The pyrrhotite body at the Falconbridge mine is known to lie at the contact of norite and quartzite and to strike east-west; the problem was to find how far in both directions the deposit extended. Proceeding to the west of the main shaft of the mine, a line was cleared running north-south, and an arbitrary point well to the south of the contact chosen as the starting point or zero station. Readings were then taken on the vertical Askania variometer every hundred feet, and the readings plotted on graph paper, the ordinates being the readings and abscissæ the distances from the zero station. A typical curve found in this way is shown in Figure 4, which represents the results of a survey made along a road that ran west of north, commencing a little east of the school house on the Garson road. It will be seen that at the station, 800 feet north of the commencing point, there is a maximum in the readings. The actual rise in the readings is about 6·4 divisions, and each division represents approximately 30 gammas, equivalent to 3×10^{-4} gauss.

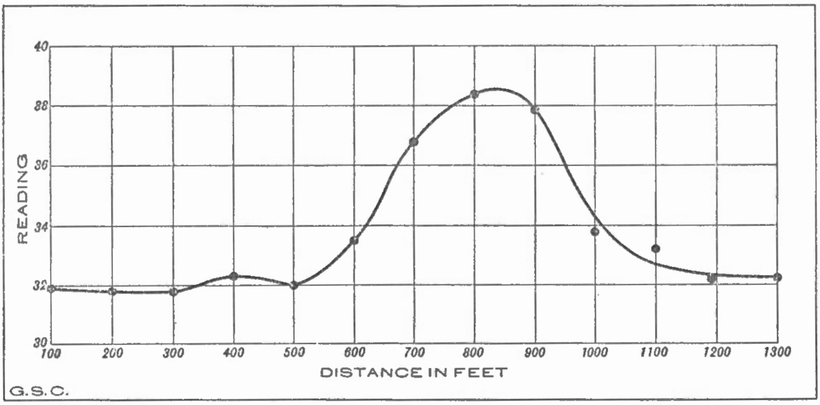

Figure 4. Magnetic survey across west part of Falconbridge pyrrhotite deposit.

Such a rise in the value of the vertical pull on the magnetic balance indicates the presence of some magnetic material, and it is customary to speak of there being an indication at the 800-foot station (Figure 4). This is not a very strong indication, however. The authors then proceeded farther west, and cleared and ran a line in a general north-south direction.

This line lay 16 degrees west of north and passed through drill hole No. 115, which was chosen as the commencing station. Measurements were then made every 100 feet north and south of this point. The resulting readings are plotted in Figure 5. Here again an indication is found over the drill hole. By comparison with the core records of this hole, it was found that ore does occur at this point.

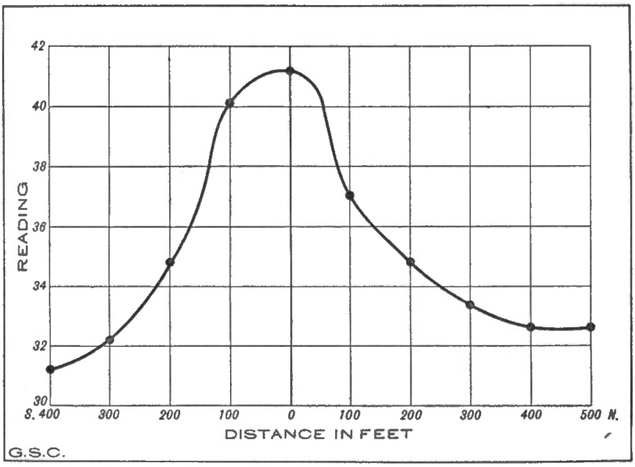

Figure 5. Magnetic survey along line passing over drill hole 115, Falconbridge pyrrhotite deposit.

Proceeding farther west to drill hole 116 and running a north-south line through it, the values found are shown in Figure 6. Here it is seen that the ore has thinned out considerably and appears to break into two parts, with no indication over the hole. As the records indicate, no ore was found by drilling. The magnetometer readings show, however, that there is a small amount on either side of the drill hole.

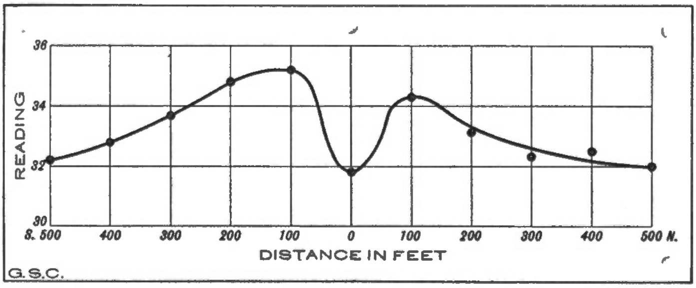

Figure 6. Magnetic survey along line passing over drill hole 116, Falconbridge pyrrhotite deposit.

The next north-south line chosen to the west was the concession line between Garson lot 12 and Falconbridge lot 1. The zero, or commencing station, was the corner of concessions III and IV on the Garson-Falconbridge lot line. The readings were taken every 100 feet as usual, and extended from 1,000 feet north of the station to 500 feet south. The results are shown in the accompanying table.

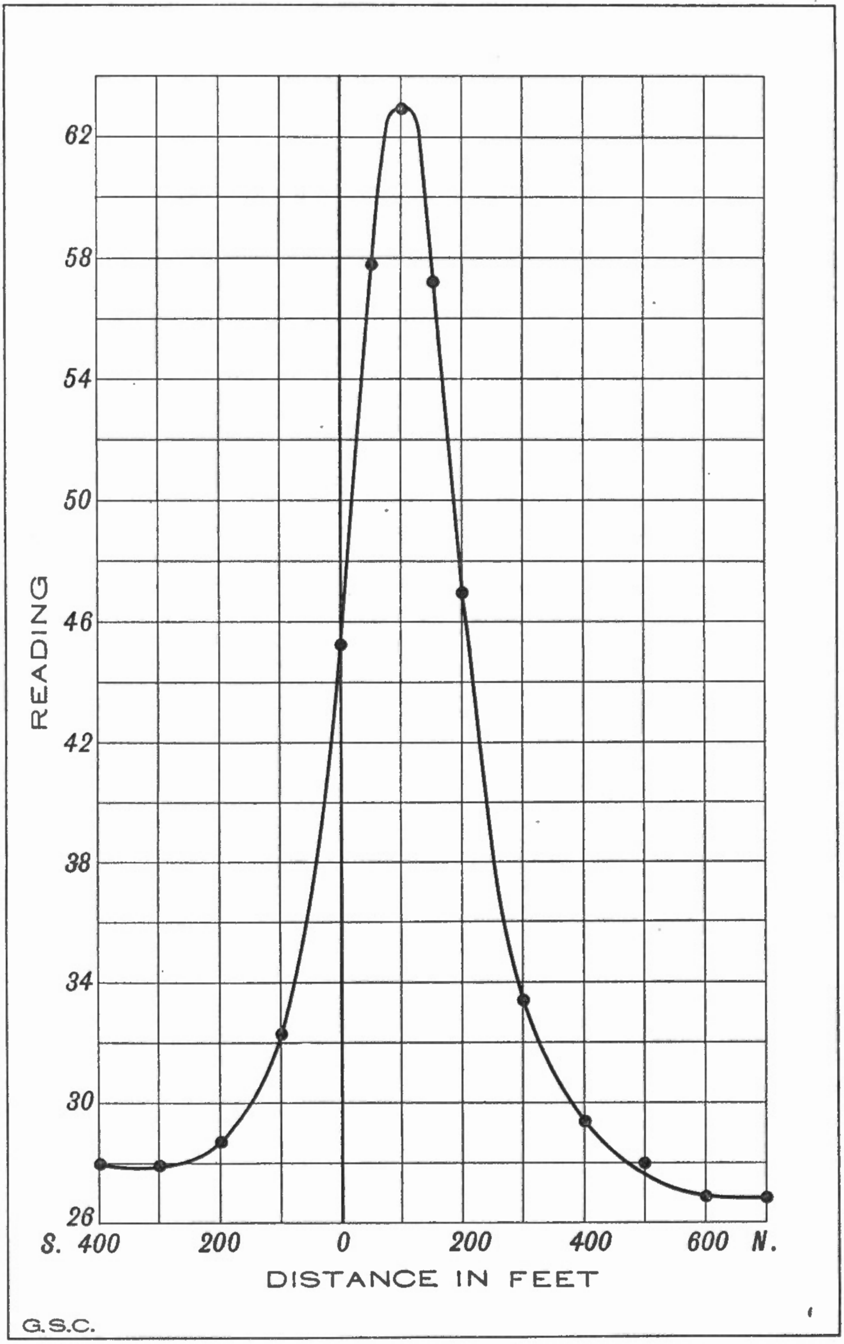

Figure 7. Magnetic survey across eastern part of Falconbridge pyrrhotite deposit.

TABLE IV

Station	Reading	Station	Reading
1000 N	31·6	200 N	31·2
900	31·0	100	31·2
800	31·2	0	29·8
700	32·2	100 S	31·2
600	31·0	200	30·8
500	31·0	300	31·3
400	31·3	400	31·3
300	31·3	500 S	31·2

An inspection of the readings will at once indicate that there is no magnetic ore crossing this line. It is concluded consequently that the deposit does not extend beyond the lot line Garson 12, Falconbridge 1. It is, of course, quite possible that ore may occur farther along the contact and that it has just ceased for a short interval.

It is naturally interesting now to trace the extent of the deposit to the east, having fixed its western extremity. Before going to the eastern known boundary, the results will be given of a survey with the vertical magnetometer over a north-south line crossing the deposit where diamond drill records show there is good ore beneath an overburden of from 112 feet to 123 feet. The readings shown are plotted in Figure 7, the zero station being 100 feet south of the deposit, and the curve indicates the presence of ore at the point 100 feet north, a result that is confirmed by diamond drilling.

A survey was now made along the line between lots 9 and 10. The small auxiliary magnet was attached to the magnetometer and was at a distance

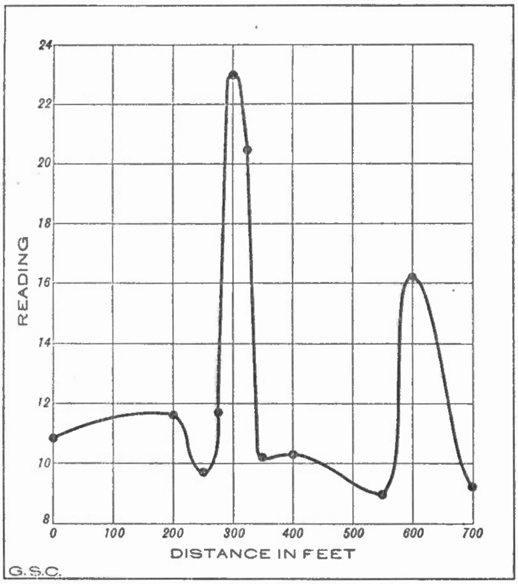

Figure 8. Magnetic surveys along line between lots 9 and 10, across Falconbridge pyrrhotite deposit.

of 34·4 cm. below the needle. This alters the zero of the scale readings, but has no effect on the general nature of the curves obtained. The readings along this line commenced at the point where the concession line III-IV intersects the line between lots 9 and 10. The land was swampy and covered with bush and trees. Drill hole No. 211 was 10 feet north and 40 feet east of our station N 300. The readings are plotted in Figure 8, and it will be seen from the curve that there is an indication at the point 300 N, but it is a very narrow peak. The norite which outcrops at a point 600 north also gives a peak. This survey will also show the necessity of taking small intervals when small indications are to be found, for with 200 feet intervals, the indication at 300 feet north would not have been discovered. It is interesting to note that the records of drill hole No. 211 give no indication of ore, the drill having missed the narrow deposit indicated by the vertical magnetometer.

The eastern boundary of the Falconbridge property between lots 8 and 9 was then visited, and a survey made south from the line between claims 17402 and 3606. The readings are plotted in Figure 9, and the results indicate that a peak occurs at 1,500 feet south which is 1,113 feet north of the concession III, IV and lot 8, 9 post. Just beyond this line there was a large surface indication or nickel "burn," and an old shaft over which the indications were too strong for the small compensating magnet.

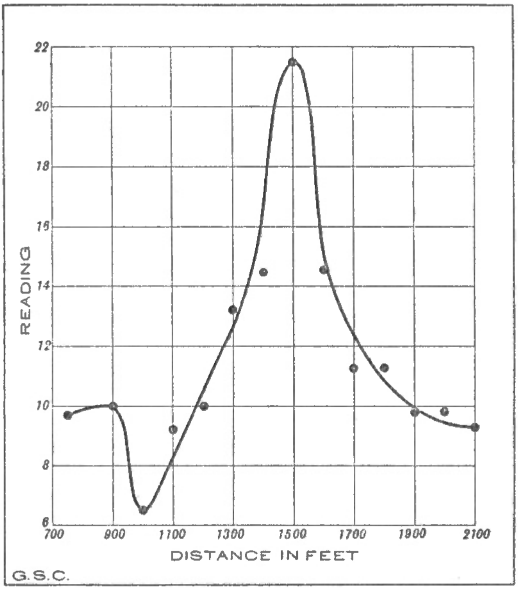

Figure 9. Magnetic survey at eastern boundary of Falconbridge mine property.

This series of magnetometric measurements illustrates very well how a magnetic, pyrrhotite deposit may be traced from one end to the other. It will be noted that in some cases where the deposit thins, stations must be chosen close together to prevent missing the narrow indications, whereas in other cases they may be chosen 100 feet or more apart. In general it is a good rule to choose stations 100 feet apart until indications are found, and then survey the region more closely by taking readings every 25 or 50 feet along the line.

In this section there has been indicated only the manner in which a deposit may be traced. No attempts to interpret the dip or approximate size of the deposit have been made. Such interpretations will be discussed in experiments III, IV, and V below.

EXPERIMENT No. II

The Method of Prospecting with a Vertical Magnetometer for Magnetic Deposits Covered with Overburden

One of the most useful purposes to which the vertical magnetic variometer may be applied is the location of magnetic deposits or dykes that are concealed beneath overburden so that their presence cannot be inferred from nearby outcrops. Such a case occurred during a magnetic survey over the western part of the Falconbridge property, beyond the region where the known pyrrhotite deposit faded out. In attempting to locate an extension of this body, or a possible extension of the Garson body, to the east of the Garson property, a line running north and south was chosen and cleared, called here the "M" line for purposes of identification (*See* Figure 10). The zero station was a telegraph pole just north of the road and readings were taken every 100 feet north and south of this point for a distance of 600 feet. By a peculiar coincidence, the first reading indicated at once that there was some magnetic material in the vicinity. The curve plotted from these observations is shown in Figure 10. It will be seen that there is a peak just about the station, or a little north of it. The general shape of the curve is similar to that obtained over the pyrrhotite deposit, except that it is broader. A line was then cleared commencing from the next telegraph pole east on the road called the "L" line. In this case a maximum occurs about 200 feet south of the zero station at the telegraph pole on the road. A line was next surveyed commencing at the second telegraph east of the "L" line, called the "J" line. The readings obtained are shown in the accompanying Table V. Short portions of lines west of the "M" line were then surveyed to trace the strike of the deposit or dyke.

TABLE V

Station	Reading
0	36·0
100 S	38·5
300	52·7
400	59·8
500	59·0
600	52·6
700 S	46·0

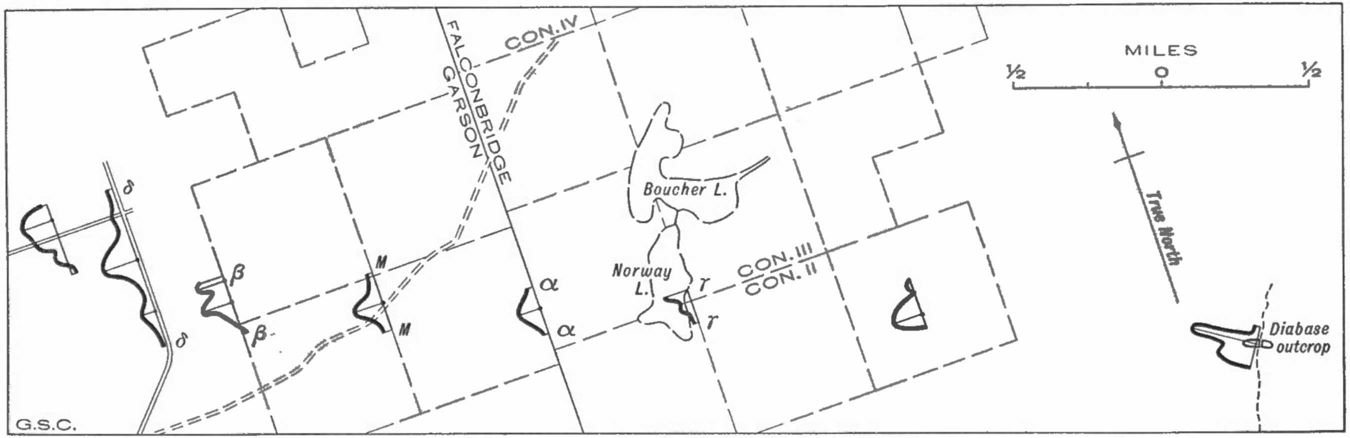

Figure 10. Location of olivine diabase dyke as indicated by Askania vertical magnetometer; the peak values are the number of magnetometer divisions above the normal indications over barren ground in the vicinity.

The line commencing at the telegraph post just west of the "M" line was called the "N" line, the next post west of this the "P" line. The readings are given in Tables VI and VII respectively. It was not necessary to extend these lines as the general strike was becoming evident. A line was next chosen commencing at the third telegraph pole west of the "P" line. The regularity of the strike allows one to choose larger intervals between the lines to be surveyed. The results of the survey along this line were plotted. An interesting feature now makes its appearance in this curve, for there appears to be a splitting of the dyke or deposit into two parts as indicated by the two maxima close together.

TABLE VI

"N" line

Station	Reading
300 N	59·1
200	64·0
100	63·6
0	55·8

TABLE VII

"P" line

Station	Reading
385 N	62·9
300	62·6
200	59·5
100	50·1
0	45·1

The results of the surveys made so far indicate that the strike of the body is very constant, also that its intensity is about the same at the different points where it has been crossed. Both of these facts are indications that the high readings are due rather to a magnetic dyke than to a pyrrhotite deposit, since the ore deposits vary both in their direction and in the intensity of the magnetic attraction, due to the irregularity in the concentration of ore.

The next line surveyed was the Falconbridge-Garson lot line, called the "α" line, *See* Figure 10. The survey was commenced just north of the road at a post marked 'Par 3202', which is on the lot line at the north-east corner of S 15083. The survey was extended both north and south along the lot line, the readings being given in Table VIII. This survey extended for over three-quarters of a mile, and only the one indication of magnetic material was found.

TABLE VIII

Station	Reading	Station	Reading
900 N	29·8	2000 S	31·8
700	31·5	2200	30·5
500	32·0	2300	32·4
250 N	31·3	2400	32·5
0	27·3	2500	34·3
200 S	29·9	2600	37·4
400	30·8	2700	45·0
600	30·9	2800	52·3
800	30·7	2900	55·0
1000	31·3	3000	53·4
1200	32·9	3100	46·1
1400	34·1	3200	39·0
1600	31·8	3300	35·6
1800	31·7	3400	33·3

A gully 50 feet deep extends from 1900 S to 2300 S with the bottom at 2100 S. A kettle-hole begins at 3300 S and at 3825 S the post concession III, IV at the southeast corner of S 15085 stands.

The maximum of this indication is at S 2900 and the peak is still very broad. Referring to Figure 10, the reader will see that the general direction of the strike is maintained. To trace the "dyke" farther west a line was surveyed along the western boundary of the Falconbridge property, labelled the "β" line in Figure 10. The zero point was at the picket near the road, and the survey was continued north. The readings are given in Table IX, and the results indicate a double peak, one at 1500 N and the other at 1900 N. These are indicated on the β line, Figure 10, the value of the peak being given. This value is the number of divisions above the normal indication over barren ground in the vicinity. It will be noted that the two peaks are of about the same value, which would suggest the dyke splitting about equally into two parts.

TABLE IX

Station	Reading	Station	Reading
2000 N	58·6	1200	36·1
1900	63·6	900	28·4
1800	43·7	700	28·8
1700	48·5	500	28·0
1600	57·6	300	30·0
1500	65·0	100 N	32·0
1400	45·3	0	31·6

A line was then surveyed along the Skeid road, called the "δ" line in Figure 10. The readings are given in Table X and the amount of the deflexions are indicated in Figure 10. It again shows that the same direction of strike is maintained and that the two peaks persist, the northern one being, however, much stronger. An additional survey farther to the west (*See* Figure 10) shows the continuation of the dyke, but no sign of outcrop was to be found. The party then went east to the north-south line passing through Norway lake and commenced the survey at the 60 N III post.

TABLE X

Station	Reading	Station	Reading
25 N[1]	34·7	13	46·0
23	35·0	11	35·3
21	43·1	9	35·6
19	39·3	8	29·8
18	47·6	7	46·0
17	59·9	6	43·6
16	67·7	4	32·6
15	75·0	2	30·6
14	56·6	0	30·1

The readings are given in Table XI, and the curve drawn from them is shown on the "γ" line of Figure 10. Other readings were taken along lines farther to the east and the resulting curves are indicated in Figure 10. It will be noted that at the extreme boundary of our survey, there is an outcrop of a diabase dyke which was magnetic, and, consequently, the magnetic indications were due to a diabase dyke and not to a pyrrhotite deposit. This experimental discovery of a magnetic dyke that does not outcrop in the vicinity is a good example of the application of geophysical methods to the determination of underground structure as well as the discovery and delineation of an ore-body. The account has been given in detail, for the presence of the dyke was not known locally, and the procedure will illustrate this particular method of magnetic surveying. Since the tracing of the indications for more than 2 miles led to an outcrop by which the nature of the dyke could be determined, it naturally seems advisable to describe other methods by which the nature of such dykes may be determined without tracing them to outcrops. The geophysical distinction between a pyrrhotite body and a magnetic diabase dyke lies chiefly in the fact that the former is a conductor of electricity, whereas the latter does not conduct much better than the surrounding ground and rock in which it occurs. This difference would at once become evident if a resistance survey across the strike were made. Such a geophysical examination was made for us by Dr. L. Gilchrist, using the Megger method[2] of the Rooney-Gish scheme, and also the single electrode probe variation.

TABLE XI

Station	Reading	Station	Reading
220 N	58·3	200 S	35·6
100 N	54·0	300 S	32·0
0	41·3	400 S	31·6
100 S	43·6		

In the Rooney-Gish system, four equally spaced electrodes are set out in a straight line. The two outer electrodes (consisting, in this case, of one or more iron stakes driven into the ground) act as the means by which the current is passed into the ground and the two inner electrodes,

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[1] The stations were telegraph poles, which averaged about 160 feet apart going north and for 400 feet south.

[2] *See* Eve and Keys: "Applied Geophysics", pp. 92-111.

called the potential stakes, also consisted of iron rods driven into the ground. If 'A' is the electrode separation, I the current in amperes, V the potential difference between the potential stakes in volts, then the mean resistivity of the ground, between the two potential electrodes, is given by

$$\rho = 2.\ \pi.\ A.\ \frac{V}{I}\ \text{ohm}-\text{cm}.$$

According to the experimental work of Rooney, this is the mean resistivity of the ground to a depth of A cm., the electrode separation being measured in cm. The value of V/I is read directly by the Megger instrument, proper corrections being made for the electrode resistances.

Dr. L. Gilchrist and his assistants made a survey using this method along the 'α' line (Figure 10), using an electrode separation of 400 feet. The whole system of four electrodes was shifted along the line, commencing at the 1800 station. The results are shown graphically in Figure 11, and the curve indicates no definite change in the resistivity over the dyke, the small variations being probably due to only surface irregularities[1].

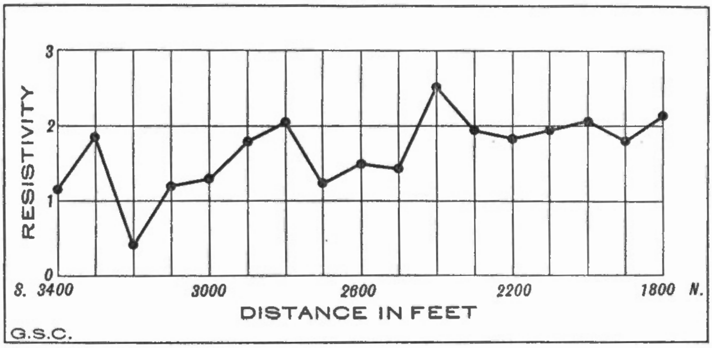

Figure 11. Resistivity survey over olivine diabase dyke.

The results of the single electrode probe were somewhat similar, and also gave no indications of any conductor in this region. The resistivity measurements thus indicate no good electrical conductor within 400 feet of the surface above the magnetic dyke. This would differentiate a diabase dyke from a pyrrhotite body, since the pyrrhotite is a good electrical conductor. The survey illustrates also the advantages of applying more than one geophysical method over a region before making interpretations of the indications obtained.

The presence of the dyke having been found, and its nature inferred from the electrical resistivity survey, is there any means of determining its dip and depth of overburden from the magnetic surveys? Before proceeding to this phase of interpretation, there will be first described some experiments performed with the horizontal Askania magnetometer[2] which are very instructive in this connexion.

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[1] See the effects of such a resistivity determination over a pyrrhotite body, Geophysical Report, by Eve and Keys, 1929, Geol. Surv., Canada, Mem. 165, pp. 115-120.

[2] *See* Eve and Keys: "Applied Geophysics", pp. 39-44.

EXPERIMENT No. III

Magnetometer Surveys over a Model Magnet

Before interpretating, from the actual curves obtained by surveys across magnetic ore-bodies and dykes, with both the vertical and horizontal Askania magnetometers, it is helpful to indicate the type of curves obtained when the instruments are passed over a small bar magnet orientated at different dips. For this purpose the needle of the variometer was set up as usual, either in the magnetic meridian (horizontal variometer), or perpendicular to it (vertical variometer). A wooden plank was placed horizontally on the ground underneath the instrument, so that its length was along the direction of the magnetic meridian. Distances in feet were marked off north and south from the centre, which was directly below the needle of the variometer. A small bar magnet, with its south pole uppermost, was then placed at the different points on the board, either vertically or in a holder, so that it lay at a given dip in either a northerly or southerly direction. Instead of leaving the magnet stationary and moving the magnetometer, the magnet was moved from station to station and the variometer kept stationary. The resulting curves will be identical in shape with the effect obtained by moving the variometer, with this difference, that when the magnet is moved from north to south it has the same effect as if the variometer had been moved from south to north with the magnet stationary.

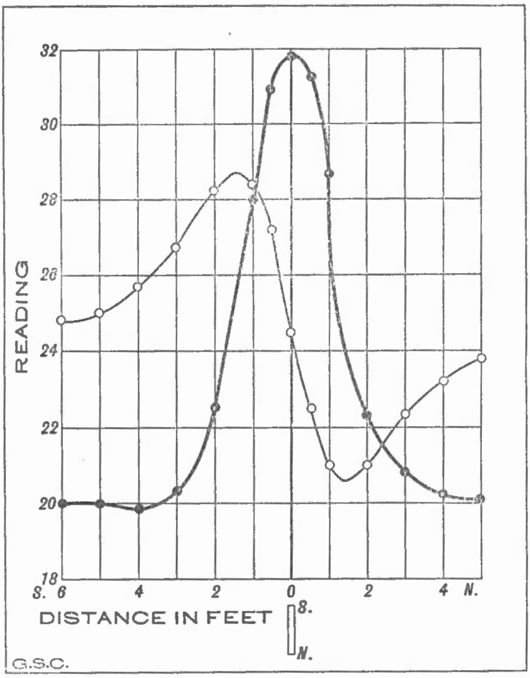

Figure 12. Horizontal (fine line with open circles) and vertical (heavy line with solid circles) components along a line crossing a vertical magnet, all in the magnetic meridian.

Readings were taken with both the horizontal and vertical variometers for each position of the bar magnet. Three positions of the bar magnet were used.

(1) The magnet vertical, south pole up.
(2) The magnet dipping to the north, 50 degrees.
(3) The magnet dipping to the south, 50 degrees.

The results of each of these experiments are plotted in Figures 12, 13, and 14 respectively. The readings on the vertical variometer are the continuous curves, and those taken on the horizontal variometer are the broken lines. Let us first discuss the curves obtained with the vertical variometer.

In the case when the disturbing magnet is vertical, the curve is symmetrical about the origin, apart from the small fluctuations due to experimental irregularities. Hence when the curve obtained from a survey made in the field with the vertical Askania variometer is a symmetrical one, it may be supposed the indication is that the ore deposit or dyke is more or less a vertical one. In Figures 13 and 14, the reader will note that the curves are no longer symmetrical about the origin, and that at the point A there is a minimum that is quite marked. When this minimum is to the north it is inferred that the dip of the magnetic body is to the north and when it is to the south the body dips to the south. It will also be noted that the side that has the steeper slope is parallel to the direction of the dip of the body. This latter fact is not always easy to ascertain and,

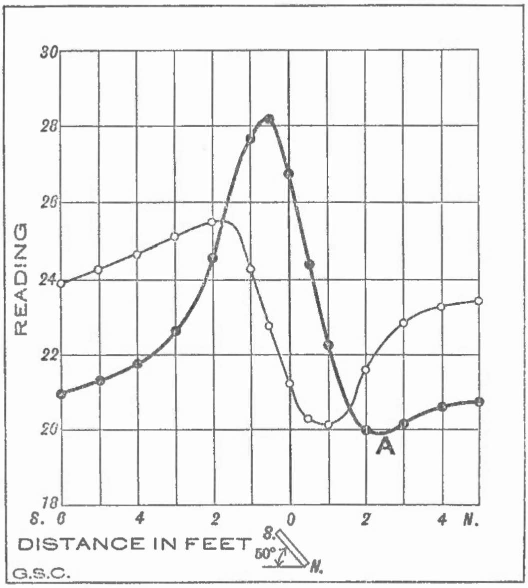

Figure 13. Horizontal (fine line with open circles) and vertical (heavy line with solid circles) components along a line crossing a magnet inclined north, all in the magnetic meridian.

therefore, the former method of noting the point A is the more reliable. The more nearly vertical the dip of the vein is, the smaller will the depression at A be.

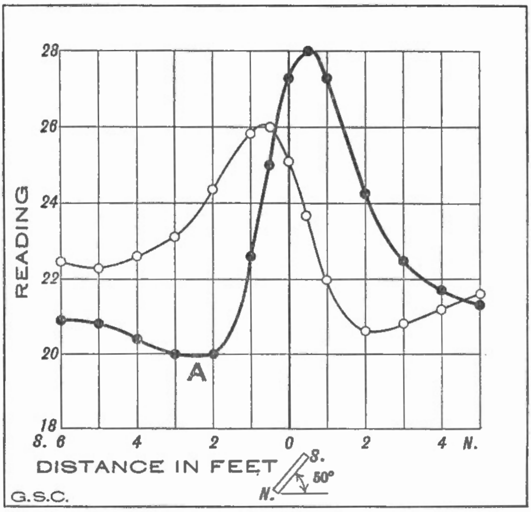

Figure 14. Horizontal (fine line with open circles) and vertical (heavy line with solid circles) components along a line crossing a magnet inclined south, all in the magnetic meridian.

In the case of the curves obtained with the horizontal Askania variometer, it will be quite apparent that when the disturbing magnet is vertical the resulting curve is nearly symmetrical about the origin. But in the other two cases there is again a definite difference between the two sides of the curve. If a line is drawn horizontally through the normal reading when the magnetometer is not disturbed by a magnetic body, it will be seen that the maximum rise is not equal to the maximum depression. Thus the mean zero reading in Figure 13 is about 25·7. The maximum increase in the deflexion from the curve is 25·5 − 23·7 = 1·8 divisions. The maximum depression on the north side is 23·7 − 20·2 = 3·5 divisions. Hence the maximum deviation from the normal is to the *north*, which indicates that the *dip* is to the *north*. Turning to Figure 14 and examining the horizontal curve in the same manner, there is obtained for the maximum deviation on the north 22 − 20·6 = 1·4 divisions and on the south, 26·0 − 22·0 = 4·0 divisions. Hence, since the maximum deviation is to the south, the dip is to the south by our interpretation which agrees with the actual dip in the experiment.

These experiments illustrate how the vertical and horizontal variometers may be used to determine the dip of a magnetic dyke. To obtain actual values of the dip in this manner is a much more difficult problem. For most geophysical surveys, the qualitative nature of the dip is of sufficient value to the mining engineer in order that he may determine the direction in which he should drill.

The curves shown in Figures 12, 13, and 14 were obtained experimentally in the way described. Such curves can also be determined mathematically by supposing an ideal bar magnet, inclined at a given angle and of definite dimensions, placed below the horizontal plane of the instrument. Thus the theoretical variations[1] in the vertical and horizontal magnetic field due to the presence of an ideal bar magnet with a dip of 45 degrees to the north, with its south pole directly below the origin of the graph, were calculated theoretically as were also the theoretical values for the case of the same magnet dipping 45 degrees to the south. The results were expressed in curves (*See* Figure 28) which when compared with the experimental ones given in Figures 13 and 14, were found to be similar. Sufficient has been said to enable the reader to determine from curves obtained by making surveys in the field, the direction of the dip of any dyke or deposit that may be discovered. As illustrations of the application of the information obtained in this experiment, the determination of the dip of the pyrrhotite body and the diabase dyke will be considered.

EXPERIMENT No. IV

The Determination of the Direction of Dip of a Magnetic Deposit from the Results of Magnetic Surveys

The results of surveys made with the vertical Askania variometer over both a pyrrhotite body and a magnetic diabase dyke have already been described in experiments Nos. II and III above. An endeavour will now be made to determine the direction of dip of these bodies. First a survey is made with the horizontal Askania variometer. The apparatus is set up along the direction of the magnetic meridian at the point and the reading taken as usual.[2] By taking stations every 100 feet across the direction of the strike of the body the variations in the horizontal component of the magnetic force due to the presence of the ore deposit or dyke, are obtained. The sensitivity of the horizontal variometer is greater than that of the vertical type, and as it is convenient to compare the relative values of the two components of the force at a point, the comparison of the sensitivity of the two instruments was first made.

To compare the values of the magnetic fields which cause a deflexion of one division on the two instruments, which is a measure of the sensitivity of the instrument, the following procedure is a simple method. The Askania instruments are provided with a long, vertical brass rod, on which there is a sliding holder for an auxiliary bar magnet. The rod is attached directly beneath the point of support of the needles in the instrument, in exactly the same place as the ordinary short holder for the auxiliary magnet is fastened. The rod is graduated with two scales, the one giving the distance beneath the point of support in the case of the horizontal variometer and the other scale giving the distance to the sliding holder from the point of support of the magnetic needles in the case of the vertical variometer. Since both instruments fit the same tripod the vertical instrument is placed on the tripod, a given bar magnet screwed into the holder north pole up, and the reading on the instrument taken. The holder may then be lowered 1 cm. and the reading again taken. Let R_0 and R_1 be the readings on the vertical variometer, when the distance to the auxiliary

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[1] *See* Appendix I for the method of obtaining these curves.
[2] *See* Eve and Keys: "Applied Geophysics", pp. 39-41.

magnet's centre is d_0 and d_1 cm. respectively. If K is the constant of the vertical variometer, that is, the field required to produce a deflexion of one scale division, there will be

$$2\,M\left(\frac{1}{d_0^3}-\frac{1}{d_1^3}\right)=K\,(R_0-R_1)$$

where M is the magnetic moment of the magnet. The length of the magnet is assumed small compared with the distances d_0 and d_1.

The horizontal variometer is now placed on the tripod and set up along the magnetic meridian in the usual manner. The auxiliary magnet is now turned to a horizontal position, with its north pole north and set at the same distance d_0 cm. below the point of support of the needles. The reading is now taken, say R'_0 and the distance increased to d_1 when the reading becomes R'_1. Then if K' is the constant of the horizontal variometer, there will be obtained

$$M\left(\frac{1}{d_0^3}-\frac{1}{d_1^3}\right)=K'\,(R'_0-R'_1)$$

$$\text{Hence}\quad \frac{K'}{K}=\tfrac{1}{2}\cdot\frac{R_0-R_1}{R'_0-R'_1}$$

$$\text{or}\quad K'=\tfrac{1}{2}\quad K\frac{R_0-R_1}{R'_0-R'_1}$$

Hence, making these readings in the manner described, the sensitivity of the two instruments can be compared.

In comparing the two instruments used in the surveys made over the ore-body and dyke, the values of the two distances were 32 cm. and 33 cm. The mean difference of the readings on the horizontal variometer, $R'_0 - R'_1 = 3{\cdot}0$ and for the vertical variometer, using the same two distances, $R_0 - R_1 = 3{\cdot}0$ divisions. It is thus seen that

$$K'=\frac{1}{2}\,K$$

Therefore, the horizontal variometer is twice as sensitive as the vertical instruments and if it is wished to bring the readings of the horizontal variometer to the same scale as those of the vertical variometer, division by 2 must be made of the values obtained on the horizontal instruments.

A survey was now made along a north-south line, crossing the Falconbridge pyrrhotite body with both the vertical and horizontal variometers. Readings were taken on each instrument over the same points. In order to compare the two values, the horizontal deflexions were divided by 2. Table XII gives the readings taken along this line.

TABLE XII

Station	Horizontal variometer		Half reading of horizontal vario-meter	Vertical vario-meter
	Actual reading	Reading +26·0		
800 N.	26·5	52·5	26·3	....
700.	25·9	51·9	26	26·9
600.	25·5	51·5	25·8	26·9
500.	22·2	48·2	24·1	28·1
400.	19·5	45·5	22·8	29·3
300.	12·6	38·6	19·8	33·4
200.	12·4	38·4	19·2	47·1
150.	18·2	44·2	22·1	57·3
100.	33·8	59·8	29·9	63·0
50 N.	49·1	75·1	37·6	57·9
0.	55·0	81·0	40·5	45·3
100 S.	50·0	76·0	38·0	32·3
200.	49·8	75·8	37·9	28·7
300.	35·8	61·8	30·9	27·9
400 S.	31·0	57·0	28·5	28·0

In order to plot the two curves on the same diagram, without altering the ordinate scale, it was necessary to shift the zero on the horizontal variometer by an arbitrary amount 26·0 divisions. Adding this to each reading does not alter the shape of the curve or its size, only shifts the zero reading so that both curves may conveniently be plotted on the same diagram using the same system of axes. The results of this survey are plotted in Figure 15 in which the full line curve represents the variation

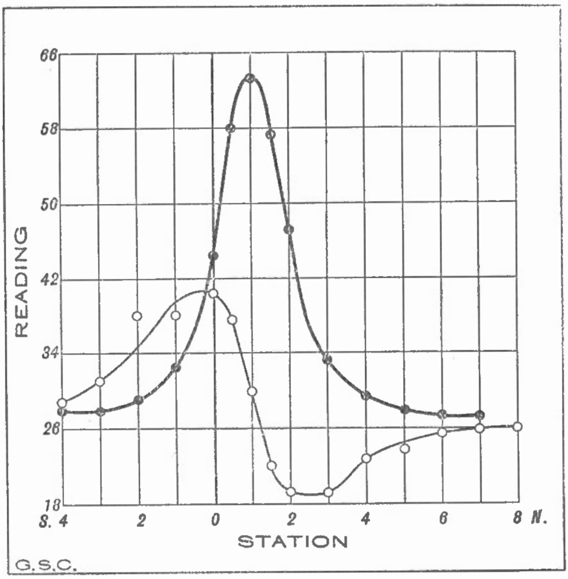

Figure 15. Horizontal (fine line with open circles) and vertical (heavy line with solid circles) components along a line crossing Falconbridge pyrrhotite deposit.

in the vertical component of the magnetic field and the broken line the variation in the horizontal component of the magnetic field over the pyrrhotite vein.

An examination of the curves drawn in Figure 15 shows that no indication of the direction of dip can be ascertained from the vertical variometer readings. If the survey had been prolonged more to the north and south, some evidence of the dip below the normal value of the vertical reading might have been found. The horizontal readings, however, do give us an indication. It will be seen that the deviation from the normal reading to the south is greater than the deviation to the north. This indicates a dip of the vein to the south. The amount of the dip is not great, for the difference in the deviation on the two sides of the centre is small.

A second survey was made over the diabase dyke. The line chosen for determining the dip was the α line, Figure 10. The readings obtained with the horizontal and vertical variometers are shown in Table XIII. Since the variations in the horizontal component are not very large, these readings have not been divided by two as would have been done if the actual values of the two components had been compared. The curves representing these variations in the vertical and horizontal components of the earth's magnetic field across the dyke are shown in Figure 16.

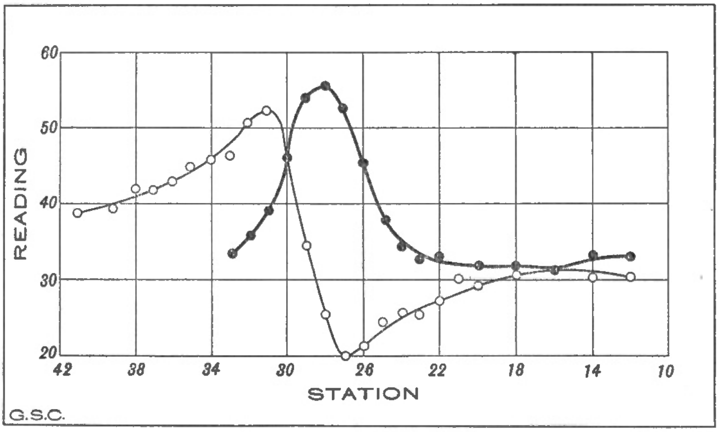

Figure 16. Horizontal (fine line with open circles) and vertical (heavy line with solid circles) components along a line crossing a diabase dyke.

The full line gives the vertical component and the broken line the horizontal component at each point. An inspection of the curves will show that there is a slight dip to the south. The actual normal value of the horizontal component at a point 2 S, far from any disturbing effect of the dyke, is 30·0. It is thus seen that the disturbance is greater to the south end of the curve than to the north in the case of the horizontal component.

TABLE XIII

Station	Horizontal reading	Vertical reading	Station	Horizontal reading	Vertical reading
12	30·0	32·9	28	25·0	55·0
14	....	34·1	29	34·0	53·4
16	31·0	31·8	30	45·5	46·1
18	30·5	31·7	31	52·0	39·0
20	29·0	31·8	32	50·0	35·6
21	29·5	30·5	33	46·0	33·3
22	27·0	32·4	34	45·5	
23	25·0	32·5	35	44·5	
24	25·5	34·3	36	42·5	
25	24·0	37·4	37	41·5	
26	21·5	45·0	38	41·5	
27	20·0	52·3	39	39·5	
			41	38·5	

There is a 50-foot gully extending from station 19 to 23 and a kettle-hole from station 34 to 41.

From the examples given in this experiment, the reader will see how useful the horizontal Askania variometer is in the determination of the direction of dip of a magnetic body. A brief discussion follows of the possibilities of determining the mean depth of such a body by means of magnetometric measurements. The magnetometer is not the best means for getting depth of overburden in the case of a body that is a good conductor of electricity, such as a pyrrhotite deposit. The Lee modification of the Rooney-Gish system is much more reliable.[1] In the case of a non-conducting diabase dyke, the magnetometer may give some indication of the approximate depth to the magnetic *centre* of the dyke, but this has no simple relation to the overburden, nor to the size of the dyke.

EXPERIMENT No. V

The Determination of the Depth of a Magnetic Body by Means of the Magnetometer

There is no simple method of finding the depth of overburden with a magnetometer, but one may obtain some indication of the approximate depth below the surface to the magnetic centre of an ore-body or dyke by using the Askania vertical and horizontal magnetometers. The methods are exceedingly rough and can only be used for comparative indications.

Two different schemes were tried out. The first was by using the vertical Askania magnetometer alone. A wooden platform 4 feet by 4 feet and 10 feet high was constructed. This platform was then carried to the line crossing the Falconbridge pyrrhotite deposit where drill records show that ore lies below an overburden of from 112 feet to 123 feet. The platform was set up at various points along this line. The vertical Askania variometer was read first on the ground and then at a height of 10 feet above the ground. The readings on the platform should be less than those on the ground, since the magnetometer is farther away from the ore-body. The readings obtained in a short survey along the line are shown in Table XIV. If the magnetic moment of the ore-body were known,

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[1] *See* Geol. Surv., Canada, Mem. 165.

actual figures of depth to its magnetic centre would be possible, but with this factor unknown the results are only of qualitative interest. The differences in the readings on the ground and on the platform are also given. It will be seen that the difference is greatest over the ore-body (known to be below the station 100 N), as would be expected. For a mathematical discussion of the theory of this experiment, the reader is referred to Appendix II.

TABLE XIV

Station	On the ground	On the platform	Difference
200 N	30·5	30·8	−0·3
150	28·9	27·2	1·7
125	32·8	30·5	2·3
100	35·8	29·0	6·8
75	33·2	30·6	2·6
50	29·6	27·0	2·6
0	17·4	16·5	0·9

A similar set of readings was made over the dyke at the M line, Figure 10. The readings are tabulated in Table XV. From the value of the differences in this case it is inferred that the dyke is deeper below the surface than the vein. It is known from the value of the maximum change in vertical component over the dyke and the ore-body that the field variations at the surface are of the same order. Hence the smaller difference in the readings for an elevation of 10 feet over the dyke leads us to infer that the dyke is deeper, that is there is probabably a greater overburden.

TABLE XV

Station	Reading on ground	Reading on platform	Difference
200 N	−5·0	−6·0	1·0
150	4·7	3·1	1·6
100	10·9	8·4	2·5
75	12·0	10·3	1·7
50	11·0	10·0	1·0
25	14·4	10·4	4·0
0	11·1	10·0	1·1

The second method used was to draw the vector diagram of the horizontal and vertical components of the magnetic field as determined by a survey with the horizontal and vertical variometers over the ore-body. In Table XVI the values of the vertical and horizontal variations from the normal magnetic components in these two directions are given. From these values the direction of the resultant vector at each point may be found

TABLE XVI

Station	Vertical difference zero=26·9	Horizontal difference zero=27·5	Station	Vertical difference zero=26·9	Horizontal difference zero=27·5
500 N	1·2	3·4 S	50	31·0	10·1 N
400	2·4	4·9 S	0	18·4	13·0 N
300	6·5	7·7 S	100	5·4	10·5 N
200	20·2	8·3 S	200	1·8	9·6 N
150	30·4	5·4 S	300	1·0	2·6 N
100	36·1	8·6 N	400 S	1·1	1·0 N

and then plotted vectorially, thus showing the direction of the resultant attraction. The figures given in Table XVI are obtained from the readings given in the last two columns of Table XII, by subtracting from the vertical readings the normal value of the vertical component in that region, namely 26·9, and subtracting 27·5 from each of the horizontal readings. When the difference is negative, it indicates a pull towards the south and the reading is followed by an S. When the difference is positive, the reading is followed by an N, signifying the pull is to the north. All the vertical readings indicate downward forces.

The vector diagram drawn from the figures given in Table XVI is given in Figure 17. The reader will see that the lines cross in a region

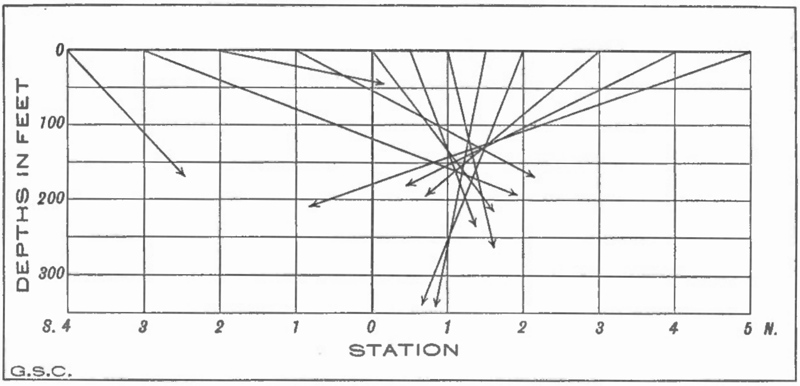

Figure 17. Vectors of resultant magnetic intensities due to ore-body, Falconbridge pyrrhotite deposit.

about 150 to 175 feet below the surface. This, of course, is only approximate, but at least it gives an indication of the depth. The top of the ore is actually about 112 feet below the surface. The south pole of the mass of pyrrhotite would be deeper than the 112 feet, however, perhaps as much as 150 feet from the surface.

A similar table has been constructed for the readings taken along the line over the diabase dyke. These are shown in Table XVII, and the vector diagram is given in Figure 18. In this case the vectors indicate that the pole is about 600 feet or more below the surface, a result that is in agreement with the platform experiments that indicated a greater depth for the dyke than for the pyrrhotite body.

TABLE XVII

Station number	Vertical difference	Horizontal difference	Station number	Vertical difference	Horizontal difference
22 N	0·6	1·5 S	28	23·2	2·5 S
23	0·7	2·5 S	29	21·6	2·0 N
24	2·5	2·2 S	30	14·3	7·8 N
25	5·6	3·0 S	31	7·2	11·0 N
26	13·2	4·2 S	32	3·8	10·0 N
27	20·5	5·0 S	33 S	1·5	8·0 N

The two methods that have been described in this section for obtaining some idea of the depth of a magnetic body by means of the horizontal and vertical variometers, will give the reader sufficient knowledge to carry out such surveys. Both methods are interesting, but the second one, of drawing the vector diagrams, is more simple. It must be kept in mind that these vectors indicate a point near the centre of attraction of the upper pole of the body and do not give the depth of overburden, which will always be less than deduced from such a diagram.

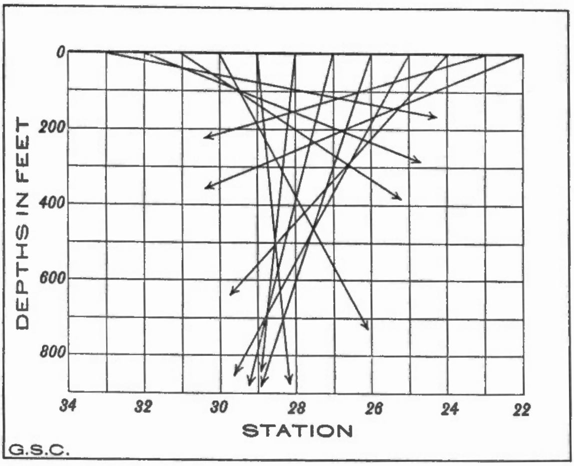

Figure 18. Vectors of resultant magnetic intensities due to a diabase dyke.

Other magnet surveys were made at the Falconbridge nickel mine, but the results are very similar to those already described. Some new indications were found that may be attributed to pyrrhotite deposits and others that undoubtedly were diabase dykes. These are collected together in Appendix III.

The reader will be convinced by the experiments that the writers have performed and described in this section, that for hunting magnetic bodies, the Askania vertical variometer is a very useful and easily operated instrument. By clearing lines across the area to be investigated and making the surveys along these lines, a large area of ground on which there are no outcrops can be rapidly surveyed. When an indication has been found, its strike will soon be found by the observations on neighbouring lines. The horizontal variometer may then be used to determine the direction of dip of the vein. By the combination of the two readings, vector diagrams will give a maximum value of the depth of overburden. An electrical survey will then test whether the body is a metallic one containing good conducting ore or say a diabase dyke containing magnetite.

SUMMARY

(1) The method of using the Askania vertical variometer for surveying a region to locate magnetic dykes and pyrrhotite bodies is described.

(2) The determination of the strike and extent of magnetic dykes and pyrrhotite bodies with the Askania vertical variometer is described.

(3) The use of the vertical and of the horizontal Askania variometers in the determination of:
  (a) the dip of a magnetic body
  (b) the amount of overburden, and
  (c) the approximate thickness
of such bodies is illustrated from experiments performed in the field.

(4) An account is given of the location and tracing of a buried diabase dyke, hitherto unknown to exist, for more than a mile. Its dip, strike, and the approximate amount of overburden were found by magnetometric readings.

(5) Small scale laboratory experiments showing the relation between the dip of a small magnet and the readings obtained on both the horizontal and vertical variometers are described, and the results compared with the theoretical curves which are also calculated.

CHAPTER III

ON THE APPLICATION OF SOME ELECTROMAGNETIC INDUCTION METHODS OF LOCATING CONDUCTING ORE-BODIES

INTRODUCTION

There are several electromagnetic induction methods of locating conducting bodies covered with overburden. Some of these have been tested and described by the authors in previous papers,[1] but there are two for which more accurate tests were still required. The two methods that will be described in this section differ principally in the position of the exciting loop. In the first method a *horizontal* loop is laid on the ground and a current of 500-cycle frequency passed through it. This alternating current will set up an electromotive force in any conductor in the region. As a result of the electromotive force, a current also of 500-cycle frequency will be produced in the conductor. Hence a secondary electromagnetic field will be produced in its vicinity and if a small coil of about 800 turns of wire, wound on a circular frame 2 feet in diameter, is placed in the region, a current will be induced in this coil by the electromagnetic field from the exciting loop as well as from the disturbing body. This current is detected by means of a pair of head-phones and an amplifier. The position of the coil for minimum audition is found and from this orientation, the location of the disturbing body may be found.

The second induction method is similar to the first, but the loop is erected in a *vertical* plane, the detecting coil being again used for finding the disturbing body. The two methods will now be described in some detail and also the results obtained in hunting for the pyrrhotite body, and for the diabase dyke, already described in Chapter II of this report.

THE INDUCTION METHOD WITH VERTICAL EXCITING LOOP

A vertical loop about 12 feet by 18 feet, consisting of 8 turns of copper wire, was erected over the ore-body on the line crossing the pyrrhotite deposit and along which the previous experiment was conducted. A current of from 7 to 8 amperes from a 500-cycle alternator was passed through this loop in order to produce an alternating electromagnetic field in the vicinity. The loop could be rotated about a vertical axis through its centre, so that the plane of the loop could be orientated in any direction.

To detect the field, a small exploring coil, about 2 feet in diameter, wound with 851 turns of No. 24 double cotton covered wire, was arranged to fit on a tripod. The same coil was used in the experiments described in Chapter I of this report. The coil was carefully tuned to the exciting loop by means of a variable condenser placed in the circuit. The two

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[1] Eve and Keys: "Applied Geophysics", Chap. IV. Also Bureau of Mines, Technical Paper No. 434 (Washington, 1928).

terminals of the condenser were attached to the ends of the coil and the telephones placed across the ends of the coil also. The capacity of the condenser was then altered until the coil was in resonance with the exciting loop. Since an amplifier is needed for distances greater than 300 to 400 feet from the loop, the input of the amplifier was attached to the two ends of the coil instead of the telephones and the telephones connected to the output terminals of the amplifier. The amplifier used by the writers was a two-stage portable instrument constructed by Mr. H. G. I. Watson of McGill University and was found very suitable for field work.

A line was chosen at some distance from the loop, 100 feet to 1,000 feet or more, which should cross the strike of the ore-body. In this case, the strike of the body is approximately east-west, so the lines were chosen running north-south. The detecting coil was then set up at stations on this line, at intervals 100 feet or so apart. For more accurate work, the stations may be chosen 50 feet apart. The loop is now turned so that its plane points towards the exploring coil. The exploring coil is orientated towards the loop with the plane of the coil vertical. In the absence of any disturbing body in the neighbourhood, the sound in the coil would now be a maximum. If the plane of the coil is turned into a horizontal position, the sound would be a minimum or zero. If an ore-body or any other conducting body be present, the resultant field at the coil will be made up of the two effects from the loop and the conductor. The effect from the loop would be a maximum when the coil is kept vertical and, therefore, its effect at the coil may be represented by a vertical vector at each station. The effect from the conductor will be a maximum when the plane of the coil points to the conductor. In Figure 19, the effect of the vertical loop is shown by H, that of the conductor O by A, and the direction of the resultant of these two by R. When the plane of the coil is set perpendicular to R, the current induced will be a minimum, but not usually zero. The fact that the current is not zero is due to the ellip-

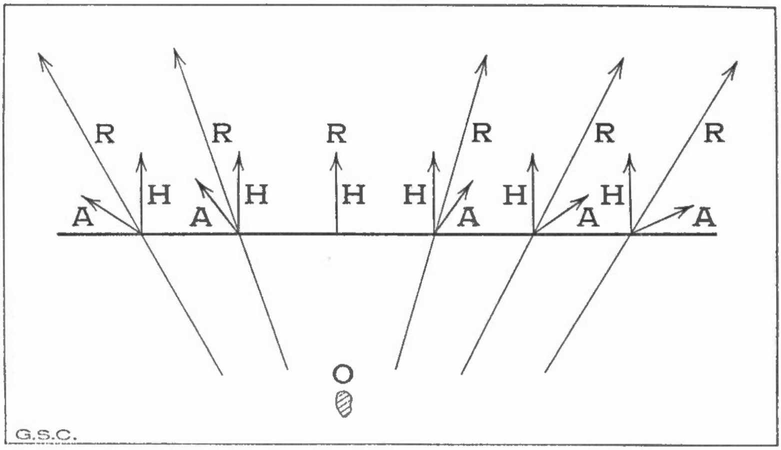

Figure 19. Directions of resultant vectors due to loop and ore-body, induction experiments.

tical polarization of the electromagnetic field.[1] To make the survey, the stations are chosen along the line and the loop adjusted with its plane pointing to the coil. The plane of the coil is pointed towards the loop and then the coil is turned about a horizontal axis until the position of minimum audition is found. In general, the coil will have a small dip either to the north or south, when in the minimum position, and this is read from the protractor or scale provided on the coil. These dips are recorded at each station, and vectors are drawn in directions perpendicular to the plane of the coil in its minimum position. These vectors will point to an imaginary line in the ground, called the electrical axis of the conductor. From experience in the field, after a survey has been made along a given line crossing the conductor, it is possible to estimate fairly accurately the approximate amount of overburden above the conductor.

The loop was first set up at a point 100 feet north of station B, which was just over the pyrrhotite body. The first survey was along a north-south line, crossing the body 100 feet east of the loop. Readings were taken of the dip every 50 feet and are given in Table XVIII. The zero station is taken on the east-west line passing through the position of the loop, which will be approximately over the deposit. The vector diagram drawn from the dips as well as a graph of these readings are shown in Figure 20. The reader will see from the results that the position of the conducting body is fairly well defined by this method. A second survey was made along a north-south line 200 feet east of the loop, the results of which are given in Table XIX and the graph plotted from them is shown in Figure 21. Again the presence of the conductor is well indicated.

TABLE XVIII

Station	Dip in degrees	Station	Dip in degrees
150 N	4 N	50	1 S
100	5 N	100	4 S
50	2·5 N	150	4·5 S
0	1 N	200 S	3·25S

TABLE XIX

Station	Dip in degrees	Station	Dip in degrees
200	1·5 N	50	0
150	2·5 N	100	0·5 S
100	1 N	150	2·5 S
50	0	200	2·0 S
0	0		

A third line 300 feet east of the loop was surveyed with the results shown in Table XX, and plotted in Figure 22. Here again the indications are good. The depth of the electrical axis indicated by these surveys is approximately 400 feet.

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[1] For a full account of this phenomenon, *See* Eve and Keys: "Applied Geophysics", Chapter IV. *Also see* pp. 141-148, for a description of this method.

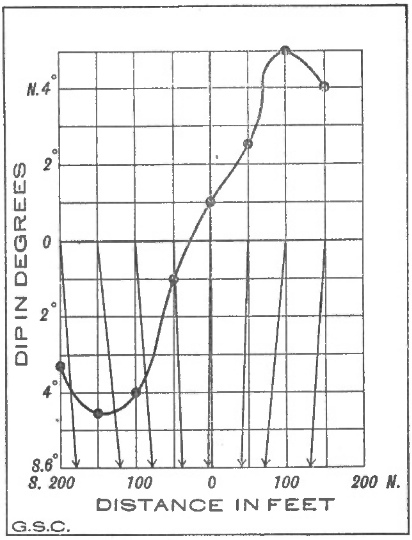

Figure 20. Dips of coil at successive stations on line 100 feet east of loop.

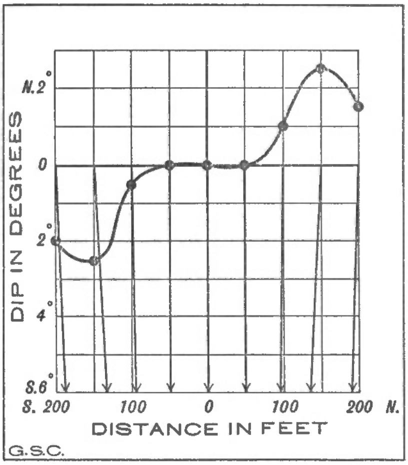

Figure 21. Dips of coil at successive stations on line 200 feet east of loop.

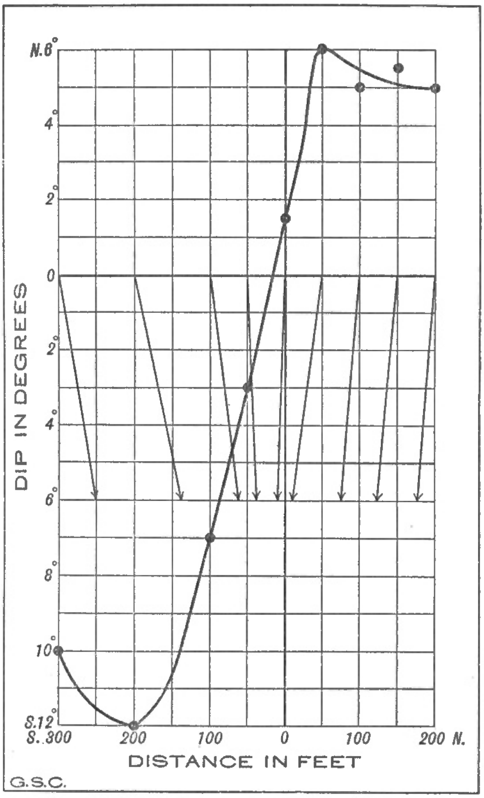

Figure 22. Dips of coil at successive stations on line 300 feet east of loop

TABLE XX

Station	Dip in degrees	Station	Dip in degrees
200 N	5 N	50 S	3 S
150 N	5·5 N	100 S	7 S
100 N	5 N	200 S	12 S
50 N	6 N	300 S	10 S
0	1·5 N		

A survey was now made along a north-south line, as far distant as 1,200 feet east of the loop, and with excellent results. Table XXI gives the readings and Figure 23 shows the results graphically. A magnetic survey, also taken along this line, indicated the pyrrhotite at the point 100 feet north of the station, agreeing in a remarkable way with the results of this induction method.

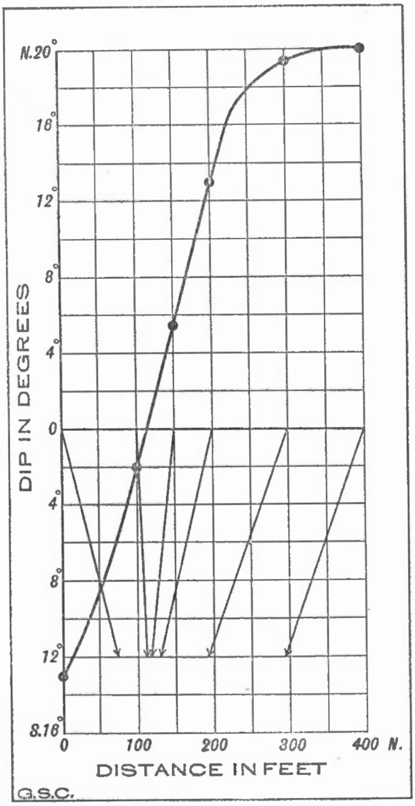

Figure 23. Dips of coil at successive stations on line 1,200 feet east of loop.

TABLE XXI

Station	Dip in degrees	Station	Dip in degrees
400 N	20 N	150	5·5 N
300	19·5 N	100	2 S
200	13 N	0	13 S

To test the effect when the loop is not directly over the conductor, the loop was shifted to a point 300 feet south of the pyrrhotite body on the B line. The exploring coil was then moved along a line 300 feet east of the B line, the zero station being the point where this north-south line crossed the pyrrhotite body. The results of this survey are given in Table XXII and plotted in Figure 24. They are again in good agreement with the known position of the conducting body.

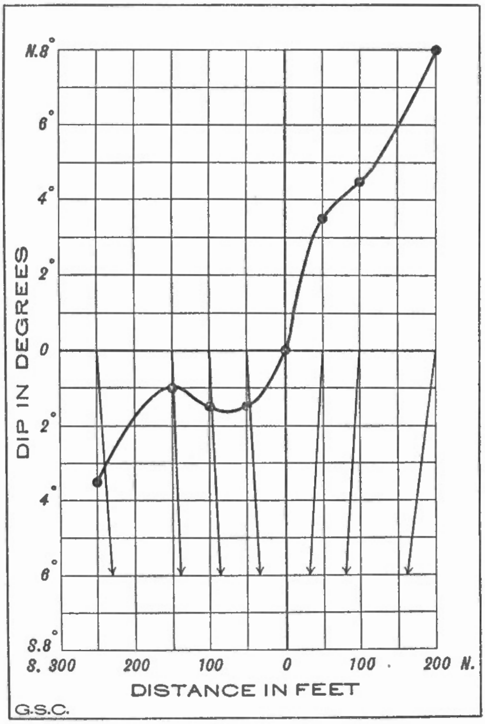

Figure 24. Dips of coil at successive stations on line 300 feet east of loop; loop 300 feet south of ore-body.

TABLE XXII

Station	Dip in degrees	Station	Dip in degrees
200 N	8 N	50	1·5 S
100	4·5 N	100	1·5 S
50	3·5 N	150	1 S
0	0	250 S	3·5 S

The result of these surveys may be summarized by saying that this induction method is very satisfactory for finding the position of a good conducting body that is buried beneath an overburden of from 100 to 200 feet in thickness.

The next problem was to apply it to the dyke and investigate if this system could be used for detecting such a structure.

The loop was, therefore, set up at the zero station of the M line, Figure 10, and excited as before with the current from a 500-cycle generator. Surveys were made with the coil along the L, J, and N lines respectively, the position of the magnetic peak on each of these lines being taken as the arbitrary zero station. The results of these three surveys are given in Table XXIII. The slight deviations found could easily be accounted for by the variations in elevation of the ground, so it is inferred that no indications of the dyke were found in any of these induction surveys. The conclusions to be drawn from the above results are that the diabase dyke does not conduct sufficiently to give indications with this induction method. It may also be concluded that with a frequency of 500 cycles, the disseminated magnetite in the dyke does not respond. The vertical loop induction method may be used, therefore, with success for tracing conductors and also for distinguishing a good conducting body from a poorly conducting body such as a magnetic diabase dyke.

TABLE XXIII

Station	Dip in degrees		
	L line	J line	N line
400 N	....	1 N	
300	1 S	1·5 N	
200	1 N	0	1 N
100	0	1 N	3·5 S
0	2 N	1 N	0·5 N
100	0·5 S	1 N	2 N
200	1·5 S	....	2 N
300	2 S	....	1 N
400	1 S	....	0
500 S	....	....	1 N

THE INDUCTION METHOD WITH HORIZONTAL EXCITING LOOP

A second method of using an exciting loop is to lay the loop horizontally on the ground instead of supporting it vertically as was described in the first part of this section. An alternating current of 7 to 8 amperes was passed through the loop, which consisted of 8 turns of wire, 15 by 15 square feet in area. The loop was placed for the first survey on the line along which the loop was placed in the previous experiment with its centre directly above the ore-body. The same detecting coil was used with amplifier and *tuned* to the exciting frequency of 500 cycles. It is very important in all induction methods that the receiving coil should be tuned to the frequency of the exciting current. In the particular experiments described in this section, the capacity required for tuning was 0·15 microfarads.

Surveys by this method should be made along radial lines passing through the centre of the exciting loop. There are two methods of orientating the coil to detect the presence of a conductor. The first is by observing the dip, from the horizontal position of the coil, for a minimum sound in the telephones. This may be called the *dip* method. The second method is to keep the plane of the coil vertical and then orient the coil about a vertical axis until the position of minimum audition is found. The angle through which the coil has been turned from the radial direction gives the *strike* of the coil. Both readings should give some indication of the presence of the conducting body.

The first survey was made along the line on which the loop was placed, and the results are given in Table XXIV. In order that the results may be recorded systematically certain conventions are followed in denoting the directions of the dip and strike. To determine the dip, the coil is at first in a horizontal position. It is then turned about a horizontal axis to the position of minimum audition, the axis of rotation being perpendicular to the radial direction to the centre of the loop along which the survey is made. When the end of the coil nearest to the loop is turned down, the reading is called "to" and when this end is turned up, the reading is termed "from." In the case of the strike, the coil is set vertically and pointed to the centre of the loop. It is then rotated about a vertical axis until the position of minimum audition is found. When the angle through which the coil has been turned, as observed by an observer vertically above the coil, is counter-clockwise, the direction is said to be positive; angles measured in the opposite direction are termed negative. The reader will understand from Table XXIV why it is that the dip at 100 S is marked "from," though the dip is towards the south, because now the coil is south of the loop and

TABLE XXIV

Station	Strike	Dip
400 N	−33°	2·5° S to
300	−34	1 S "
200	+42	1 N from
150	?	3·5 N "
100 N	+20·5	6·5 N "
100 S	−6	8·5 S "
150	−11	4·5 S "
200	−38	2·5 S "
300	−30·5	2 S "
400	−20·5	2·5 S "

the end nearest the loop is turned up. The results of this survey are plotted in Figure 25. The dip indicates the presence of a conducting vein at about the station where the dip is a maximum. The strike on the other hand crosses the zero line 60 feet south of the central station, indicating the ore-body to be beneath that point. The pyrrhotite body is actually beneath the zero point, so it is concluded that the dip appears to give the more satisfactory result.

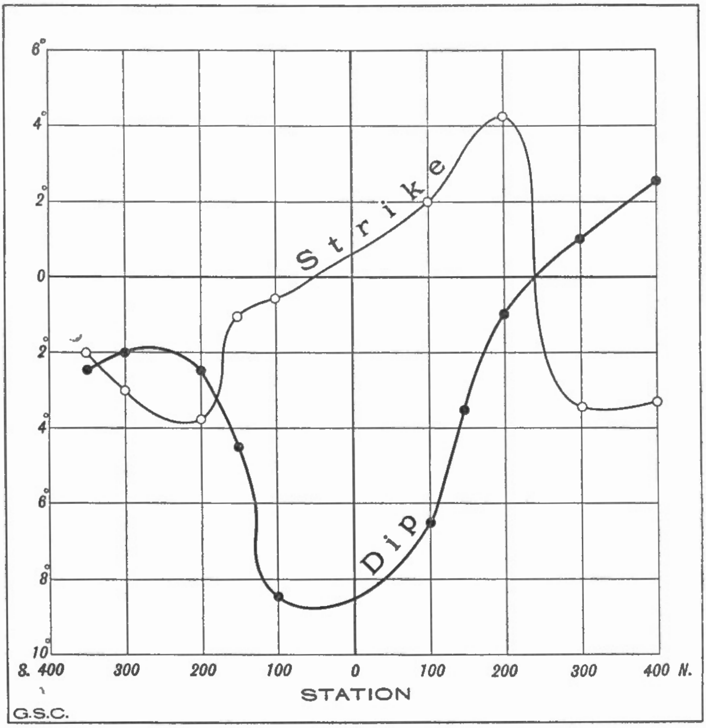

Figure 25. Dips and strikes at successive stations; loop horizontal.

A second survey was made when the loop was placed at a point 300 feet farther south on the B line, so it was well off the ore deposit. A radial line was surveyed at an angle of 45 degrees to the north-south B line. The readings were taken in exactly the same manner as already described and are shown in Table XXV.

TABLE XXV

Station	Strike	Dip
707	−81	5·5 from
566	+76	7 to
424	+56	8 to
283	+77	0·5 to
141	+12	6 from

In this case the strike does not seem to give any very definite information without additional knowledge, but the dip indicates the presence of a conductor about the point 424 feet from the loop. This actually is the point where the line chosen crosses the deposit at an angle of 45 degrees. Again it is seen that the *dip* is the more reliable indicator.

The results of these surveys will indicate to the reader that this horizontal loop method is quite good if the angle of dip is used. The strike is not so easy to interpret. Surveys were also made along lines tangential to the loop, but the interpretation of the results in these cases presents much difficulty, and it is concluded that surveys should always be made along radial lines from the centre of the exciting loop.

Enough work has been indicated in this section to give the reader an idea of the possibilities and relative value of the two induction methods described. They depend, of course, on the penetrating power of the electromagnetic radiation used to excite the ore-body or conductor. The question of the penetration of the 500-cycle frequency waves that have been used in these experiments has already been dealt with in the first part of this report. With higher frequencies, it may be possible to detect disseminated ore such as occurs in the diabase dyke, but with the 500 cycles this is not possible. The absorption of the electromagnetic radiation by the earth increases with the rise in frequency and consequently what is gained by increasing the frequency may be lost through the consequent increase in absorption.

From the experimental investigations carried out with the magnetometers and the induction methods, two outstanding features of geophysical investigations have been illustrated. The first indicates clearly how the most recent type of magnetometers may be used in the field for locating magnetic dykes and other bodies. The body being located, it may be traced and its dip ascertained with approximate accuracy. Secondly, the good conducting bodies, which are more mineralized than the diabase dykes, may be distinguished from the diabase dykes by the induction methods. This combination of two relatively simple methods is sufficient for locating all the magnetic dykes in any region. This fact is of particular interest to those desiring to find the minerals often associated with magnetite and pyrrhotite. The electromagnetic induction methods may, of course, be used for the location of any conductor, whether mineral or damp clay. The reader should keep this fact in mind, that when the electrical methods are used, they may locate conductors, but these conductors are not necessarily mineralized. Only a good geologist, with a fair knowledge of the local formations, can give a verdict as to whether a conductor found in any particular locality under survey is likely to be a mineralized body, or simply some underground damp clay or conducting fissure. Even then, the diamond drill must be the final method of determining the exact nature of the "find."

SUMMARY

(1) Experiments are described illustrating the successful use of a vertical loop and small detecting coil in the location of a pyrrhotite deposit, when alternating current of 500 cycles is used to energize the loop.

(2) Using a small, tuned receiving coil, 20 inches in diameter, 841 turns of wire, a pyrrhotite body was easily detected and located more than 1,200 feet from a loop, consisting of 8 turns 12 by 18 feet excited with 7-8 amperes.

(3) The use of a horizontal loop, excited with alternating current and the detection of the disturbing influence of a pyrrhotite body on the resulting electromagnetic field, detected with a tuned exploring coil, is described. The "dip" and "strike" methods of making observations are compared, the dip method giving the most satisfactory results in the experiments described.

(4) The application of the vertical loop, electromagnetic method to the problem of distinguishing a magnetic diabase dyke from a pyrrhotite deposit is described. The diabase dyke gives no response to the 500-cycle radiation, the pyrrhotite body on the other hand being readily detected.

APPENDIX I

Theoretical Variations in the Horizontal and Vertical Magnetic Fields along a Plane above an Ideal Bar Magnet

Suppose a bar magnet SN of pole strength m is inclined at an angle to the plane ABCD. Consider the force on unit magnetic pole at P. AB is the magnetic meridian, with the north magnetic pole towards B. Let CS and DN be lines perpendicular to AB through the south and north pole respectively of the bar magnet SN, Figure 26. Let PS = r; PN = R; PC = x; CD = k. If the angle NPC = α and the angle SPC = β, there is obtained for the horizontal force along AB

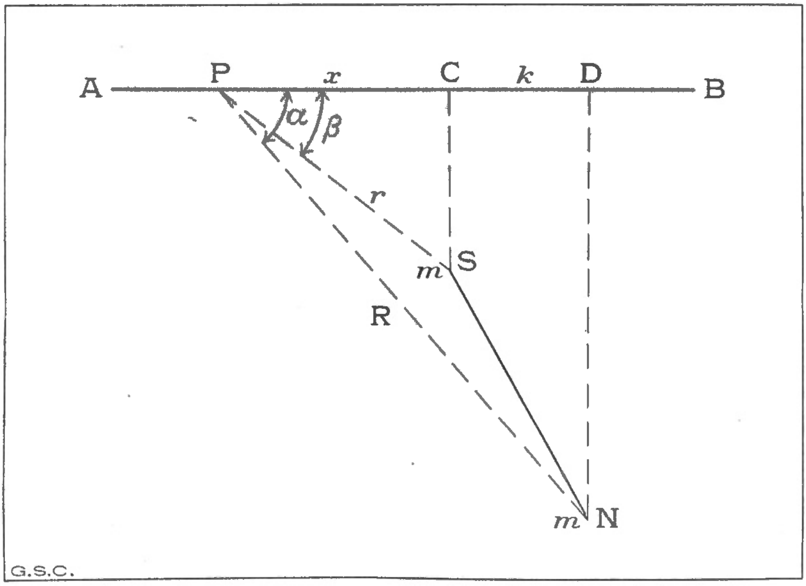

Figure 26. Diagram illustrating mathematical discussion.

$$H = H_0 + \frac{m}{r^2}\cos\beta - \frac{m}{R^2}\cos\alpha$$

where H is the resultant horizontal force and H_0 the normal value of the horizontal component of the earth's field when the magnet is absent.

$$\text{But } \cos\alpha = \frac{x+k}{R}, \text{ and } \cos\beta = \frac{x}{r}$$

$$\text{Hence} \quad H = H_0 + m\left(\frac{x}{r^3} - \frac{x+k}{R^3}\right)$$

$$\text{or the variation in } H = H - H_0 = m\left(\frac{x}{r^3} - \frac{x+k}{R^3}\right)$$

Now let a specific case be taken in which $m = 1$, $d = ES = 2$, $D = ND = 4$.

Then if the variation in H

be $y = \frac{x}{(x^2 + 4)^{\frac{3}{2}}} - \frac{x + 2}{[(x + 2)^2 + 16]^{\frac{3}{2}}}$

a table may be made giving the relation between x and y. Table XXVI is derived by giving x the values indicated, and calculating the corresponding values of y. From this table a curve is drawn using x as abscissæ and y as the corresponding ordinate. The curve drawn from these values is shown by the broken line in Figure 14.

TABLE XXVI

(The point C is considered as origin)

x	y	x	y
6	0·013	−0·5	−0·077
5	0·019	− 1	−0·104
4	0·029	− 2	−0·088
3	0·045	− 3	−0·050
2	0·066	− 4	−0·022
1	0·073	− 5	−0·008
0·5	0·025	− 6	−0·002
0	−0·022		

The vertical components of the force are found in a similar way. The force of attraction between unit pole at P, Figure 26, and the south pole, S, is as before along PS. If the force along PS is multiplied by sin β, the vertical component of the attraction is obtained, which will be downwards. In the same way the force of repulsion between the unit north pole at P and the pole N of the magnet will be along NP. When this force is multiplied by sin α, the vertical component, which is upwards, is obtained. The difference between these two components gives us the resultant downward force on unit pole at P due to the magnet NS. In mathematical form, we obtain

$$\begin{aligned} V &= V_0 + \frac{m}{r^2} \sin \beta - \frac{m}{R^2} \sin \alpha \\ &= V_0 + m\left(\frac{d}{r^3} - \frac{D}{R^3}\right) \\ &= V_0 + m\left(\frac{d}{(x^2 + d^2)^{\frac{3}{2}}} - \frac{D}{[D^2 + (x + k)^2]^{\frac{3}{2}}}\right) \end{aligned}$$

in which V is the resultant vertical force at P, V_0 is the normal value of the vertical component of the earth's magnetic field in the absence of the magnet NS. The other letters have the same meaning as given earlier.

The variation in the vertical component is thus given by y, where

$$y = m\left(\frac{d}{(x^2 + d^2)^{\frac{3}{2}}} - \frac{D}{[D^2 + (x + k)^2]^{\frac{3}{2}}}\right)$$

If different values are assigned to x, the corresponding values of y may be calculated. As before it will be supposed $m = 1$; $d = 2$; $D = 4$. Taking C as the origin, the following Table XXVII has been derived in the manner just explained.

TABLE XXVII

x	y	x	y
6	0·002	−0·5	0·177
5	0·005	− 1	0·122
4	0·012	− 2	0·026
3	0·028	− 3	−0·014
2	0·066	− 4	−0·022
1	0·147	− 5	−0·019
0·5	0·190	− 6	−0·014
0	0·205		

These results are plotted on the continuous curve shown in Figure 14. In a similar way, other examples may be worked out. The theoretical curves given in Figure 28 were derived as follows.

The magnet NS, dipping to the south, is shown in Figure 27. ACDB is the magnetic meridian, the earth's north pole being towards B. C and D are the feet of the perpendiculars from N and S respectively on AB.

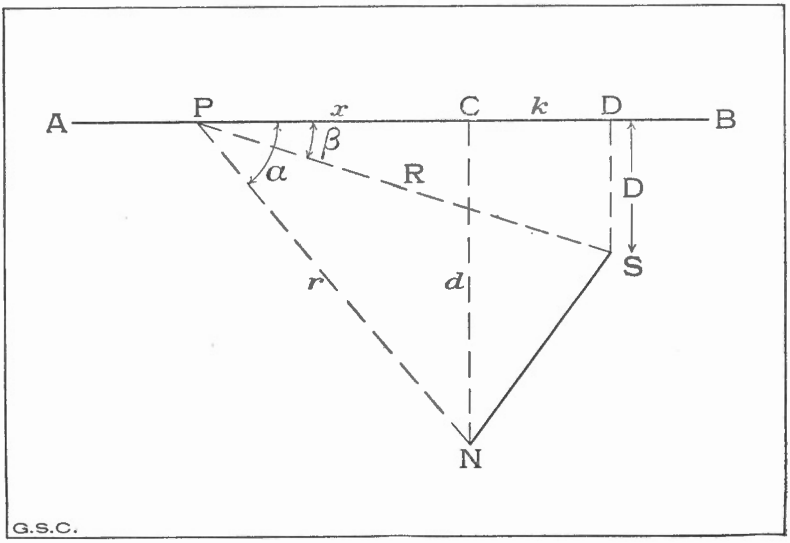

Figure 27. Diagram illustrating mathematical discussion.

C is taken as origin and the force on unit pole considered at P, due to the south and north poles of strength m at S and N. Let PC = x; CD = k; CN = d; DS = D; PN = r and PS = R. Let the angle CPN = α and the angle CPS = β. Then the horizontal component of the magnetic field at P given by H is obtained, where H is given by the following expression

$$\begin{aligned} H &= H_0 + \frac{m}{R^2}\cos\beta - \frac{m}{r^2}\cos\alpha \\ &= H_0 + m\left(\frac{x+k}{R^3} - \frac{x}{r^3}\right) \\ &= H_0 + m\left(\frac{x+k}{[(x+k)^2 + D^2]^{\frac{3}{2}}} - \frac{x}{(x^2+d^2)^{\frac{3}{2}}}\right) \end{aligned}$$

where H_0 is the normal value of the horizontal component of the earth's magnetic field at P. The variation in the horizontal component is then given by y, where

$$y = m\left(\frac{x+k}{[(x+k)^2+D^2]^{\frac{3}{2}}} - \frac{x}{(x^2+d^2)^{\frac{3}{2}}}\right)$$

Considering the case where d = 2; k = 2 and D = 4, there is obtained for the value of y, taking m = 1,

$$y = \frac{x+2}{[(x+2)^2+4]^{\frac{3}{2}}} \qquad \frac{x}{(x^2+16)^{\frac{3}{2}}}$$

The values for y corresponding to each value of x are given in Table XXVIII and the curve plotted from these values is shown in the broken line, Figure 28.

TABLE XXVIII

x	y	x	y
6	−0·002	−0·5	0·104
5	−0·001	− 1	0·104
4	0·002	− 2	0·022
3	0·008	− 3	−0·065
2	0·022	− 4	−0·066
1	0·050	− 5	−0·041
0·5	0·069	− 6	−0·029
0	0·038		

The vertical components are obtained as already explained. The value of the vertical component V at P is given by the following equation, assuming the values for k, d, and D given above.

$$\begin{aligned} V &= V_0 + \frac{m}{R^2}\sin\beta - \frac{m}{r^2}\sin\alpha \\ &= V_0 + m\left(\frac{D}{R^3} - \frac{d}{r^3}\right) \\ &= V_0 + m\left(\frac{D}{[(x+k)^2+D^2]^{\frac{3}{2}}} - \frac{d}{(x^2+d^2)^{\frac{3}{2}}}\right) \end{aligned}$$

Hence the variation in $V = V - V_0 = y$ is given by

$$y = \frac{2}{[(x+2)^2+4]^{\frac{3}{2}}} - \frac{4}{(x^2+16)^{\frac{3}{2}}}$$

The curve drawn from these figures given in Table XXIX, is shown in the continuous graph in Figure 28.

TABLE XXIX

x	y	x	y
6	−0·007	−0·5	0·069
5	−0·010	− 1	0·120
4	−0·014	− 2	0·205
3	−0·017	− 3	0·147
2	−0·022	− 4	0·066
1	−0·016	− 5	0·028
0·5	0·002	− 6	0·012
0	0·026		

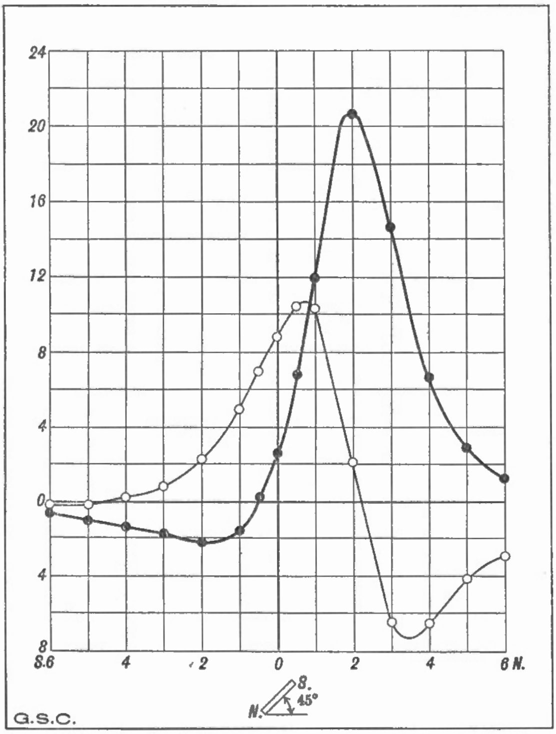

Figure 28. Calculated horizontal (fine line with open circles) and vertical (heavy line with solid circles) components over a magnet dipping 45 degrees south.

APPENDIX II

The Determination of the Depth and Approximate Thickness of a Magnetic Body from Magnetometer Readings Made on the Surface

The results obtained and described in experiment No. V are difficult to determine with precision. The wooden platform contained many nails which may have affected the readings on the delicate Askania instrument used to measure the variation in the vertical component of the magnetic field on the surface and on the top of the platform.

The following theory of the experiment will indicate the possibilities of such measurements, but unfortunately the experimental conditions were not as good as they might have been. Let it be supposed that there is a narrow magnetic dyke of thickness 1 cm. and extending a long distance either way. Thus in Figure 29, let the dyke of thickness 1 cm. extend east and west to such a distance that it may be considered infinite in so far as its relation to a point P over the centre of the dyke is concerned. Let the depth of overburden to the top of the dyke be D cm. If σ be the magnetic density on 1 cm^2. top and bottom of the dyke, then the vertical pull on unit magnetic pole at P, due to a slice dx wide of the top of the

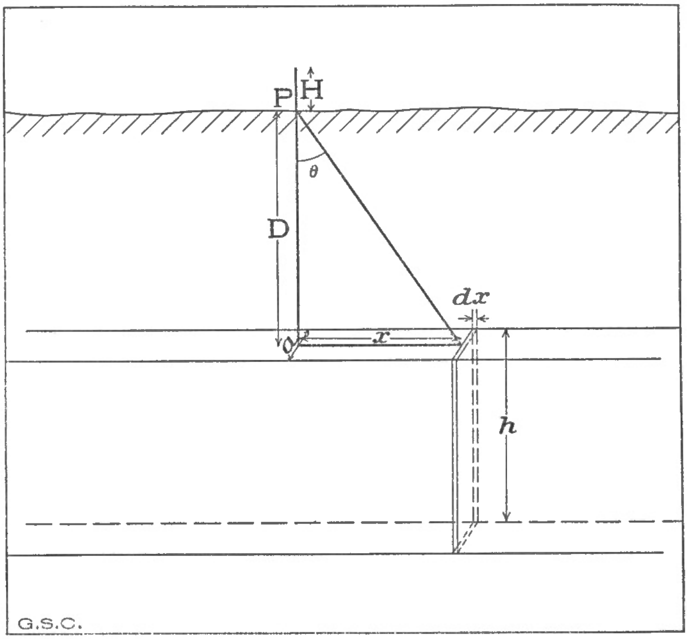

Figure 29. Diagram illustrating mathematical discussion.

dyke, at a distance x cm. horizontally from the vertical through P, will be given by

$$dV_1 = \frac{\sigma\, a\, dx}{D^2 + x^2} \cdot \frac{D}{\sqrt{D^2+x^2}} \text{ and } V_1 = \int_{-\infty}^{+\infty} \frac{D\, \sigma\, a\, dx}{(D^2+x^2)^{\frac{3}{2}}}$$

Now put $x = D \tan\theta$.

Then there is obtained

$$V_1 = \int dV_1 = \frac{\sigma a}{D}\int \frac{\sec^2\theta\, d\theta}{\sec^3\theta} = \frac{\sigma a}{D}\int_{-\pi/2}^{\pi/2} \cos\theta\, d\theta = \frac{2\sigma a}{D}$$

In a similar way it may be shown that the vertical repulsion due to the opposite polarity at the bottom of the dyke is

$$V_2 = -\frac{2\sigma a}{D + h}$$

where h cm. is the thickness of the dyke.
Hence the resultant force on unit pole at P due to the dyke, measured in gauss, will be given by

$$V = 2\sigma a\left(\frac{1}{D} - \frac{1}{D + h}\right) = \frac{2\sigma a h}{D(D + h)}$$

If a reading is now taken on a platform, H cm. above P, the resultant vertical force in this new position is given by

$$V - \Delta V = \frac{2\sigma a h}{(D + H)(D + H + h)}$$

Now these two fields will each produce a deflexion on the vertical magnetometer. Suppose the deflexions in the two cases are θ_1 and θ_2 respectively, then

$$\frac{V}{V - \Delta V} = \frac{(D + H)(D + H + h)}{D(D + h)} = \frac{\theta_1}{\theta_2} = r$$

Hence

$$(D + H)(D + H + h) = r.\, D(D + h)$$

Let it be supposed that for a first approximation, h is very much greater than D. In such a case it follows that

$$\frac{V}{V - \Delta V} = \frac{D + H}{D} = r$$

Hence $D = \dfrac{H}{r - 1}$

In our experiments, let us suppose that the readings over the ore-body are 33·2 and 30·6 when the instrument is on the ground and on the platform, respectively. This corresponds to the readings at the point 75 feet N in Table XIV. This value is chosen instead of the value at 100 N since there is evidently an error in this case.

Using these values, the approximate thickness of the overburden D is first calculated, obtaining

$$\frac{D + H}{D} = \frac{D + 10}{D} = \frac{33 \cdot 2}{30 \cdot 6} = 1 \cdot 085$$

from which is obtained

$$D = 118 \text{ feet approximately.}$$

This gives the distance from the surface to the south *pole* of the body, and since the magnetic poles are always a small distance inside the ore, the depth to the top of the ore would be less than this. The above result is thus in fair agreement with the known depth of from 110 to 120 feet.

The approximate thickness or extent of the body downwards in a vertical direction must now be found. Using the value of D = 118 feet found above and inserting it in equation (1) it follows that

$$\begin{aligned} 128\ (128 + h) &= 1 \cdot 085\ (118 + h)\ 118 \\ 16384 + 128\ h &= 15108 + 128 \cdot 03\ h \\ 1276 &= 0 \cdot 03\ h \\ h &= 42{,}000 \text{ feet approximately.} \end{aligned}$$

This value will be large owing to the fact that it was assumed that it was large in determining the value of D. If the value of D = 120 feet is taken, which is about the value that is found from electrical surveys and diamond drill records, a more reasonable depth for h is obtained. Thus

$$\begin{aligned} 130\ (130 + h) &= 1 \cdot 085 \times 120\ (120 + h) \\ 1690 + 13\ h &= 1561 + 12 \cdot 84\ h \\ 149 &= 0 \cdot 02\ h \\ h &= 6{,}000 \text{ feet.} \end{aligned}$$

The reader must remember that these calculations are made in the case of a deposit that has a vertical dip, whereas the body now being considered in the field has a variable dip, which may amount to as much as 60 degrees.

Turning attention to the diabase dyke, similar calculations may be made. For example, the zero station on the "M" line will be considered, Table V. The reading on the ground at this spot was = 11·1 divisions, but the zero reading of the instrument was found to be −16·3, which gives the value of the reading at the zero station = 27·4 divisions. On the platform, the reading would, therefore, be 26·3 divisions, which is 1·1 divisions less. Using these values and supposing for a first approximation that h is very much greater than D, the value of D may be found, which is the approximate thickness of overburden. Thus

$$\begin{aligned} D &= \frac{10}{\dfrac{27 \cdot 4}{26 \cdot 3} - 1} = \frac{10}{1 \cdot 033 - 1} = \frac{10}{0 \cdot 033} = \frac{10000}{33} \\ &= 333 \text{ feet.} \end{aligned}$$

Now it is known by experience that this value is too small. Let a larger value, therefore, be taken, say 350 feet for D, and calculate the thickness in a vertical direction of the diabase dyke, h from our equation (1).

$$\begin{aligned} 350\ (350 + h) &= 1{\cdot}033 \times 340\ (340 + h) \\ 122{,}500 + 350h &= 119{,}415 + 351{\cdot}22\ h \\ 3085 &= 1{\cdot}22\ h \\ h &= 2{,}500 \text{ feet approximately.} \end{aligned}$$

These results confirm the authors' view expressed in the report that the diabase dyke is under a greater overburden and is probably thicker than the ore-body. The magnetometer curves also indicate that the diabase dyke is much broader than the pyrrhotite body. It is seen in this way that the above calculations do give some idea of the extent and overburden of a magnetic body or dyke, but unless the dip of the ore-body is practically vertical the method will only be approximate at best. But such approximate measurements may often be of service and it is for that reason that they are given here.

APPENDIX III

Magnetic Surveys with the Askania Vertical Variometer Over the Northeast Section of the Falconbridge Ore-body

A number of good lines had been cut for assessment work in the northeastern section of the Falconbridge property, in which there were only a few outcrops. Several of these lines were surveyed and some indications were found. Further work will be needed to decide whether any of the indications are from pyrrhotite, but the major disturbances appear more like those due to the presence of magnetic dykes. The region surveyed is shown in Figure 30 below, in which the numbers are given as well as the approximate paths surveyed. The first line chosen was a long one running north and south, marked AB on the diagram. The readings commenced at No. 2 post, which is at the southeast corner of 17876, and were repeated every 100 feet going north. Four indications were found. The first was 2,550 feet north, the second 3,800 feet, the third 4,100 feet, and the fourth about 4,700 feet. The readings taken on this survey are given in Table XXX. A survey was then made from

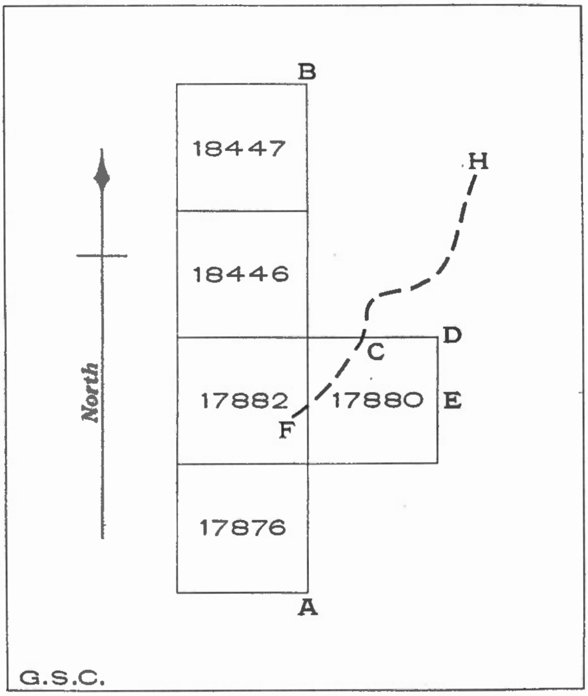

Figure 30. Area surveyed with vertical magnetometer.

TABLE XXX

Station	Reading	Station	Reading
0	−11·8	27	− 3·5
1	−12·0	28	− 3·6
2	−12·0	29	− 5·8
3	−11·5	30	− 6·0
4	−12·1	31	− 6·5
5	−11·8	32	− 6·8
6	−11·3	33	− 9·0
7	−12·2	34	− 7·8
8	−11·5	35	− 6·8
9	−11·4	36	− 5·8
10	−12·2	37	− 5·3
11	−11·0	38	− 1·2
12	−11·2	39	− 3·8
13	−11·2	40	− 5·4
14	−10·3	41	+ 1·0
15	−14·7	42	− 5·2
16	−11·0	43	− 7·0
17	−10·6	44	− 7·0
18	−10·3	45	− 4·8
19	−10·0	46	− 2·7
20	−10·5	47	− 1·0
21	−11·0	48	− 2·0
22	−10·3	49	− 2·0
23	−10·6	50	− 1·8
24	− 8·2	51	− 7·2
25	− 3·6	52	− 6·8
25·5	− 1·5	53	− 8·4
26	− 4·5	54	− 6·2

C to D, C being 700 feet west of D. The readings for this survey are given in Table XXXI. The party next turned south and surveyed from

TABLE XXXI

Station	Reading	Station	Reading
C	−4·8	400	−7·6
100	−6·6	500	−7·8
200	−6·8	600	−8·0
300	−7·0	700	−8·2

D to E crossing over an outcrop. The outcrop was not magnetic and when the magnetometer was set up over the various formations that were visible, no indications were obtained. The only indication was in the swamp at station 200. The results of this survey are given in Table XXXII. A further survey was made along a road sketched in Figure 30, from the point F to a point H northeast of F. The readings found along this line are given in Table XXXIII. The results of this survey show that there are no indications along the line FH. There is something

TABLE XXXII

Station	Reading	Station	Reading
D	−8·2	500	−7·6
100	−3·5	600	−9·7
200	−0·9	700	−9·6
300	−8·2	800	−10·2
400	−9·8		

crossing AB, however, which does not extend to the road. Further work is required to determine its strike and nature.

TABLE XXXIII

Station	Reading	Station	Reading
1500 H	−8·0	400	−6·9
1400	−8·2	300	−5·0
1300	−7·8	200	−8·0
1200	−7·8	100 N	−4·8
1100	−8·6	C	−4·1
1000	−9·4	100 S	−2·0
900	−8·5	200	−1·8
800	−7·2	300	−4·5
700	−7·0	400	−7·9
600	−7·1	500	−9·3
500	−7·5	600 F	−9·0

One other line was surveyed, northwest of Falconbridge mine. The line was the bed of an old railroad which had been used for hauling lumber many years ago. There were no indications on this line. The readings taken on this survey are given in Table XXXIV.

TABLE XXXIV

Station	Reading	Station	Reading
0	−9·7	1650	−11·1
150	−9·1	1800	−11·3
300	−11·1	1950	−11·0
450	−9·8	2100	−11·9
600	−11·0	2250	−11·3
750	−10·2	2400	−10·7
900	−10·0	2580	−10·7
1050	−10·0	2730	−11·3
1200	−11·0	2900	−9·1
1350	−11·6	3050	−11·1
1500	−12·0	3210	−12·3

The results given in this appendix are of interest only as supplemental examples of the method of making a magnetic survey of a region with the Askania vertical variometer.

PART II

GEOPHYSICAL INVESTIGATIONS MADE IN 1930

By L. Gilchrist

INTRODUCTION

The following report comprises the results of electrical and magnetic laboratory measurements on specimens of ore and surrounding materials, a description of electrical investigations made in the field, and the results obtained from the investigations together with the conclusions that appear to be warranted by the results.

The measurements on the specimens were made in the Physics Laboratory, University of Toronto, and at the place where the field work was carried out.

The investigations in the field were made where the following deposits were known to exist:

Deposit of chromite on the property of the Vanadium Company of New York, in the neighbourhood of Caribou lake, Quebec.
Deposit of pyrite on the property of the Graselli Chemical Company, of Cleveland, at Clyde lake, Renfrew county, Ontario.
Deposit of pyrrhotite at the Falconbridge mine, Sudbury district, Ontario.
Deposit of lignite at Blacksmith rapids, Abitibi river, Ontario.

The field work at Caribou lake was carried out with the assistance of Mr. J. T. Wilson and Mr. W. H. Gillean; at Clyde lake with Mr. J. T. Wilson, Mr. W. H. Gillean, and Mr. R. H. Hawkins; at Falconbridge mine and at Blacksmith rapids with Mr. Wilson and Mr. R. H. Hawkins.

Considerable assistance was also given by a party in charge of Mr. A. H. Miller, including Mr. A. Corbett and Mr. E. Muldoon, at Caribou lake and at Clyde lake; and at Blacksmith rapids by Messrs. A. R. Crozier, A. D. Williams, and other members of the staff of the Department of Mines of the Province of Ontario.

INVESTIGATION AT CARIBOU LAKE, QUEBEC, IN THE NEIGHBOURHOOD OF A CHROMITE DEPOSIT

RESISTIVITIES OF SPECIMENS OF CHROMITE AND DUNITE

Preliminary magnetic tests on specimens of chromite and of dunite showed a pronounced effect on a Brunton compass by the chromite and no observable effect by the dunite. The resistivities of specimens of the chromite and dunite which were in the form of rectangular parallelopipeds, were measured in three directions and were found to be as follows:

Chromite: $2 \cdot 6 \times 10^6$, $3 \cdot 8 \times 10^6$, and $2 \cdot 3 \times 10^6$ ohms per cm. cube.
Dunite: 39×10^6, 70×10^6, and $53 \cdot 5 \times 10^6$ ohms per cm. cube.

These specimens were dry. Their resistivities were somewhat higher than that usually associated with ground water which is 10^4 to 10^5 ohms per centimetre cube. Although the resistivity of the chromite was considerably lower than that of the dunite, it was realized that the presence of ground water would be effective in lowering the resistivity of both and it, therefore, appeared desirable to make resistivity measurements of the materials in place, if possible in a well-drained locality near a deposit of chromite.

Specimens obtained from the field of investigations gave the following values for resistivity measured in one direction.

(a) Drill core, Beaver mine, Thetford Mines district.
Dry chromite: $1{\cdot}3 \times 10^6$ ohms per cm. cube.

(b) Specimens from the property of the Vanadium Company, Caribou Lake district.
Moist dunite: $0{\cdot}382 \times 10^6$ ohms per cm. cube.
Moist, impure chromite: $0{\cdot}120 \times 10^6$ ohms per cm. cube.
Moist, impure chromite: $0{\cdot}34 \times 10^6$ ohms per cm. cube.
Moist chromite (apparently rich): $0{\cdot}086 \times 10^6$ ohms per cm. cube.
Dry chromite: $1{\cdot}96 \times 10^6$ ohms per cm. cube.

The results suggest that the presence of water is effective in lowering the resistivity of all of the specimens and it appears to be more effective in the specimens that are rich in chromite.

ELECTRICAL SURVEY OF THE NEIGHBOURHOOD OF A DEPOSIT OF CHROMITE ON THE PROPERTY OF THE VANADIUM COMPANY OF NEW YORK

Measurements of Average Resistivity by Central Electrode Method[1]

The arrangement of the electrodes in this method is shown in Figure 34.

Through a point A (*See* Figure 31) an east-west and a north-south line were run. The central current electrode was placed at point A, and four end-current electrodes were placed at, respectively, points 120 metres north, south, east, and west of the central current electrode. The currents passing through the end current electrodes were equalized by means of auxiliary resistances. Commencing 2 metres from the central electrode (Point A), two potential electrodes were placed successively at points 3 metres apart and the resistances of the successive interbowl sections were measured by means of a "megger" earth tester. The average resistivity (ρ) of these interbowl sections was calculated from,

$$\rho = 2\pi R \frac{a\,b}{b-a}$$

where a and b are the respective distances from the central electrode to the near and remote edges of an interbowl section. The results are given in Tables I and II.

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[1] For description of general arrangement, *See* "Studies of Geophysical Methods, 1928 and 1929"; Geol. Surv., Canada, Mem. 165, pt. III, by L. Gilchrist.

TABLE I

East			West		
Stations and distances (in metres)	R ohms	$\rho \div 10^4$ ohms per cm. cube	Stations and distances (in metres)	R ohms	$\rho \div 10^4$ ohms per cm. cube
A - 1 E (2)			A - 1 W (2)		
1 E - 2 E (3)	17·1	3·58	1 W - 2 W (3)	22·2	4·65
2 E - 3 E (3)	11·2	9·37	2 W - 3 W (3)	17·3	14·5
3 E - 4 E (3)	3·4	6·26	3 W - 4 W (3)	8·3	15·3
4 E - 5 E (3)	2·49	8·02	4 W - 5 W (3)	4·54	14·6
5 E - 6 E (3)	1·935	9·65	5 W - 6 W (3)	1·60	7·98
6 E - 7 E (3)	1·29	9·2	6 W - 7 W (3)	1·63	11·6
7 E - 8 E (3)	0·82	7·9	7 W - 8 W (3)	0·86	8·28
8 E - 9 E (3)	0·61	7·65	8 W - 9 W (3)	0·73	9·13
9 E - 10 E (3)	0·372	5·91	9 W - 10 W (3)	0·48	7·6
10 E - 11 E (3)	0·337	6·54	10 W - 11 W (3)	0·39	7·55
11 E - 12 E (3)	0·219	5·13	11 W - 12 W (3)	0·27	6·3

TABLE II

North			South		
Stations and distances (in metres)	R ohms	$\rho \div 10^4$ ohms per cm. cube	Stations and distances (in metres)	R ohms	$\rho \div 10^4$ ohms per cm. cube
A - 1 N (2)			A - 1 S (2)		
1 N - 2 N (3)	37·1	7·74	1 S - 2 S (3)	4·6	9·64
2 N - 3 N (3)	16·9	14·15	2 S - 3 S (3)	4·9	4·1
3 N - 4 N (3)	8·075	14·85	3 S - 4 S (3)	10·9	20·1
4 N - 5 N (3)	4·025	12·95	4 S - 5 S (3)	5·27	17·0
5 N - 6 N (3)	1·72	8·57	5 S - 6 S (3)	3·23	16·1
6 N - 7 N (3)	1·84	13·1	6 S - 7 S (3)	1·78	12·7
7 N - 8 N (3)	1·66	16·0	7 S - 8 S (3)	0·603	5·8
8 N - 9 N (3)	1·18	14·75	8 S - 9 S (3)	0·353	4·42
9 N - 10 N (3)	0·89	14·1	9 S - 10 S (3)	0·623	9·85
10 N - 11 N (3)	0·466	9·05	10 S - 11 S (3)	0·202	3·92
11 N - 12 N (3)	0·343	8·02	11 S - 12 S (3)	0·178	4·16

Location of Equipotential Lines between Two, Long, Parallel, Current Electrodes

Two well-grounded, parallel line electrodes were placed in position, one along a north-south line 120 metres east of point A (Figure 31), the other along a north-south line 120 metres west of point A. The electrodes were 480 metres long and each extended equal distances north and south of the east-west line through point A. A direct current generator with a slip ring alternator was used as source of supply and was connected directly to the parallel electrodes. The frequency of alternation was about 400 a second. A telephone receiver with an amplifier was attached to two exploring electrodes by which lines of equipotential were located on the surface of the ground. Three equipotential lines were traced crossing the east-west line at, respectively, point A, a point 29 metres east of A, and 53 metres east of A. These are shown on Figure 31. Since it was difficult to

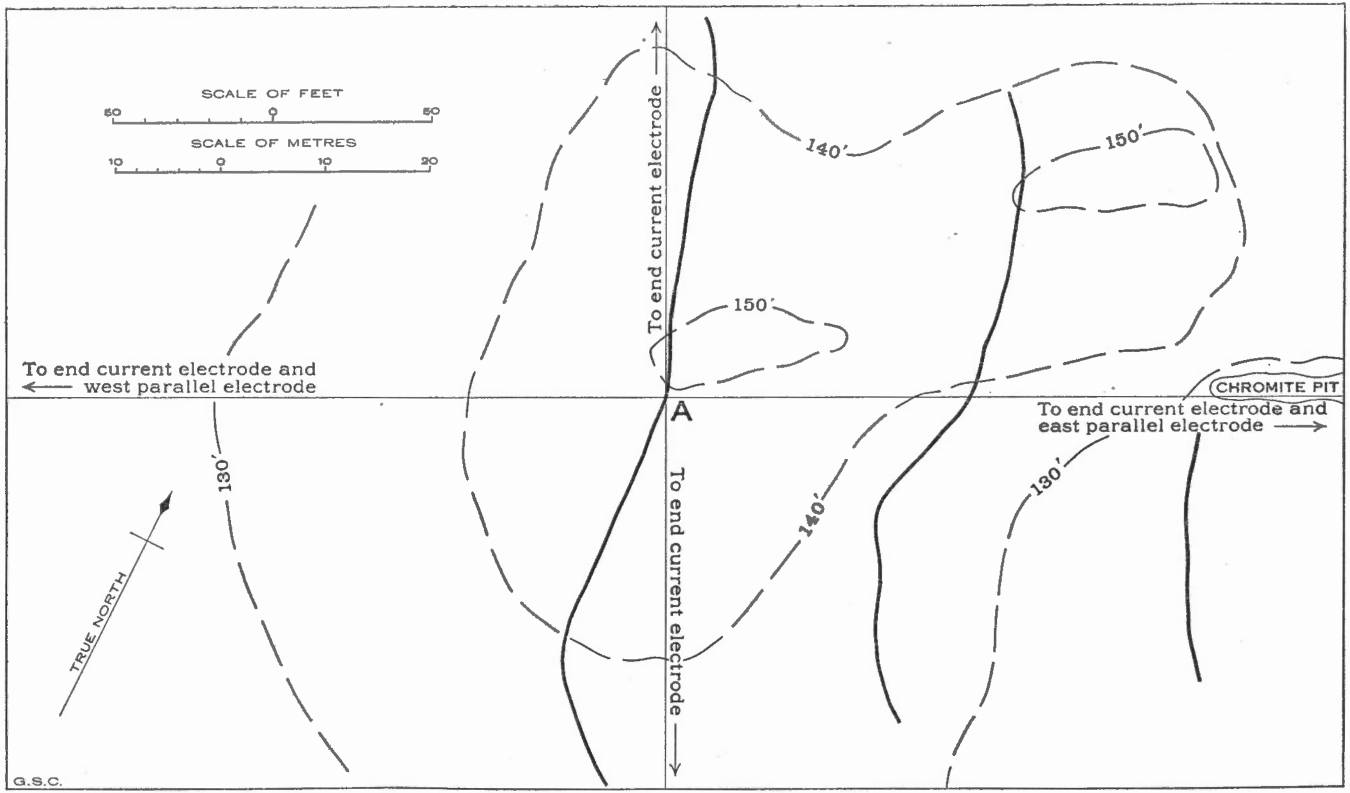

Figure 31. Electrical survey near chromite deposit, Thetford district, Quebec; heavy lines are equipotential lines.

obtain sharp minimal sounds in the telephone receiver these equipotential lines must not be considered as located accurately. They serve, however, to indicate approximately the distribution of conductivity in the region.

CONCLUSIONS FROM EXPLORATIONS I AND II

(1) Although there is a general indication of better conductivity in the immediate neighbourhood of the deposit of chromite, especially on the northwest side of the deposit, than exists in more distant portions of the region, it cannot be said that the indications are pronounced or definite.

(2) It should be noted that the average resistivities of the overburden and also of the rock in the neighbourhood was about $\frac{1}{100}$ of that of the specimens of chromite measured in the laboratory. Moreover, it is slightly greater than the resistivity of ground water. This leads to the suggestion that even though the region was somewhat elevated there was sufficient water permeating the overburden and rock to be highly effective in lowering the resistivity.

(3) It is suggested that comparatively good conductivity in the neighbourhood of the deposit as indicated by both electrical methods used might be due to a greater occlusion of water in the ore-body than in the surrounding material.

ELECTRICAL SURVEY OF THE NEIGHBOURHOOD OF CALDWELL PYRITE MINE, BLITHFIELD TOWNSHIP, RENFREW COUNTY, ONTARIO

This deposit has been described by M. E. Wilson.[1] Only the information given by Wilson in his report was available at the time the geophysical investigations were made. Considerable mining operations had been conducted after the date of Wilson's examination and much further information regarding underground conditions had been obtained. Some months after the completion of the geophysical work, the additional information was made available by the Grasselli Company at the request of Mr. T. B. Caldwell. The information in Wilson's report served as a guide in the choice of location and procedure in the geophysical investigations and the information subsequently obtained from the Grasselli Company serves as a check on the interpretation of the results of the investigation. For the latter purpose copies have been made of some of the maps and figures supplied by the Grasselli Company and on these have been placed the locations of the places at which measurements were made.

Measurement of the Average Resistivity by the Central Electrode Method and by the Single Electrode Method

(a) A central current electrode was placed at the point A at the intersection of lines I and II, Figure 32, and end current electrodes were placed east and west along line I and north and south along line II at distances of 800 feet from the point A. Switches were inserted in each

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[1] Geol. Surv., Canada, Sum. Rept. 1919, pt. E, pp. 30-35.

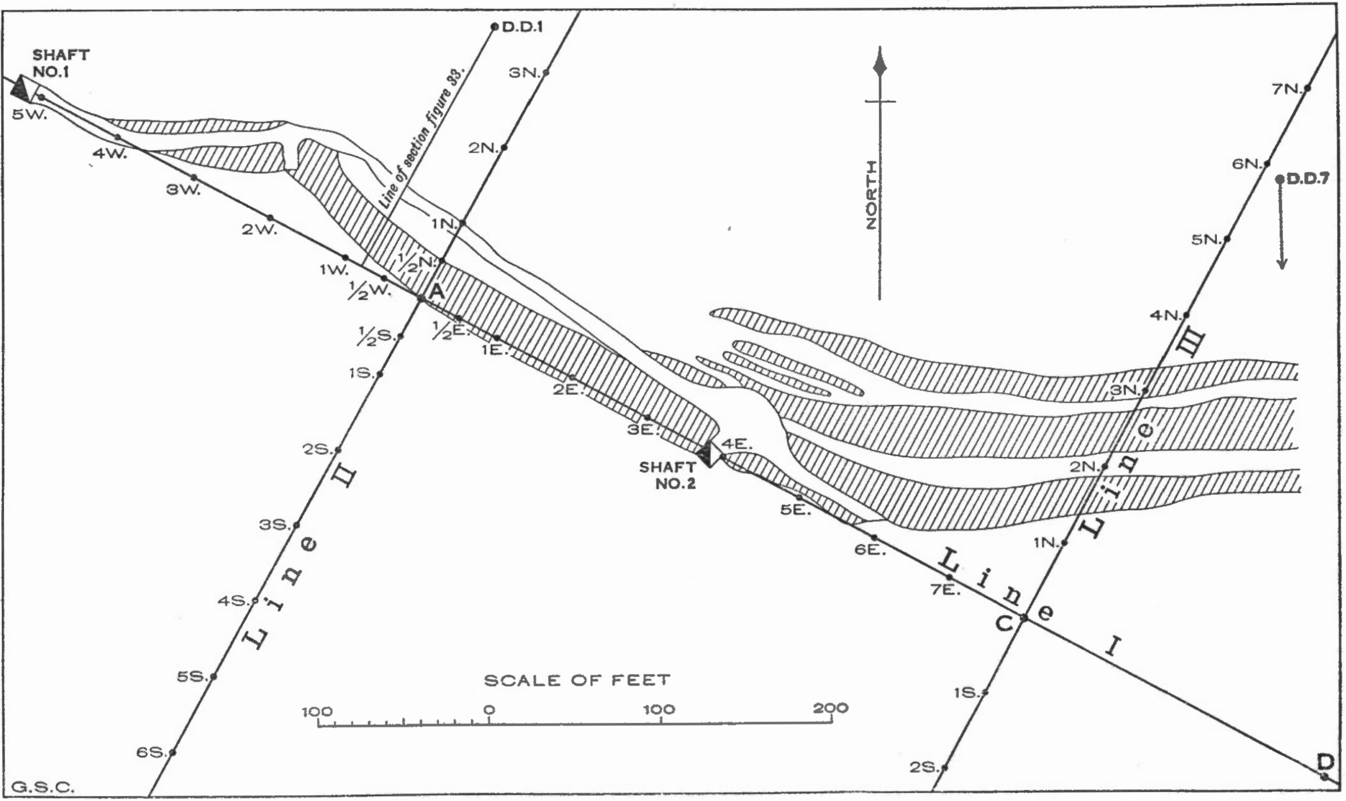

Figure 32. Caldwell pyrite mine showing workings and ore-bodies on first level and positions on surface of lines, etc., employed in making electrical survey.

of the circuits leading to the end current electrodes so that measurements could be made with one, two, three, or four end current electrodes in use at will. With only one end current electrode in use then the central current electrode at A became the single electrode in what is usually described as the "single electrode method" of making measurements. The latter method has been largely used by Crosby and Leonardon,[1] by Konigsberger,[2] and Alty[3], and by others.

In both the central electrode method and the single electrode method the formula which is made use of in order to calculate the average resistivity, ρ, of an interbowl section, is

$$\rho = 2\pi R \frac{a\,b}{b-a} \quad (1)$$

where a is the distance from the central or single current electrode A to the near potential electrode, i.e. the inner edge of the interbowl section, and b is the distance from A to the remote potential electrode, i.e. the outer edge of the interbowl section, and R is the resistance in ohms of the interbowl section. As has been pointed out by several investigators, this formula has been developed for a homogeneous medium uniform in conductivity and is applicable in the single electrode method only in the immediate neighbourhood of the single electrode at A, the effect of the distant current electrode being neglected, the immediate neighbourhood being considered by several investigators as extending from A at least to a value for b of one-fifth of the distance from A to the distant current electrode. Other investigators, e.g. C. and M. Schlumberger, allow for the effect of the distant end current electrode and make use of a formula somewhat different from formula (1). Formula (1) may be written

$$\frac{1}{\rho} = \frac{1}{2\pi R}\left(\frac{1}{a} - \frac{1}{b}\right)$$

Instead of this formula these investigators use

$$\frac{1}{\rho} = \frac{1}{2\pi R}\left(\frac{1}{a} - \frac{1}{b} - \frac{1}{c} + \frac{1}{d}\right) \quad (2)$$

where ρ, R, a and b have the same significance as in formula (1) and c is the distance from the potential electrode near A and the distant current electrode and d is the distance from the remote potential electrode to the distant current electrode. Formula (2) like formula (1) has been developed for a homogeneous medium.

For the actual field conditions under which geophysical explorations are made the medium is usually neither homogeneous nor uniform in conductivity and in these cases both formula (1) and formula (2) may be quite misleading if used in connexion with the single electrode method. If, instead of the single current electrode, a central current electrode with several end current electrodes of equal resistance symmetrically placed about the central electrode is used then either formula (1) or formula (2) is applicable in many cases in conjunction with measurements

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[1] Crosby, Irving G., and Leonardon, E. G.: Proceedings of Am. Inst. Min. Eng., Boston Meeting, August, 1928.

[2] Konigsberger, J. G.: Proceedings Am. Inst. Min. Eng., Boston Meeting, August, 1928; Zeit. fur Geophysik 6, No. 2, 1930, pp. 71-73.

[3] Alty, T., and Alty, S.: Can. Jour. Research, vol. 3, No. 6, p. 521.

made in the neighbourhood of the central electrode, even if there is considerable lack of homogeneity or of uniformity of conductivity in the medium, in order to indicate approximately the location of changes in homogeneity or conductivity. For more precise delineation of these changes, however, even with the central electrode method a more comprehensive formula based on the actual distribution of potential on the surface of the ground is required. Formulæ applicable for the case of parallel overlying layers of media of different conductivities have been developed by J. N. Hummel,[1] by Stefanesco and C. and M. Schlumberger,[2] by E. A. Lancaster-Jones,[3] and D. O. Ehrenberg and R. J. Watson[4] and more recently by Peters and Bardeen[5].

All formulæ deduced on the supposition of existing parallel horizontal layers with continuity of flow across the boundaries of the layers are probably inadequately applicable to the actually existing conditions in general and, especially, these formulæ are inadequate for the case where narrow, steeply-dipping veins or lenses of good conductivity are embedded in surrounding poor conducting rock, which was the condition existing at the deposit of pyrite.

On this account it was considered that either formula (1) or formula (2) could be used in connexion with the central electrode method to calculate the average resistivities and thus give an indication of the changes in conductivity with changes in distance from the central electrode at least for short distances. Confidence in the use of these formulæ was enhanced for distances from the central electrode when a change from four symmetrically-arranged end current electrodes, to eight end current electrodes made no changes in the measured results of interbowl resistance.

In the operation of the central electrode method a central electrode was placed at A and four or eight distant end current electrodes of equal resistances were placed symmetrically about A, and the layout was so arranged that one or more of the distant end current electrodes could be used at will. Potential electrodes were placed at stations 50 feet apart along lines I and II, the nearest potential electrode stations being 25 feet distant from the central electrode at A. In order to minimize the inductive effects due to the cables joining the central electrode and source of electrical current to the end current electrodes, these cables were placed some distance from the line of the potential electrodes and from the cables leading to the potential electrodes.

The results of the measurements of R which are presented were obtained with a "megger" earth tester. The actual reading on the earth tester

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[1] Hummel, J. N.: Z. fur Geophysik 5, 5-6, p. 228.

[2] Stefanesco, S., in collaboration with C. et M. Schlumberger: J1, de Physique et Radium, Serie VII, T, L. No. 1, pp. 132-140 (April, 1930).

[3] Lancaster-Jones, E. A.: The Mining Magazine, June, July, Sept., 1930.

[4] Ehrenburg, E. O., and Watson, R. J.: Tech. Pub. No. 400, Am. Inst. Min. Eng., Feb., 1931.

[5] Peters, L. J., and Bardeen, J.: The University of Wisconsin, Engineering Experimental Station Bull., ser. No. 71 (1930).

was corrected for potential electrode resistance. An attempt was made to obtain measurements, also, by means of a source of direct current and a potentiometer and milliammeter. A rotary, double commutating switch was used in order that the current through the ground might be alternating. Owing to the presence of self-potentials associated with the ore-body it was difficult to make these measurements accurately and the use of the method at the pyrite deposit was discontinued. The results obtained through the latter method are not presented. They were meagre, but were in general accord with the results obtained with the "megger" earth tester. Moreover, as the frequency of alternation could be changed the method served as indication of the frequencies and magnitude of the currents in the cables which could be used without incurring serious inductive effects on the distribution of potential in the ground.

In Table III are given the results of the measurements of the inter-bowl resistances, R, along lines I and II, and the calculated values of ρ derived by means of formula (1), the central current electrode being at A and the four end current electrodes being 800 feet distant from A.

In Table IV, the values of R and ρ obtained from the measurements along the north part of line II are repeated in the columns headed NESW. In the columns headed EW are given the values of R and ρ obtained when only the east and west end current electrodes were used. In the columns headed N are given the values of R and ρ when only the north end current electrode was used. The last case is that of the single electrode method. It should be noted that when either the four end current electrodes or the east and west end current electrodes were used the values of R and ρ were much the same even for the distance, b, of the remote potential electrode 300 feet away from the central electrode, whereas when only the north end current electrode was used, the values of R and ρ as calculated from formula (1), viz., $\frac{1}{\rho} = \frac{1}{2\pi R}\left(\frac{1}{a} - \frac{1}{b}\right)$, even for the distance b of 150 feet, i.e. less than one-fifth of the distance between the current electrodes, were double the values when either four or two end current electrodes were used. Even the values of ρ calculated from formula (2), viz., $\frac{1}{\rho} = \frac{1}{2\pi R}\left(\frac{1}{a} - \frac{1}{b} - \frac{1}{c} + \frac{1}{d}\right)$ and which are also given in the table, are much too high.

The values of ρ obtained by the central electrode method along line II are presented in Figure 33 with, for comparison, a vertical section (*See* Figure 32) through drill hole No. 1, 40 feet west of line II, giving the position of the ore-body inferred from the records of the mining company.

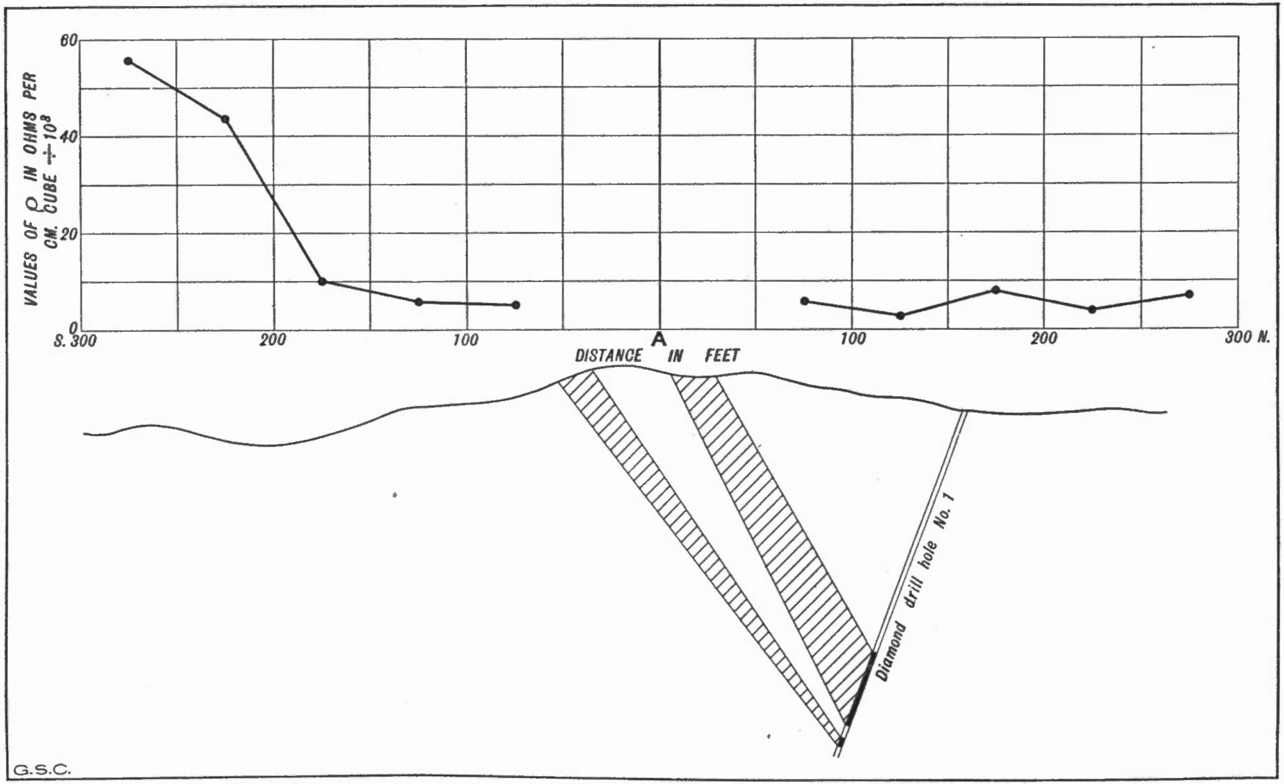

Figure 33. Values of ρ obtained along line II (Figure 32), and section along a line passing through diamond drill hole No. 1 (ore shown by solid black, assumed ore by pattern of diagonal ruling).

TABLE III
(Four end current electrodes, 800 feet distant from point A)

Stations and distances (in feet)	R_1 ohms (observed)	Correction factor for electrode resistance	R ohms (corrected)	$\rho \div 10^3$ ohms per cm. cube formula (1)
North A − 1 N (50)				
1 N − 2 N (50)	0·26	1·278	0·331	6·35
2 N − 3 N (50)	0·055	1·238	0·068	3·92
3 N − 4 N (50)	0·06	1·165	0·069	8·0
4 N − 5 N (50)	0·02	1·214	0·024	4·66
5 N − 6 N (50)	0·02	1·288	0·025	7·4
South A − 1 S (50)				
1 S − 2 S (50)	0·22	1·178	0·259	4·97
2 S − 3 S (50)	0·070	1·136	0·080	4·6
3 S − 4 S (50)	0·075	1·216	0·091	10·5
4 S − 5 S (50)	0·175	1·258	0·220	42·2
5 S − 6 S (50)	0·185	1·053	0·195	56·2
East A − 1 E (50)				
1 E − 2 E (50)	0·12	1·215	0·143	2·74
2 E − 3 E (50)	0·035	1·231	0·043	2·47
3 E − 4 E (50)	0·025	1·143	0·028	3·28
4 E − 5 E (50)	0·02	1·136	0·022	4·35
5 E − 6 E (50)	0·01	1·079	0·010	3·11
West A − 1 W (50)				
1 W − 2 W (50)	0·49	1·227	0·60	11·5
2 W − 3 W (50)	0·03	1·129	0·034	1·95
3 W − 4 W (50)	0·02	1·028	0·020	3·05
4 W − 5 W (50)	0·02	0·989	0·019	3·8
5 W − 6 W (50)	0·02	1·208	0·024	6·95

TABLE IV
(End current electrodes, 800 feet distant from point A)

Stations and distances (in feet)	R ohms (corrected)			$\rho \div 10^3$ ohms per cm. cube; formula (1)			$\rho \div 10^3$ ohms per cm. cube; formula (2)
	NESW	EW	N	NESW	EW	N	N
A − 1 N (50)							
1 N − 2 N (50)	0·331	0·342	0·343	6·35	6·6	6·72	6·65
2 N − 3 N (50)	0·068	0·055	0·135	3·92	3·21	7·84	7·58
3 N − 4 N (50)	0·069	0·058	0·116	8·0	6·67	14·0	13·0
4 N − 5 N (50)	0·024	0·024	0·06	4·66	4·66	11·65	10·12
5 N − 6 N (50)	0·025	0·025	0·064	7·4	7·4	18·5	13·70

(b) The four end current electrodes were placed 600 feet from the central current electrode and measurements of R by means of a megger were again obtained. The values of ρ were calculated from formula (1), viz., $\frac{1}{\rho} = \frac{1}{2\pi R}\left(\frac{1}{a} - \frac{1}{b}\right)$. The values of R and ρ for the south part of line II are given in Table V. Measurements of R were made with four, two, three, and one, end current electrodes in use and the results of these measurements are given in Table V under the headings NESW, NS, EW, etc.

TABLE V

(End current electrodes 600 feet distant from point A)

Stations and distances (in feet)	R, ohms (corrected)															Correction factor
	NESW	NS	EW	NE	NW	SE	SW	NSE	NSW	NEW	SEW	N	E	S	W	
A – ½ S (25).........	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	....
½ S – 1 S (25).........	3·8	3·8	3·8	3·8	3·8	3·8	3·8	3·8	3·8	3·8	3·8	3·8	3·8	3·8	3·8	1·1
1 S – 2 S (50).........	0·21	0·26	0·18	0·18	0·17	0·26	0·25	0·23	0·22	0·18	0·23	0·23	0·21	0·32	0·18	1·16
2 S – 3 S (50).........	0·086	0·12	0·065	0·06	0·032	0·15	0·12	0·11	0·086	0·043	0·11	0·043	0·086	0·196	0·06	1·09
3 S – 4 S (50).........	0·137	0·228	0·057	0·068	0·034	0·26	0·22	0·18	0·15	0·045	0·156	0·057	0·11	0·46	0·045	1·14
4 S – 5 S (50).........	0·33	0·57	0·12	0·12	0·036	0·65	0·56	0·42	0·39	0·085	0·42	0·073	0·195	1·09	0·048	1·22
5 S – 6 S (50).........	0·31	0·56	0·081	0·086	0·021	0·61	0·54	0·47	0·427	0·064	0·46	0·06	0·17	1·2	0·043	1·08
	$\rho \div 10^3$, ohms per cm. cube formula (1)															formula (2) S–end current electrode
A – ½ S (25).........	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	....
½ S – 1 S (25).........	36·5	36·5	36·5	36·5	36·5	36·5	36·5	36·5	36·5	36·5	36·5	36·5	36·5	36·5	36·5	36·13
1 S – 2 S (50).........	3·95	5·05	3·51	3·51	3·29	5·05	4·83	4·39	4·17	3·51	4·39	3·73	3·95	6·15	3·51	5·04
2 S – 3 S (50).........	5·11	7·02	3·83	3·19	1·92	8·94	7·02	6·38	5·11	2·55	6·38	2·55	5·11	11·5	3·19	10·57
3 S – 4 S (50).........	20·4	3·4	8·5	10·2	5·1	39·1	32·3	27·2	23·8	6·8	25·5	8·5	17·0	69·7	6·8	58·69
4 S – 5 S (50).........	63·7	111	23·5	23·5	7·07	127	108	84·8	75·5	16·5	84·8	14·2	37·7	212	9·4	148·4
5 S – 6 S (50).........	89·7	161	23·2	24·7	6·2	176	154	120	108	185	117	15·4	43·3	303	12·3	173·1

The values of ρ calculated from formula (1) are given under the headings NSEW, NS,EW, NE, etc., and in the last column the values of ρ as calculated from formula (2), viz., $\frac{1}{\rho} = \frac{1}{2\pi R}\left(\frac{1}{a} - \frac{1}{b} - \frac{1}{c} + \frac{1}{d}\right)$ are given. These are the corrected values for the effect of the distant end current electrode. The results in the last column are, of course, those for the case where the central electrode at A becomes the single electrode in what is known as the "single electrode method" of making measurements.

The differences between the values of R and ρ obtained when using four end current electrodes and those obtained when using three, two, or one, end electrodes, are very evident. The differences are especially pronounced for the case where A becomes a single electrode with one distant end current electrode. It will be noted that in this case either formula (1) or formula (2) is far from adequate even for the case where the value of b (the distance of the remote potential electrode from A) was only one-fifth of the distance from A to the end current electrode; for greater distances from A than this the measured values of R and the calculated values of ρ by means of formula (1) or (2) become quite misleading.

It is of interest to note that when two end current electrodes were used and measurements were made along a line at right angles to the line joining the two end current electrodes, the results did not differ as much from the results obtained when four end current electrodes were used, as did the results in the other cases, but the agreement was not nearly so good even for this case as when the end current electrodes were 800 feet distant from the central current electrode (*See* Table IV).

In Table VI are given the values of R from measurements along line II for the case where four end current electrodes were placed, respectively, north, east, south, and west of the central current electrode at point A.

TABLE VI

(Four end current electrodes 600 feet distant from point A)

Stations and distances (in feet)	R ohms (corrected)	Stations and distances (in feet)	R ohms (corrected)
A - 1 N (50)	....	A - 1 S (50)	....
1 N - 2 N (50)	0·254	1 S - 2 S (50)	0·21
2 N - 3 N (50)	0·118	2 S - 3 S (50)	0·086
3 N - 4 N (50)	0·074	3 S - 4 S (50)	0·137
4 N - 5 N (50)	0·048	4 S - 5 S (50)	0·33
5 N - 6 N (50)	0·039	5 S - 6 S (50)	0·31

As may be seen by comparing the results expressed in Tables V and III, the general trend of change in the resistivity ρ with change in distance from the central electrode is similar whether the end current electrodes are 600 or 800 feet away from the central current electrode. The values for R and ρ for any particular interbowl section obtained when the end current electrodes were 600 feet from the central current electrode cannot agree with those obtained when the end current electrodes were 800 feet distant, because measurements were not made of precisely the same interbowl sections in the two cases. However, the total measured resistances in the interbowl section 50 to 300 feet north of point A are strictly comparable, for the potential electrodes were at the same positions during the making of both sets of measurements. With end current electrodes 800 feet distant, the total resistance is 0·517 ohms (*See* Table III); with the end current electrodes 600 feet distant, the total resistance is 0·533 ohms (*See* Table VI). It is evident, therefore, that up to distances of 300 feet from the central current electrode the apparent values of R differed but slightly whether the end current electrodes were at a distance of 800 feet or 600 feet.

(c) The four end current electrodes were placed 500 feet from the central current electrode and the values of R and ρ were again obtained. The results obtained with this arrangement of the end current electrodes differed but slightly in general trend from the results obtained with the end current electrodes at either 800 feet or 600 feet from the central electrode. The effect of the end current electrodes was apparent, however, in an increase in the potential drop when the distances, b, of the remote potential electrode from the central electrode were greater than one-third of the total distance between the central electrode and the end current electrodes. Although this effect of the distant end current electrodes was fairly symmetrical about the central current electrode it was evident that the calculated results for ρ from the simple formula, viz.,

$$\frac{1}{\rho} = \frac{1}{2\pi R}\left(\frac{1}{a} - \frac{1}{b}\right)$$

would require some correction. The actual results of the measurements of R and the calculated values of ρ are not presented for this case, as similar effects are portrayed more clearly and accurately in the next case where the end current electrodes were placed at a distance of 400 feet from the central current electrode. The effect of the end current electrodes on the measurements has also already been made clear in the previous cases, where the end current electrodes were at distances of 800 feet and 600 feet, respectively, from the central current electrode.

(d) The four end current electrodes were placed 400 feet from the central current electrode. Measurements of the interbowl resistances, R, were made by means of the "megger" earth tester. The interbowl stations were approximately the same as those made use of in the cases where the end current electrodes were placed respectively 800 feet, 600 feet, and 500 feet from the central electrode. As in the previous cases it was arranged that four, three, two, or one, end current electrodes could be used at will. In the case where only one end current electrode was used the central current electrode became as before the "single electrode" in the single current electrode method. As in the previous cases, the values of ρ were calculated from formula (1), $\frac{1}{\rho} = \frac{1}{2\pi R}\left(\frac{1}{a} - \frac{1}{b}\right)$ and in the "single electrode" cases the values of ρ were also calculated from the modified formula (2), $\frac{1}{\rho} = \frac{1}{2\pi R}\left(\frac{1}{a} - \frac{1}{b} - \frac{1}{c} + \frac{1}{d}\right)$

The results for R and ρ are given in Table VII; the headings of the columns NESW, and N, indicating the end current electrodes which were in use when the measurements of R were made.

It is again apparent from Table VII that the effect of the distant current electrode on the distribution of potential on the surface of the ground and consequently on the apparent values of R and ρ is very much greater when a single current electrode is used than when a central current electrode is used, even when the modified formula (2) is used in determining ρ for the single electrode case.

TABLE VII

(End current electrodes 400 feet distant from point A)

Stations and distances (in feet)	R ohms (corrected)		$\rho \div 10^3$ ohms per cm. cube; formula (1)		$\rho \div 10^3$ ohms per cm. cube; formula (2)
	NESW	N	NESW	N	N
North					
A - 1 N (50)					
1 N - 2 N (50)	0·255	0·419	4·9	8·1	7·71
2 N - 3 N (50)	0·151	0·365	8·8	21·1	17·5
3 N - 4 N (50)	0·141	0·407	16·7	47·5	29·3
4 N - 5 N (50)	0·151	0·558	28·8	108·5	41·7
5 N - 6 N (50)	0·259	0·982	73·3		
	NESW	S	NESW	S	S
South					
A - 1 S (50)					
1 S - 2 S (50)	0·287	0·42	5·52	8·1	7·71
2 S - 3 S (50)	0·151	0·448	8·76	25·9	21·4
3 S - 4 S (50)	0·315	0·642	36·4	74·1	45·6
4 S - 5 S (50)	0·795	1·51	150·4	289	111·1
5 S - 6 S (50)	0·908	3·71	258	1062	181·3
	NESW	E	NESW	E	E
East					
A - 1 E (50)					
1 E - 2 E (50)	0·138	0·172	2·65	3·31	3·15
2 E - 3 E (50)	0·012	0·065	0·687	3·78	3·13
3 E - 4 E (50)	0·057	0·143	6·54	16·35	10·07
4 E - 5 E (50)	0·033	0·065	6·30	12·6	4·84
5 E - 6 E (50)	0·026	0·053	7·50	15·0	2·5
	NESW	W	NESW	W	W
West					
A - 1 W (50)					
1 W - 2 W (50)	0·56	0·58	10·75	11·1	10·6
2 W - 3 W (50)	0·051	0·11	2·97	5·94	4·92
3 W - 4 W (50)	0·046	0·103	5·31	11·8	7·2
4 W - 5 W (50)	0·058	0·23	11·30	44·3	17·0
5 W - 6 W (50)	1·12	4·82	320·0	1390	237·3

In Table VIII, column headed NESW, the total values of R for the section, stations 1 N to 6 N (250 feet), are given for the four cases where four end current electrodes were set 400, 500, 600, and 800 feet away from the central current electrode. In the third column headed N, are given the total values of R obtained in three cases when only the north end current electrode was used.

TABLE VIII

Distance of end current electrodes from central electrode	R, ohms, section 1 N to 6 N	
	NESW	N
Feet		
800	0·517	0·718
600	0·533	....
500	0·647	1·435
400	0·957	2·731

In the experiments the stations of the potential electrodes at 50 feet and at 300 feet were not in precisely the same place in all four cases. This, together with other small sources of experimental error, would account for only small differences in the values of R and consequently in the values of ρ, much smaller than the differences shown in the table. It is, therefore, evident that the simple formula for calculating ρ is inadequate even in the central electrode method, at least for distances from the central electrode greater than one-half the distance between the central and the end current electrodes.

(e) Eight end current electrodes were placed 400 feet from the central current electrode. They were placed, respectively, north, northeast, east, southeast, south, southwest, west, and northwest of the central current electrode (*See* Figure 34). All current and potential electrodes were placed in carefully measured positions and were kept in a fixed position and it was arranged by means of switches that all measurements could be made without disturbing the electrodes and still any number of end

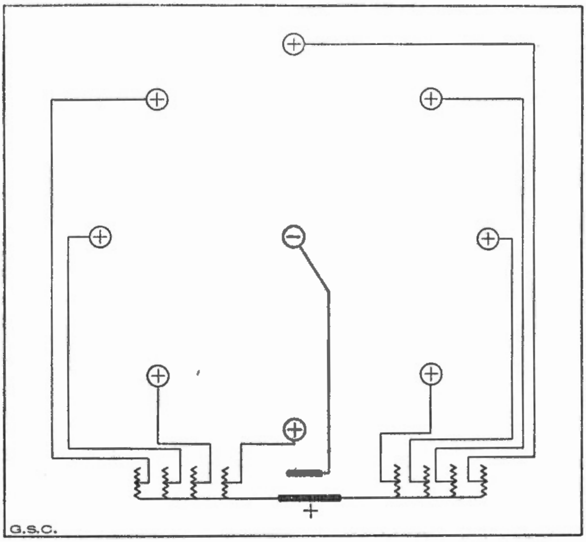

Figure 34. Arrangement for central electrode method.

current electrodes from one to eight could be used at will. Measurements of R were made along the south part of line II, first with four and then with eight end current electrodes in use. The potential electrodes were placed along the line at carefully measured distances from the central electrode, of 25, 50, 100, 150, 200, 250, and 300 feet, and all were left in position during both sets of measurement.

Instead of measuring R for successively adjacent interbowl sections, the potential electrode nearest the central current electrode, that is, 25 feet distant from the central current electrode, was used throughout as one of the potential electrodes. By this means the distance a remained constant and the distance b became successively 50 feet, 100 feet, 150 feet, 200 feet, 250 feet, and 300 feet. The values obtained for R by the successive measurements are shown in Tables IX and X in which several of the sets of values are from two distinct sets of observations. The headings of the columns give the end current electrodes used.

The values of R were the same when eight, viz., N, E, S, W, NE, SE, SW, and NW, or four, viz., N, E, S, W, end current electrodes were used for all distances of b up to 250 feet and for the distance, b = 300 feet, differed by less than 5 per cent. Apparent slight discrepancies with the results in Table VII are of no significance since the potential stakes could not be placed in precisely the same places in the two cases.

The effect of the distant end current electrodes is clearly seen by comparing the values of R when eight, six, and two (N and S) end current electrodes were used and when two end current electrodes E and W were used. The differences can hardly be ascribed to inductance effects due to currents in the cables, especially as these currents were very small.

The increase in the effect on the apparent values of R of the distant end current electrode when the central current electrode became a single current electrode is shown by the values in the columns headed N and S compared with those in the other columns.

A comparison of the values of R given in the columns headed NS, N, and S for the two sets (Tables IX and X) shows how closely the results corresponded in successive sets of measurements and thus indicates how accurately instrumental readings could be repeated.

TABLE IX

Stations and distances (in feet)	R, ohms				
	8 N, E, S, W, NE,SE,SW, NW	2 N, S	6 E, W, NE, SE, SW, NW	1 N	1 S
A – ½ S (25)					
½ S – 1 S (25)	3·45	3·45	3·45	3·45	3·45
½ S – 2 S (75)	3·81	3·86	3·76	3·69	3·98
½ S – 3 S (125)	4·00	4·28	3·96	3·75	4·76
½ S – 4 S (175)	4·04	4·71	3·92	3·69	5·81
½ S – 5 S (225)	4·91	6·11	4·36	3·72	8·81
½ S – 6 S (275)	5·68	8·21	4·74	3·66	12·59

TABLE X

Stations and distances (in feet)	R, ohms				
	4 N, E, S, W	2 N, S	2 E, W	1 N	1 S
A – ½ S (25)					
½ S – 1 S (25)	3·45	3·45	3·45	3·45	3·45
½ S – 2 S (75)	3·76	3·86	3·64	3·69	3·98
½ S – 3 S (125)	3·96	4·28	3·75	3·75	4·76
½ S – 4 S (175)	4·04	4·76	3·65	3·69	5·81
½ S – 5 S (225)	4·91	6·11	3·60	3·66	8·81
½ S – 6 S (275)	5·92	8·21	3·61	3·71	12·59

(f) Measurements of R by means of a milliammeter potentiometer and rotary double reversing key were again made use of and the difficulties that had been met with previously due to self potentials associated with the ore-body were largely overcome by using higher applied potential differences between the potential electrode stations. The apparent values of R were consistently higher than those obtained with the megger, probably due to the diminished currents owing to the insulating sections in the slip rings of the double reversing key. However, the sequence of values of R for successive interbowl sections correspond in the two sets of measurements. The speed of the double reversing key was about 10 to 20 per second and it was found that the measurements were but slightly affected by these changes in speed and to the same extent indeed whether measurements were made along the direction in which current cables were placed or in a direction at right angles. This indicates again that inductive effects due to the presence of the cables were negligibly small.

Measurement of the Average Resistivity by the Wenner Method

(a) While measurements were being made at the point A by the central electrode method, it was arranged that measurements could also be made by the Wenner method for depths α of one-third of 1,600 feet, 1,300 feet, 1,000 feet, and 800 feet, respectively, both along the north-south and east-west lines. The measured values of R and the calculated values of ρ from the formula $\frac{1}{\rho} = \frac{1}{2\pi R}\frac{1}{\alpha}$ are given in Table XI. The lowest depth used was one-third of 800 feet, i.e. 266·6 feet. The greatest depth for which ρ was obtained by the central electrode method was for the interbowl section 250 feet to 300 feet. The values of ρ for the north-south and east-west lines obtained by the central electrode method are also given in Table X for comparison. It is apparent that the good conductor (probably the ore-body) extends much farther along the east-west direction than was explored by the central electrode method. Even in the north-south direction the average resistivity is low and the increase with depth is not pronounced, though for all depths the average resistivity is at least tenfold greater than that in the east-west direction. A quantitative comparison of the values of ρ by the Wenner method and by the central electrode method cannot be made satisfactorily, for owing to the presence of the ore-body the Wenner formula $\frac{1}{\rho} = \frac{1}{2\pi R}\frac{1}{\alpha}$ is probably inadequate as it was developed for a uniform homogeneous conducting body.

TABLE XI

Current electrode stations and distances (in feet) north and south of point A	Potential electrode stations; distances (in feet) north and south of point A	α	R, ohms (corrected value)	$\rho \div 10^3$, ohms per cm. cube		
					5 N – 6 N Table III	5 S – 6 S Table III
8 N – 8 S (400)	133·3	266·6	1·44	73·4	7·4	56·2
10 N – 10 S (500)	166·6	333·2	1·04	66·3	....	....
12 N – 12 S (600)	200·0	400·0	1·17	89·3	....	....
16 N – 16 S (800)	266·6	532·2	1·37	140·4	....	....

Current electrode stations and distances (in feet) east and west of point A	Potential electrode stations; distances (in feet) east and west of point A	α	R, ohms (corrected value)	$\rho \div 10^3$, ohms per cm. cube		
					5 E – 6 E Table III	5 W – 6 W Table III
8 E – 8 W (400)	133·3	266·6	0·199	10·20	3·11	6·95
10 E – 10 W (500)	166·6	333·2	0·080	5·10	....	....
12 E – 12 W (600)	200·0	400·0	0·129	9·95	....	....
16 E – 16 W (800)	266·6	532·2	0·138	13·40	....	....

MEASUREMENT OF AVERAGE RESISTIVITY ρ ALONG THE LINE III CROSSING THE LINE I AT THE POINT C (*See* Figure 31)

It has been shown that in a region where uniformity of conductivity does not exist, the measured values of R and the calculated values of ρ as obtained by the single electrode method, even by the means of the modified formula $\frac{1}{\rho} = \frac{1}{2\pi R}\left(\frac{1}{a} - \frac{1}{b} - \frac{1}{c} + \frac{1}{d}\right)$, are unsatisfactory, especially at some distance from the single current electrode. For purposes of comparison measurements were made along the line III by the single electrode method and also by the Wenner method. The two current electrodes were placed 900 feet apart. For measurements by the Wenner method the two potential electrodes were placed respectively 300 feet and 600 feet south from the north current electrode. For measurements by the single electrode method the two potential electrodes were placed 250 feet and 300 feet south, respectively, from the north current electrode. The first measurements were made with the north current electrode 150 feet south of point C and the south current electrode 1,050 feet south of point C, then the layout was moved north along the line III in successive stages of 50 feet until the north current electrode was 600 feet north of the point C. The values of R and ρ obtained are given in Table XII. In the case of those obtained by the Wenner method ρ was calculated from the Wenner formula $\frac{1}{\rho} = \frac{1}{2\pi R}\frac{1}{\alpha}$ where α = 300 feet. In the case of those obtained

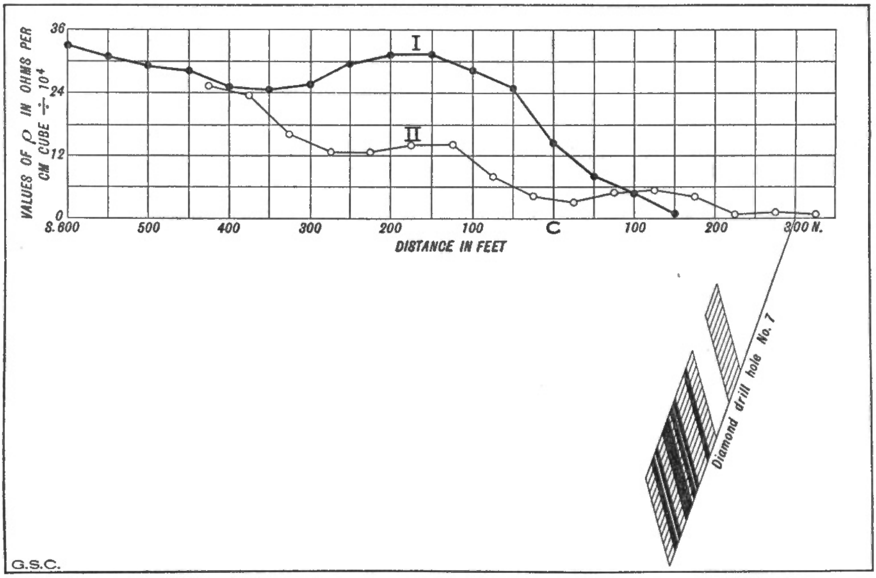

Figure 35. Values of ρ obtained along line III (Figure 32): I by Wenner method, II by single electrode method, and projection (on vertical plane containing line III) of diamond drill hole No. 7 (ore shown by solid black, disseminated ore and some barren rock by pattern of diagonal ruling). Note: The interbowl sections used in the two methods are not coincident but follow in succession. The values of ρ are, therefore, different except for sections: (a) at a distance from the ore-body where the conductivity is uniformly low; and (b) where the good conducting ore-body exists in both interbowl sections and dominates the conductivity.

by the single electrode method, ρ was calculated from the formula $\frac{1}{\rho} = \frac{1}{2\pi R}\left(\frac{1}{a} - \frac{1}{b} - \frac{1}{c} + \frac{1}{d}\right)$. The values of ρ from both methods are also presented in Figure 35. On this figure there is also shown a vertical section through drill hole No. 7 on a line parallel and close to line III.

TABLE XII

(Stations are 50 feet apart and are numbered consecutively north (1 N, 2 N, etc.) and south (1 S, 2 S, etc.) from point C)

Current electrode stations	Wenner method			Single electrode method		
	Potential electrode stations	R, ohms (corrected value)	$\rho \div 10^4$ ohms per cm. cube	Potential electrode stations	R, ohms (corrected value)	$\rho \div 10^4$ ohms per cm. cube
21 S – 3 S	9 S – 15 S	5·8	33·3	8 S – 9 S	1·04	25·04
20 S – 2 S	8 S – 14 S	5·47	31·4	7 S – 8 S	0·98	23·59
19 S – 1 S	7 S – 13 S	5·08	29·0	6 S – 7 S	0·66	15·88
18 S – 0	6 S – 12 S	4·83	27·7	5 S – 6 S	0·50	12·04
17 S – 1 N	5 S – 11 S	4·33	24·9	4 S – 5 S	0·50	12·04
16 S – 2 N	4 S – 10 S	4·22	24·2	3 S – 4 S	0·57	13·72
15 S – 3 N	3 S – 9 S	4·4	25·2	2 S – 3 S	0·57	13·72
14 S – 4 N	2 S – 8 S	5·06	29·1	1 S – 2 S	0·32	7·70
13 S – 5 N	1 S – 7 S	5·45	31·3	0 – 1 S	0·192	4·57
12 S – 6 N	0 – 6 S	5·55	31·9	1 N – 0	0·139	3·37
11 S – 7 N	1 N – 5 S	4·88	28·0	2 N – 1 N	0·208	5·05
10 S – 8 N	2 N – 4 S	4·31	24·7	3 N – 2 N	0·23	5·53
9 S – 9 N	3 N – 3 S	2·52	14·6	4 N – 3 N	0·20	4·81
8 S – 10 N	4 N – 2 S	1·55	8·9	5 N – 4 N	0·077	1·85
7 S – 11 N	5 N – 1 S	0·84	4·8	6 N – 5 N	0·08	1·88
6 S – 12 N	6 N – 0	0·25	1·4	7 N – 6 N	0·077	1·85

It is apparent from Table XII and from Figure 35 that the results of the measurements of average resistivity by either the Wenner method or the single electrode method diminish greatly as approach is made to the region in which the ore-body exists and the gradient of change is similar in the two cases. Now it may be recalled that in the results obtained at the point A, along line II, by the single electrode method, the values of the average resistivity in the region containing the ore-body, i.e. on the north side of line I, were very much lower than the values of the average resistivity on the south side of line I, i.e. in a direction away from the ore-body. In these two sections, i.e. through the point A and through the point C, there is, therefore, general agreement. However, from the results at the point A along line II it was also shown that the use of the formula which has been deduced for a homogeneous conducting medium, viz., $\frac{1}{\rho} = \frac{1}{2\pi R}\left(\frac{1}{a} - \frac{1}{b} - \frac{1}{c} + \frac{1}{d}\right)$ for the calculation of ρ was quite inadequate and likely to be misleading, and it was pointed out that the presence of the good conducting body and consequent lack of homogeneity rendered the formula inadequate. From the results obtained along line III it is, therefore, probable that the formula used with the Wenner method, viz., $\frac{1}{\rho} = \frac{1}{2\pi R}\,\frac{1}{\alpha}$, which also has been deduced for a homogeneous conducting method, is also inadequate. The resistivity obtained by the single electrode method for the interbowl section with northern rims at 6N and 7N is quite low. This would indicate a good conducting body north and east of that located by the drill hole. The measurements are, however, too meagre to warrant more than the suggestion that further explorations in north and east directions would be desirable.

A very interesting feature of the two sets of results should be carefully noted. The interbowl sections used in the Wenner method differ greatly in shape from the interbowl sections used in the single electrode method and follow them in immediate succession as progress is made along line III. The values of ρ obtained by both methods should be the same only if the material of the interbowl sections is the same or if an extensive good conducting material exists in both interbowl sections and, therefore, dominates the conductivity. A study of Figure 35 shows that the values of ρ were the same at a considerable distance from the ore-body where the material was presumably fairly homogeneous and also in the immediate neighbourhood of the ore-body where the highly conducting material was effective in both interbowl sections. It is evident, therefore, that there are decided advantages in carrying out both sets of measurements in this way.

Measurement of the Average Resistivity with Central Electrode in Drill Hole No. 7 and at the Ore-body about 275 Feet Below the Surface

The west end current electrode was placed at the point A 600 feet west of the point D (*See* Figure 32). The east, south, and north end current electrodes were placed about 600 feet distant from the point D. Measurements were made by placing one potential electrode at the point D and the other potential electrode successively at stations 50 feet, 100 feet, 150 feet, 200 feet, 250 feet, 300 feet, 350 feet, and 400 feet from the point D along the east, south, west, and north lines. The results of this experiment are not presented; they were too meagre and, therefore, difficult of interpretation. It is probable that the fixed potential electrode would have been in a more suitable position if it had been placed in drill hole 7 about 25 feet above the central current electrode.

Electrical Probing of Drill Hole No. 7

Two current electrodes were used. One current and one potential electrode were joined together and placed at the point A (Figure 32). The second current electrode and the second potential electrode were joined together and gradually lowered into drill hole No. 7. The resistance was measured with a megger. Two sets of measurements were made.

(a) Insulating tape was wrapped about the current electrode in the drill hole so that it could not come in contact with the wall of the drill hole. The end of the electrode made contact, however, with the water in the drill hole. The current thus passed from the end of the electrode through the water in the drill hole to the wall of the drill hole.

(b) The insulating tape was removed and a heavy piece of iron was attached to the end of the current electrode so that it would make good contact with the wall of the drill hole.

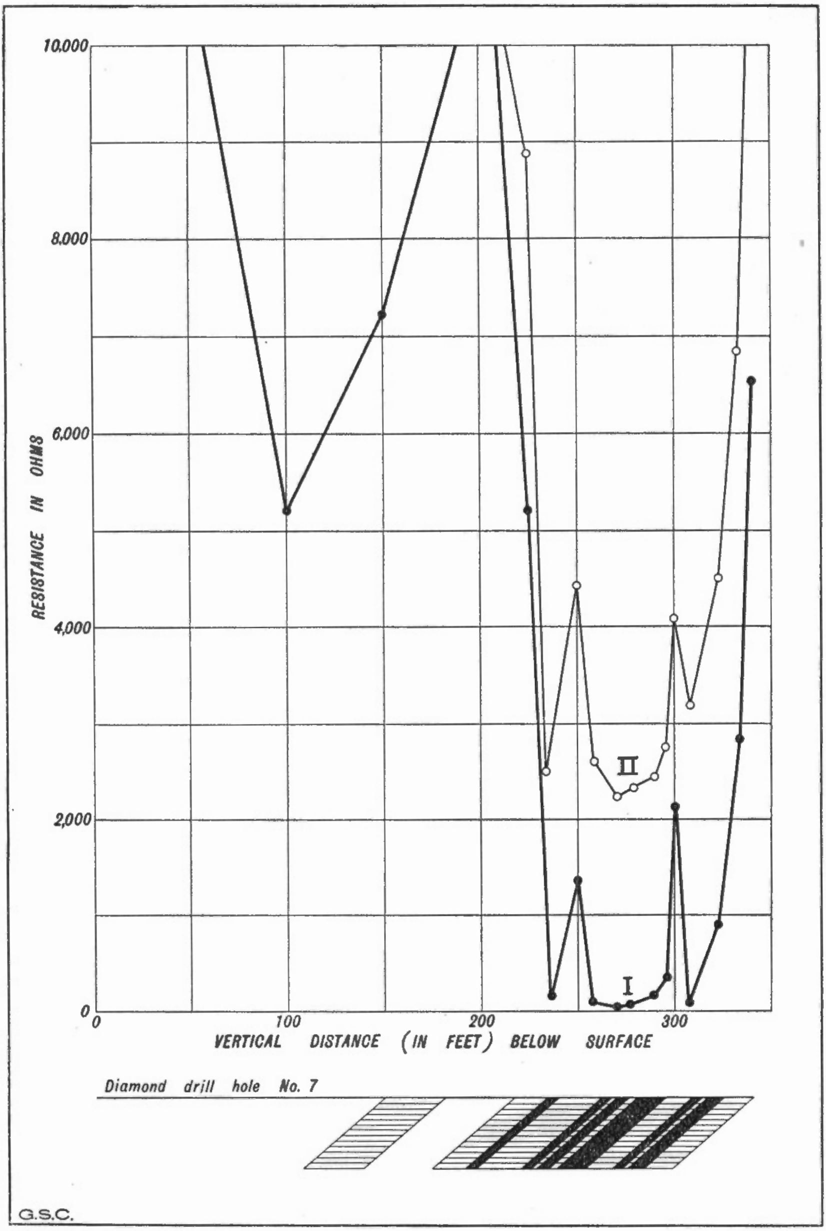

Figure 36. Values of R obtained in diamond drill hole No. 7 (I, by direct contact with wall of hole; II, without direct contact with wall of hole), and section along diamond drill hole (ore shown by solid black; disseminated ore and some barren rock by pattern of horizontal ruling).

The results of both sets of measurements are given in Table XIII and are also shown on Figure 36. The differences in the values of the resistance in case *(a)* indicate approximately the respective positions of rock and ore as given in the log of the drill hole. In case *(b)* the resistances are much lower than in case *(a)* and where the electrode made contact with the ore the resistance fell to a very low value indeed. Moreover, the changes in the values of the resistance corresponded very closely with changes from rock to disseminated ore and to rich ore as given by the log of the drill hole.

The results indicate strongly a use that might be made of drill holes in investigating the conductivity of the adjacent region. If, for example, at the bottom of the drill hole a central current electrode be placed and a set of systematically situated end current electrodes of equal resistance be arranged on the surface of the ground then the centre of potential on the surface of the ground for this system may be obtained readily by the usual equipotential method. If, now, the central current electrode be transferred to the centre of potential and an electrode at the bottom of the drill hole be connected in parallel with the end current electrodes and be of equal resistance with each of the other end current electrodes then the distribution of conductivity in the region adjacent to the drill hole may be obtained in the ordinary way.

TABLE XIII

Vertical to depths to points at which measurements were made	R, ohms		Vertical to depths to points at which measurements were made	R, ohms	
	Set a	Set b		Set a	Set b
50	29,680	20,492	275	2,328	120
100	10,560	5,200	285	2,528	210
150	11,600	7,244	295	2,766	290
200	27,280	23,440	300	4,016	2,105
225	8,800	5,248	310	3,150	150
235	2,590	200	320	4,530	960
250	4,328	1,410	330	6,880	2,864
260	2,640	120	340	14,100	6,560
270	2,200	100			

INVESTIGATIONS AT THE FALCONBRIDGE MINE

Resistivity Measurements Across a Dyke

At the request of Professor A. S. Eve, Professor D. A. Keys, and Dr. F. W. Lee, resistivity measurements were made across a dyke whose existence had been indicated by magnetic measurements carried out by these investigators. The data associated with the resistivity measurements are presented on pages 88-92 of this report.

Resistivity Measurements Across the Falconbridge Pyrrhotite Deposit

In the summer of 1929 a very brief investigation had been made of the resistivity in the neighbourhood of the Falconbridge ore-body. A central electrode had been placed at point B, Figure 37, and two end

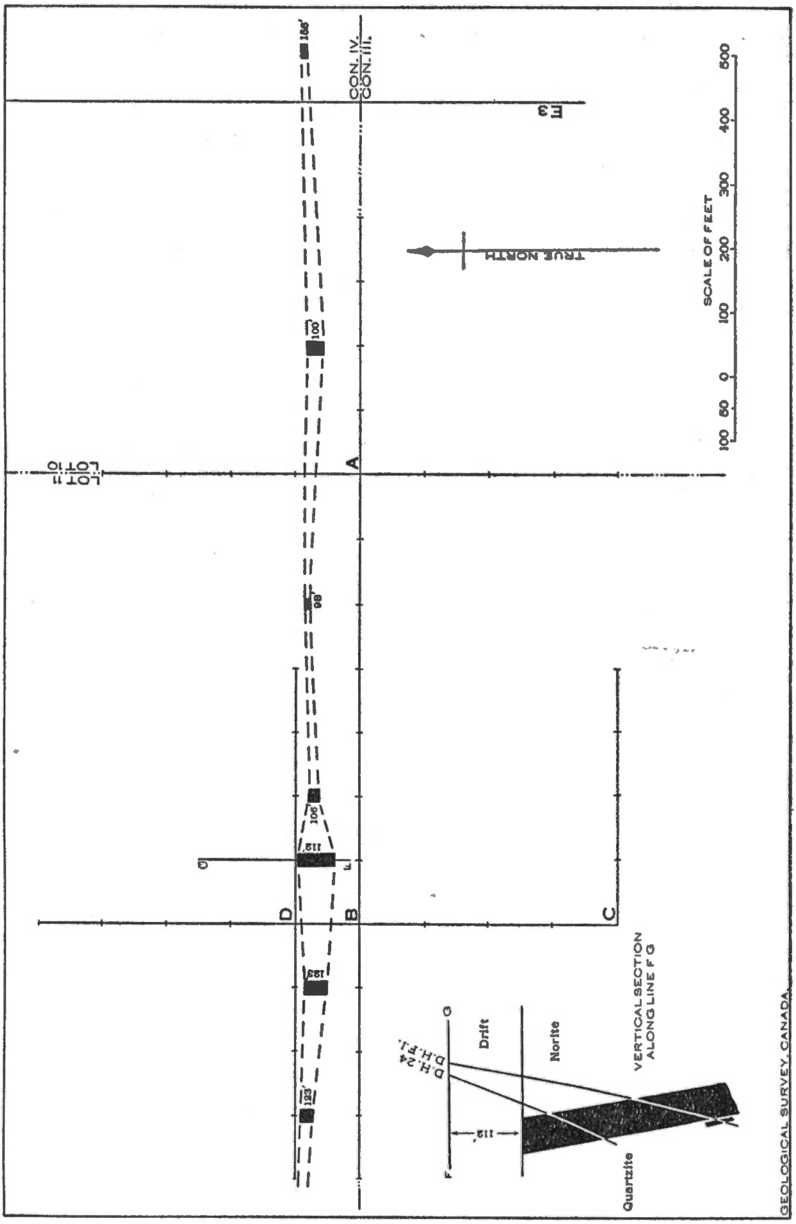

Figure 37. Plan and vertical cross-section of Falconbridge ore-body.

current electrodes were placed at a considerable distance east and west of B. A direct current was used and a milliammeter and a potentiometer with a hand reversing switch were used in order to obtain the resistance. A few measurements were made along the north-south line passing through B. The results of these measurements had been presented in Memoir 165, pages 179-188.

It appeared desirable to extend the investigations. A central electrode was placed at the point B and four end current electrodes were placed north, south, east, and west of the central current electrode and at a distance of 600 feet from it. Potential electrode stations were arranged along the north, south, east, and west lines at intervals of 50 feet.

The values of the interbowl resistance R measured by means of the megger and the calculated values of ρ from the formula

$$\frac{1}{\rho} = \frac{1}{2\pi R}\left(\frac{1}{a} - \frac{1}{b}\right)$$

are presented in Table XIV. Values of interbowl resistance R were also determined from the measurements of potential fall with a potentiometer and of current with a milliammeter, a double rotating commutating key being placed in the circuit. The self potentials in this region were not sufficient to interfere seriously with the measurements by this method and the resulting corrected values of R agreed fairly closely with those obtained with the megger. In Table XV are presented the values of R obtained with the two sets of instruments on the east and west lines.

TABLE XIV

Stations and distances (in feet)	R, ohms (corrected value)	$\rho \div 10^4$ ohms per cm. cube	Stations and distances (in feet)	R, ohms (corrected value)	$\rho \div 10^4$ ohms per cm. cube
North of B			East of B		
B – ½ N (25)			B – ½ E (25)		
½ N – 1 N (25)	100·2	96·4	½ E – 1 E (25)	108·0	103·0
1 N – 2 N (50)	39·1	75·0	1 E – 2 E (50)	31·1	59·6
2 N – 3 N (50)	7·3	42·0	2 E – 3 E (50)	6·42	37·0
3 N – 3½N (25)	1·8	37·2	3 E – 3½E (25)	1·46	29·5
3½N – 4 N (25)	0·885	23·6	3½E – 4 E (25)	1·09	29·2
4 N – 4½N (25)	0·823	28·3	4 E – 4½E (25)	0·64	22·1
4½N – 5 N (25)	0·451	19·4	4½E – 5 E (25)	0·47	20·3
5 N – 6 N (50)	0·687	19·7	5 E – 6 E (50)	0·81	23·2
6 N – 8 N (100)	1·22	28·0	6 E – 8 E (100)	1·06	24·4
South of B			West of B		
B – ½ S (25)			B – ½ W (25)		
½ S – 1 S (25)	131·5	126·0	½ W – 1 W (25)	107·0	102·4
1 S – 2 S (50)	39·1	73·8	1 W – 2 W (50)	35·1	68·1
2 S – 3 S (50)	7·3	42·7	2 W – 3 W (50)	6·69	38·4
3 S – 3½S (25)	1·36	27·6	3 W – 3½W (25)	....	....
3½S – 4 S (25)	1·03	27·8	3½W – 4 W (25)	1·09	28·9
4 S – 4½S (25)	0·973	33·5	4 W – 4½W (25)	0·61	21·1
4½S – 5 S (25)	0·565	24·2	4½W – 5 W (25)	0·44	18·9
5 S – 6 S (50)	1·06	30·4	5 W – 6 W (50	0·68	19·5
6 S – 8 S (100)	1·54	35·6	6 W – 8 W (100)	1·24	28·3
			8 W – 9 W (50)	0·49	16·3

TABLE XV

Stations and distances (in feet)	R, ohms		Stations and distances (in feet)	R, ohms	
	Measured by megger	Measured by potentiometer and milliameter		Measured by megger	Measured by potentiometer and milliameter
East of B			West of B		
B – 1 E (50)			B – ½ W (25).....		
1 E – 2 E (50)........	31·1	32·8	½ W – 1 W (25).....	1·07	1·01
2 E – 3 E (50)........	6·42	6·05	1 W – 2 W (50).....	35·1	35·5
3 E – 3½E (25)........	1·46	1·65	2 W – 3 W (50).....	6·69	....
3½E – 4 E (25)........	1·09	1·00	3 W – 3½W (25).....	....	1·73
4 E – 4½E (25)........	0·64	0·523	3½W – 4 W (25).....	1·09	1·07
4½E – 5 E (25)........	0·47	0·519	4 W – 4½W (25).....	0·61	0·70
5 E – 6 E (50)........	0·81	0·69	4½W – 5 W (25).....	0·44	0·55
6 E – 8 E (100).......	1·06	1·07	5 W – 6 W (50).....	0·68	0·60
			6 W – 8 W (100)....	1·24	1·30

The overburden in the region investigated was dry and sandy and the resistivity near the surface was very high and gradually diminished with depth. It might be expected that as the bowl sections approached the rock there would be a gradual increase in the resistivity, an effect, however, which would be greatly lessened wherever a considerable body of ore was included. That is, where ore was present the average resistivity would decrease rapidly. Since the ore lies a little north of point B, the effect would be more pronounced in the results of measurements along the north line than along the south line. It is indeed a little more in evidence in the measurements along the north line (*See* Table XIV), but there is neither a rapid increase nor a rapid decrease in resistivity evident in any direction. This would suggest that there is not a sharply defined contact of rock and ore-body nor a continuous extensive conductor in any direction, but that instead the conductor is in lenses. An examination of the cores from drill hole Nos. F, 1,100 feet west of the north-south line, and from two other nearby holes F2 and F3, showed that a disseminated condition existed. The resistivities of specimens from the cores were measured in the laboratory and the results are given in Table XVI. These results indicate an obvious explanation of the values of resistivity given in Table XIV.

TABLE XVI

Diamond drill hole	Depth below surface (in feet)	Nature of specimen	ohms per cm. cube
F 1..................................	380 – 406	Ore..........................	÷ 0·034
F 1..................................	420	Rock........................	$7 \cdot 2 \times 10^6$
F 1..................................	423	Ore..........................	0·034
F 1..................................	below 430	Rock and disseminated ore.	÷10
F 2..................................	150	Rock with sulphides.........	$2 \cdot 7 \times 10^6$
F 2..................................	212	Disseminated ore...........	$0 \cdot 85 \times 10^6$
F 2..................................	231·5	Ore..........................	0·12
F 2..................................	below 280	Rock and disseminated ore.	÷10^7
F 3..................................	0 – 236	Rock and disseminated ore.	÷10^7
F 3..................................	231	Ore..........................	0·052
F 3..................................	249	Ore..........................	0·031
F 3..................................	below 278	Disseminated ore and rock.	÷10^7

It is suggested that the region in which the Falconbridge ore-body is located would be highly suitable for an investigation with a central line electrode method rather than with a central point electrode method. A central line electrode would be placed parallel to the strike and fairly close to the position of the known ore-body, but extending much beyond it, and distant line electrodes would be placed one on each side of the central electrode and parallel to it. As in the central electrode method, the resistance of the end line electrodes should be equalized and the resistance of the central line electrode uniformly distributed in order that symmetry would be provided. Measurements of the distribution of potential or the resistivities at regular intervals along a series of lines at right angles to the line electrodes should give fairly definite indications of the positions of good conductivity portions and should also indicate the regions where discontinuities of the ore-bodies or disseminated ore conditions existed.

INVESTIGATIONS IN THE ONAKAWANA LIGNITE FIELD, ABITIBI RIVER, ONTARIO

The investigation was carried out under the auspices of the Department of Mines of the province of Ontario with the co-operation of the Geological Survey and the Ontario Research Foundation.

The investigating party comprised Mr. J. T. Wilson, student assistant, Geological Survey, Mr. R. H. Hawkins of the staff of the Ontario Research Foundation, and the writer. The progress of the investigation was also facilitated by the assistance in the field of Mr. R. H. Crozier and the staff at the Onakawana lignite field. The expenses of transportation and living associated with the investigation were borne by the Department of Mines of the province of Ontario.

A preliminary laboratory examination of the resistivity of specimens of the materials from the region was made. Specimens as nearly as possible in the same condition as they existed in place were obtained by Dr. W. S. Dyer of the Department of Mines, Ontario. The measurements of resistivity were made by Dr. A. E. R. Westman and Mr. R. H. Hawkins of the Research Foundation in the laboratory of the Department of Physics, University of Toronto. A summary of the results of these measurements on muskeg, clay, and lignite is presented in Table XVII. From the table it is seen that although the muskeg is a better conductor than the clay it is a poorer conductor than the wet lignite. The results of the measurements indicated the possibility of successfully applying electrical methods in the field to determine the position of the lignite, if the upper layer of muskeg were not sufficiently conductive to act as a screen preventing the penetration of the electrical current to the deeper layers of overburden and to the lignite.

TABLE XVII

Specimen	Resistivity, ohms per cm. cube
Water shaken with a portion of clay	$\doteq 4440$
Muskeg saturated with water	$\doteq 8950$
Boulder clay from shaft No. 1, typical of clay in contact with lignite	$\doteq 11000$
Wet lignite	$\doteq 900$
Lignite dried to the crumbling point	$\doteq 3800$
Silt from a depth of 2 feet in shaft No. 7	$\doteq 1880$
Silt from a depth of 4 feet in shaft No. 7	$\doteq 7620$
Boulder clay from shaft No. 1	$\doteq 2500$
Marine clay from shaft No. 1	$\doteq 2500$
Fire clay from shaft No. 1	$\doteq 1880$

The investigation was of special interest for the following reasons:

(1) The deposit of lignite is in the form of an extensive, almost horizontal, layer covered by horizontal layers of clay and muskeg. High resistivity materials such as dry sand are absent and rock is some distance below the layer of lignite. In these respects the conditions differed greatly from the regions containing the deposits that were previously investigated. It is the type of deposit contemplated in the theoretical papers of Hummel, and others, and more recently of Bardeen and Peters, in which the conclusion is reached that changes in conductivity could not be correlated definitely with the boundaries of successive layers. In these theoretical discussions the successive layers are treated as simple, continuous conductors carrying electrical current, in much the same way as metallic conductors, in which case a condition of refraction or sudden change in the lines of flow or the lines of equipotential at the boundaries of successive layers does not exist. This condition also implies the non-existence of sudden changes in drop of potential on the surface of the ground outward from the single current electrode, and also a distribution of potential about a single current electrode in what is known as the "single electrode method" of investigation that diverges greatly from a condition of symmetrical distribution as distances from the single current electrode are increased. Our previous investigations have at least shown that where there are pronounced changes in conductivity in underlying materials at depth there are corresponding rapid changes in the drop in potential at the surface of the ground. Moreover, in many cases, e.g. the pyrite deposit, there was a fair correlation between the rapid changes in potential and the location of the existing underground materials. Further, it has been found generally that the distribution of potential about the single current electrode was much more nearly symmetrical than could be expected if the conduction was of such a character as is to be found in simple continuous conductors like metal conductors. This would imply the existence in the materials of the earth of discontinuities and a scattering or dispersion of the electrical currents, which does not exist in simple metallic conduction and which has not been contemplated in any of the theoretical investigations to which reference has been made. The strong probability of the existence of both of these conditions owing to the character of the material in the lignite region greatly enhanced interest in the investigation.

(2) The muskeg on the surface and the lignite at depth were quite wet, while the intervening clay was hard and comparatively dry. From Table XVII it is seen that although the muskeg is a better conductor than the underlying clay it is a poorer conductor than the wet lignite, i.e. there is a poor conducting layer between two comparatively good conducting layers. It was hoped that this condition, in conjunction with the property of dispersion of currents, if these conditions existed generally, might be sufficient to ensure that the results of resistivity measurements would indicate approximately the location of the lignite.

The investigating party left for the field on Monday, August 11, and returned on Monday, August 25, the actual time in the field was from Thursday, August 14, until Friday, August 22. Measurements were made at the following points:

(a) At drill hole No. 29 where two layers of lignite 11 and 20 feet thick, respectively, are known to exist under an overburden of about 74 feet.

(b) At drill hole No. 23 where lignite is absent but where Cretaceous clay exists below a depth of 112 feet.

(c) At drill hole No. 10 where lignite 36 feet thick exists under an overburden of about 61 feet.

(d) At a point 400 feet west of drill hole No. 10, where the depth of overburden is apparently greater than at drill hole No. 10 as indicated by the logs of neighbouring drill holes.

(e) At a point 800 feet west of drill hole No. 10 where the depth of overburden is apparently still greater, as indicated by the logs of neighbouring drill holes.

Values of resistivity were obtained from the results of measurements of interbowl resistances R, using the "megger" earth tester and also the potentiometer and milliammeter. Both the central electrode and the single electrode methods were used. The arrangement for the central electrode method consisted of a central electrode and four symmetrically placed end current electrodes. The end current electrodes were placed at distances of 800 feet, 400 feet, and 300 feet, but the measurements of the interbowl resistances, R, remained much the same. An illustration of this fact is present in Table XVIII, giving the results of measurements at drill hole No. 10. In this case the measurements were made along the north line. The values of R were obtained with a "megger" earth tester with the end current electrodes at 800 feet and at 400 feet from the central electrode. The values of ρ were also calculated (using the formula, $\frac{1}{\rho} = \frac{1}{2\pi R}\left(\frac{1}{a} - \frac{1}{b}\right)$ from the values of R obtained with the potentiometer and milliammeter, and, as shown in Table XVIII, agree approximately with those obtained with a "megger." The measurements of R with the potentiometer and milliammeter for the interbowl sections remote from the central current electrode are much more accurate than those with the "megger," as these values of R were very small, in fact less than 1 ohm and there is considerable margin of error in the readings of the "megger" for these magnitudes. The results of measurement at drill hole 10 are also presented in Figure 38.

It was found, further, that the results from the single electrode method with the current stakes separated by at least 400 feet did not differ from the results obtained with the central electrode method at least to a distance b, for the remote potential electrode, of 200 feet from the central electrode. Because of this subsequent measurements were made chiefly by the single current electrode method and in general were made along lines in the directions north, south, east, and west from the single current electrode.

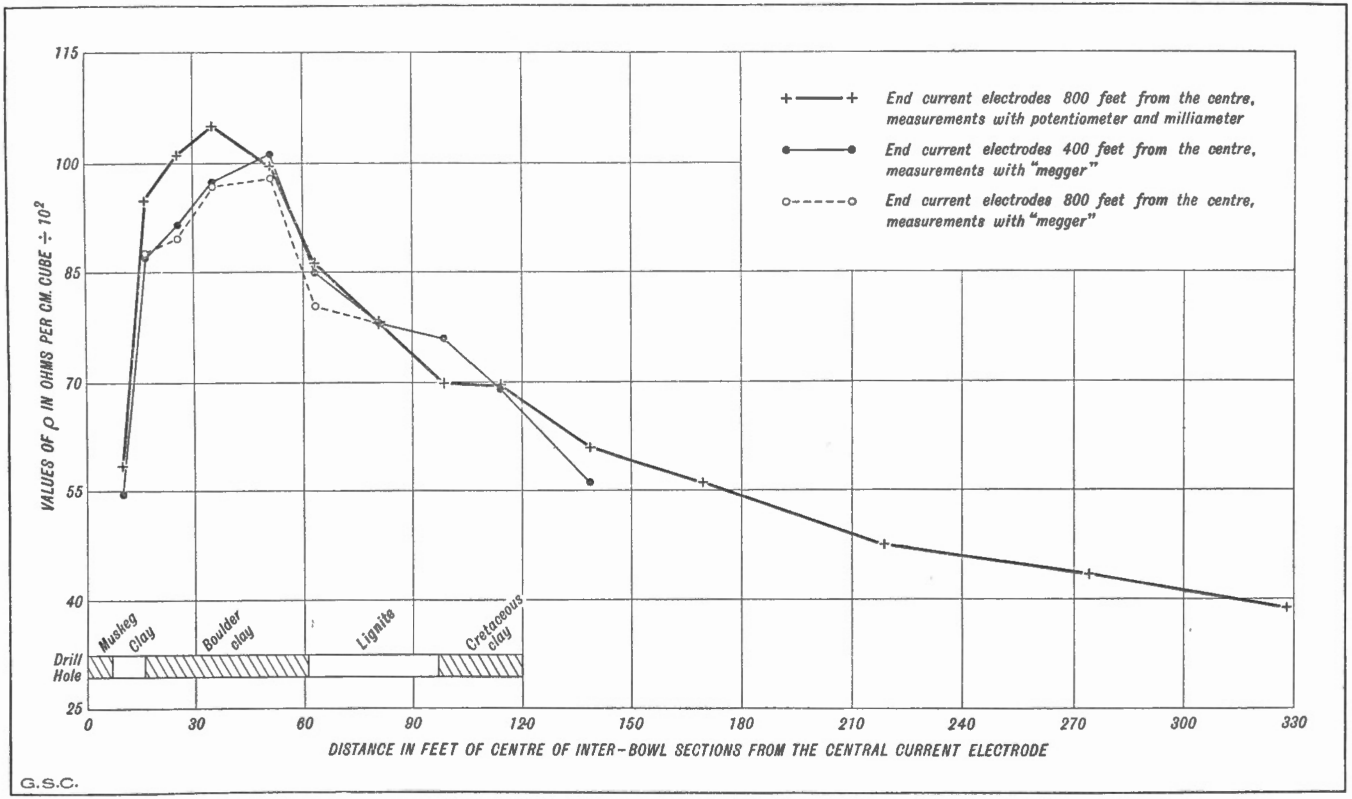

Figure 38. Values of ρ obtained on line north of central electrode at drill hole No. 10.

TABLE XVIII

Potential electrode stations	Measurements with megger				Measurements with potentiometer and milliammeter	
	End current electrodes 400 feet from centre		End current electrodes 800 feet from centre		End current electrodes 800 feet from centre	
	R ohms	$\rho \div 10^2$ ohms per cm. cube	R ohms	$\rho \div 10^2$ ohms per cm. cube	R ohms	$\rho \div 10^2$ ohms per cm. cube
Feet						
5– 10	2·86	54·8	2·85	54·7	3·05	58·5
10– 20	2·27	87·0	2·28	87·5	2·48	95·0
20– 30	0·80	91·5	0·78	89·7	0·88	101·0
30– 50	0·68	97·5	0·675	96·9	0·735	105·0
50– 60	0·175	101·0	0·17	97·9	0·173	99·5
60– 70	0·105	85·0	0·10	80·5	0·107	86·2
70– 90	0·13	78·0	0·13	78·5	0·130	78·4
90–110	0·08	76·0	0·08	76·0	0·074	69·8
110–130	0·05	69·0	0·05	69·0	0·051	69·6
130–150	0·03	56·0	0·03	56·0	0·0326	61·0
150–200	....	....	....	....	0·0488	56·2
200–250	....	....	....	....	0·0247	47·4
250–300	....	....	....	....	0·0151	43·4
300–350	....	....	....	....	0·0096	38·7

In order to compare the variation in resistivity, ρ, with depth, the values of R which have been determined are the average values obtained in more than one direction from the single current electrode. In the case of drill hole 29, measurements were made along the north, east, south, and west lines; at drill hole 23, along the north, east, and south lines; at drill hole 10, along the north and west lines; at the point 400 feet west of drill hole 10, along the south line; and at the point 800 feet west of drill hole 10, along the south line. The results of measurement are presented in Table XIX. For comparison the following are the logs of the drill holes.

Log of drill hole No. 10	Feet
Muskeg	0– 2
Clay	2– 16
Boulder clay	16– 61
Lignite	61– 97
Cretaceous clay	97–120

Log of drill hole No. 12	
Sand and silt	0– 10
Gravel, boulder clay, and sand	10– 82
Lignite	82–100
Cretaceous clay	100–115

Log of drill hole No. 23	Feet
Marine clay	0– 16
Boulder clay and sand	16–112
Cretaceous clay	112–130

Log of drill hole No. 29	
Muskeg	0– 4
Marine clay	4– 17
Boulder clay	13– 66
Cretaceous clay	66– 74
Lignite	74– 85
Clay	85–112
Lignite	112–132
Clay Cretaceous clay	132–140

TABLE XIX

Potential electrode stations	Drill hole 29		Drill hole 23		Drill hole 10		Point 400 feet west of drill hole 10		Point 800 feet west of drill hole 10	
	R	$\frac{\rho}{10^3}$	R	$\frac{\rho}{10^3}$	R	$\frac{\rho}{10^3}$	R	$\frac{\rho}{10^3}$	R	$\frac{\rho}{10^3}$
Feet										
5– 10...	....	....	....	....	2·85	71·7	2·67	51·2	3·74	71·7
10– 20...	....	....	....	....	2·08	79·63	1·71	65·6	2·18	83·5
20– 30...	....	....	....	....	0·79	91·6	0·70	80·5	0·86	98·7
10– 30...	1·89	54·8	1·74	50·1	2·87	87·0	....	....	....	....
30– 50...	0·50	71·0	0·45	64·8	0·667	95·5	0·645	92·5	0·71	103·0
50– 60...	....	....	....	....	0·167	96·45	....	....	....	....
60– 70...	....	....	....	....	0·11	88·5	....	....	....	....
50– 70...	0·21	69·6	0·237	79·3	0·275	92·2	0·29	97·0	0·305	102·0
70– 90...	0·11	66·4	0·145	87·6	0·135	81·7	0·13	78·4	0·165	99·5
90–110...	0·067	63·1	0·10	94·9	0·08	76·0	0·08	76·0	0·09	85·0
110–130...	0·04	54·5	0·073	99·7	0·05	69·0	0·05	68·0	0·055	75·0
130–150...	0·022	41·3	0·053	100·0	0·03	56·0	0·023	43·0	0·03	56·0
150–200...	....	....	0·077	88·3	0·045	52·0	....	....	....	....
200–250...	....	....	0·04	77·0	0·025	48·0	....	....	....	....
250–300...	....	....	0·023	67·0	0·015	43·0	....	....	....	....
300–350...	....	....	0·017	67·7	....	....	....	....	....	....

The following conclusions appear to be warranted.

(a) In the results obtained at drill holes 29 and 10 and at the points 400 feet west of 10, and 800 feet west of 10, there is a very rapid change in resistivity in the neighbourhood of depths corresponding to the location of the lignite. At drill hole 10 the change is so rapid that it approaches abruptness.

(b) The results obtained at drill hole 23 where lignite is absent, are pronouncedly different from the results at the other places. To 120 feet in depth the resistivity steadily increases to over 10,000 ohms per cm. cube, remains high to a depth of 150 feet, then gradually diminishes to a minimum little less than 7,000 ohms per cm. cube and which is very much higher than the minimum resistivity found to exist at the other points. Further, although there was no lignite at drill hole 23 there exists, commencing at a depth of about 105 feet, wet Cretaceous clay in which there were particles of lignite and which probably has a resistivity lower than that of the overlying boulder clay and sand.

(c) An obvious, though rather rough, interpretation of the results of the electrical measurements at the two points, 400 feet and 800 feet west of hole 10, is in agreement with the conditions inferred to exist. At drill hole 10 there is an overburden of 61 feet and 36 feet of lignite; at drill hole 12, which lies west of hole 10 and about 1,700 feet west of the point 400 feet west of hole 10, the overburden is 86 feet and the thickness of lignite 18 feet. Consequently at the point 400 feet west of drill hole 10, it may be expected that the lignite lies about 65 feet below the surface and is about 32 feet thick, and at the point 800 feet west of drill hole 10, the lignite may be expected to lie at a depth of 70 feet and be about 25 feet thick.

(d) None of the results are in conformity with the conclusions from the theoretical investigations of Hummel, Schlumberger, and Stefanesco, and others, to whom reference has already been made. It would appear, therefore, that theoretical investigations must take account of conditions other than those that exist in simple continuous conductors, that there are in fact conditions in the materials of the earth which give rise to rapid if not abrupt changes in the distribution of potential, and that there is at least a rough correlation between these changes and the location of the successive layers of materials.

GENERAL CONCLUSIONS

The resistivities of pyrite and pyrrhotite were much less than the resistivity of the surrounding materials. The pyrite deposit was readily delineated by field measurements. The pyrrhotite deposit was not so readily delineated apparently owing to the broken and disseminated character of the materials at the deposit. The resistivity of the lignite was only about one-fourth to one-fifth of that of the surrounding materials. The results of the field measurements showed that the depth of overburden could be determined fairly definitely at the places at which measurements were made. The resistivity of chromite was in general lower than that of the surrounding dunite and in both materials it was much affected by water, as these materials had a higher resistivity than water. While the results of the field measurements gave a general indication of the location of the chromite deposit the indication was neither definite nor pronounced, and it would appear that the presence of water made it very difficult to obtain definiteness of delineation by the electrical methods used in the field investigations.

The instruments and equipment used in these investigations were largely the property of the Department of Physics of the University of Toronto.

Acknowledgment is also made of a great deal of assistance in the construction of tables and figures for this report received from Mr. Allan Smith of the Department of Physics, University of Toronto.

PART III

GRAVITATIONAL AND MAGNETOMETRIC INVESTIGATIONS

By A. H. Miller (Dominion Observatory)

INTRODUCTION

This report contains an account of surveys made with the torsion balance and the magnetometer during the season of 1930, in continuation of the joint investigation agreed upon between the Department of Mines and the Department of the Interior in 1929. During the season of 1930 surveys were made with the magnetometer in the vicinity of Thetford, Quebec, in the Serpentine Belt, also of a pyrite deposit near Calabogie, Ontario, and of a fault near Hazeldean, Ontario. Surveys with the torsion balance were made of the above-mentioned pyrite deposit and of the Hazeldean fault. The latter survey was made at a point along the fault about 3 miles to the west of the 1929 survey and at a point where only one type of formation (the Precambrian) is encountered on the upthrow side of the fault. Work on the Hull-Gloucester fault was continued by the establishment of forty-four stations in the vicinity of those established the previous year.

As the work for the season was begun at Thetford the report begins with a discussion of the results obtained with the magnetometer, after which follows an account of the torsion balance surveys.

SURVEYS WITH THE MAGNETOMETER

CHROMITE DEPOSIT AT CARIBOU LAKE

A survey of an area about 400 by 800 feet was made with both horizontal and vertical magnetometers in the vicinity of a small showing of chromite remaining at the end of a pit that had previously been mined. The results are plotted in Figures 39 and 40. It is clear there are very large anomalies in the vicinity of the ore. Whether these anomalies can be related directly to the existence of the chromite is doubtful. No measurements have as yet been made of the susceptibilities of either the chromite or the country rock, but the deflexions produced on one of the vertical magnetometers by about two dozen samples of the country rock and the chromite of approximately the same size at the same distance from the magnet, were determined and it was found that in every case the effect produced by the country rock was larger than that by the chromite. In some cases the effect produced by the country rock was many times larger than that obtained from the chromite. This happens to be in agreement with the large negative intensity (−5066, *See* Figure 39) over the station at the end of the pit where the instrument was set up directly over the

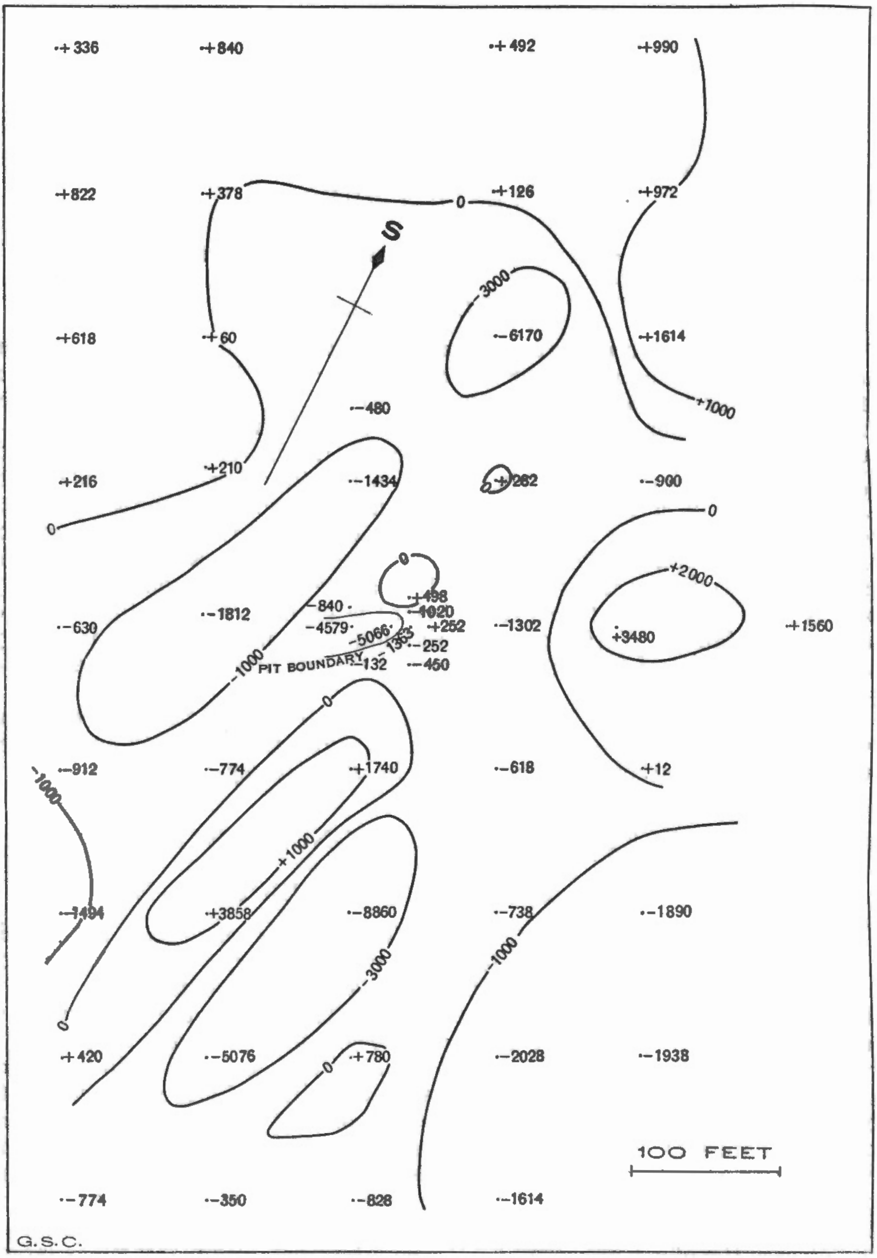

Figure 39. Magnetometer survey in vicinity of Vanadium pit, Caribou lake, Quebec; vertical magnetic intensity expressed in gammas (one gamma equals 10^{-5} c.g.s. unit).

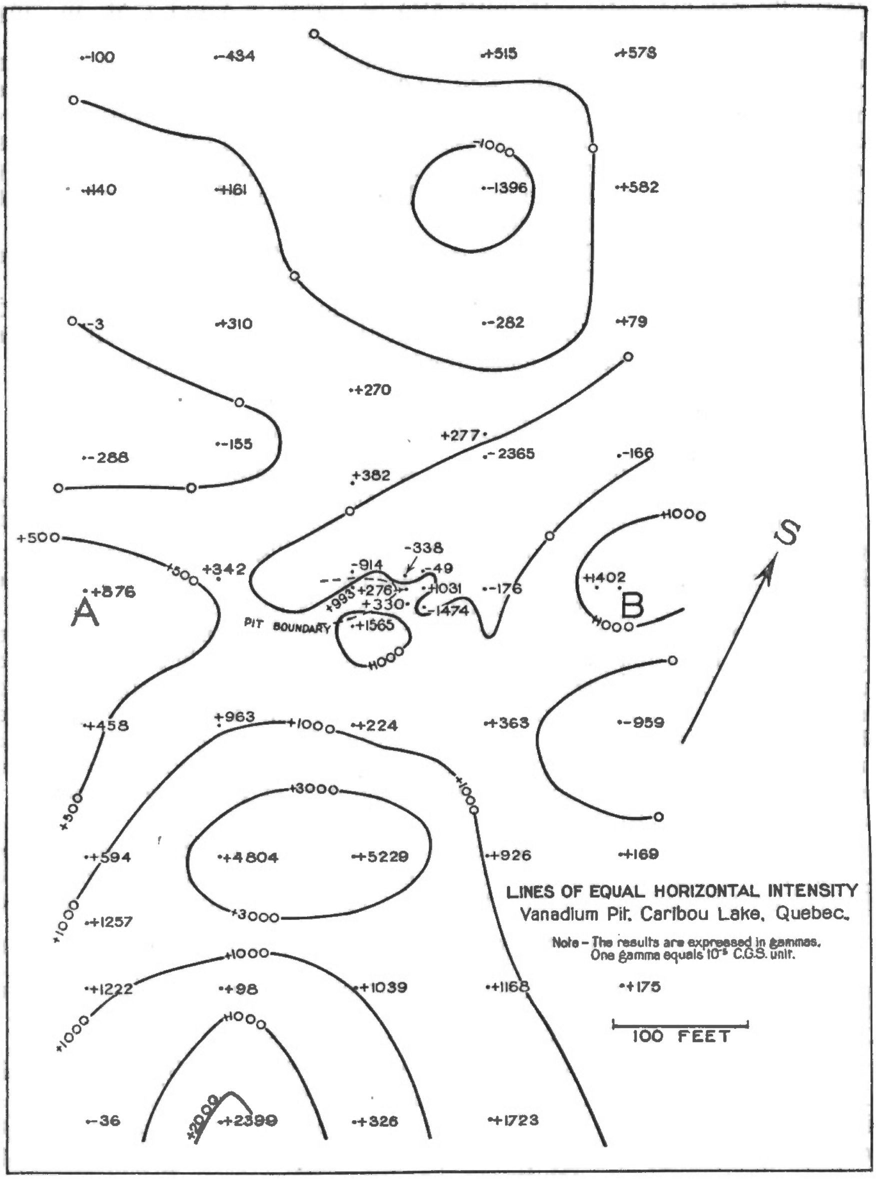

Figure 40. Lines of equal horizontal intensity, Vanadium pit, Caribou lake, Quebec.

chromite showing. However, until additional samples are collected and their susceptibilities measured it would not be advisable to attach undue importance to this large anomaly over the ore-body. It is possible that parts of the country rock may be less susceptible than the chromite or even practically non-magnetic. It must also be borne in mind that, judging from the measurements taken on the Pennington dyke east of Thetford, the average value of the susceptibility of the rocks of the intrusive is of the order of magnitude of approximately $10,000 \times 10^{-6}$ c.g.s. unit, in which case anomalies of the order of 4,000 gammas could be attributed to simply surface effects produced by the rock itself. In cases where the susceptibilities were larger than this average value the anomalies would be correspondingly larger, as they might also be expected to be in certain cases where the rock surface becomes very irregular.

Short traverses, with the vertical magnetometer, of the Beaver mine at Thetford and of Pit No. 6, Black Lake Asbestos and Chrome Company, Black lake, were also made; but, as they do not indicate anything beyond the fact that large variations in the magnetic intensity are encountered, as in the above case, it was not considered worth while plotting the results.

THE PENNINGTON DYKE

Two traverses a few hundred feet apart were made, with the vertical magnetometer, of the Pennington dyke at a point a few miles east of Thetford. Both the traverses were made along trenches where the depth of cover of the dunite was about 6 feet. Very similar results were obtained along the two traverses. The results obtained from the first traverse are shown in Figure 41. The continuous line shows the observed values and the dotted line a theoretical curve computed on the supposition that the dyke is uniformly magnetized. The general agreement between the two curves is good, indicating that the existing conditions generally speaking are explained. The maximum of the theoretical curve with respect to the observed curve is displaced noticeably to the left. It is probable that this fact has its explanation in the fact that the more basic and probably also more magnetic rocks are to be found in the part of the dyke to the right (or, on the ground, to the north).

In the case of a dyke very close to the surface, as in the present case, it can be shown by integrating the effects produced by the magnetic charges on the surfaces of the dyke that for points outside the dyke the disturbance in the vertical intensity is equal to $2\eta_s \sin\theta \log\frac{s_2}{s_1}$. For points over the surface of the dyke the disturbance can be shown to be equal to

$$2\pi\eta_T - 2\pi\eta_s \cos\theta + 2\eta_s \sin\theta \log\frac{s_2}{s_1}.$$

In these expressions η_T and η_s represent the surface density of magnetic charge on the top and sides of the dyke respectively, θ is the dip of the dyke, and s_2 and s_1 are the distances from the stations or selected points to the two edges of the dyke. For the strike and dip mentioned and magnetic inclination 75 degrees it can be shown that $\eta_s = 0 \cdot 688\ \eta_T$. The value of η_T was determined by solving the above equations for η_T for the observed values in the vertical disturbance at a point midway between the maximum and the minimum and two other points at equal distances from the two edges and on opposite sides of the centre of the dyke. The mean of the three values gave for η_T the value 588×10^{-5} c.g.s. unit. As η_T is equal to the magnetic susceptibility of the rock forming the dyke,

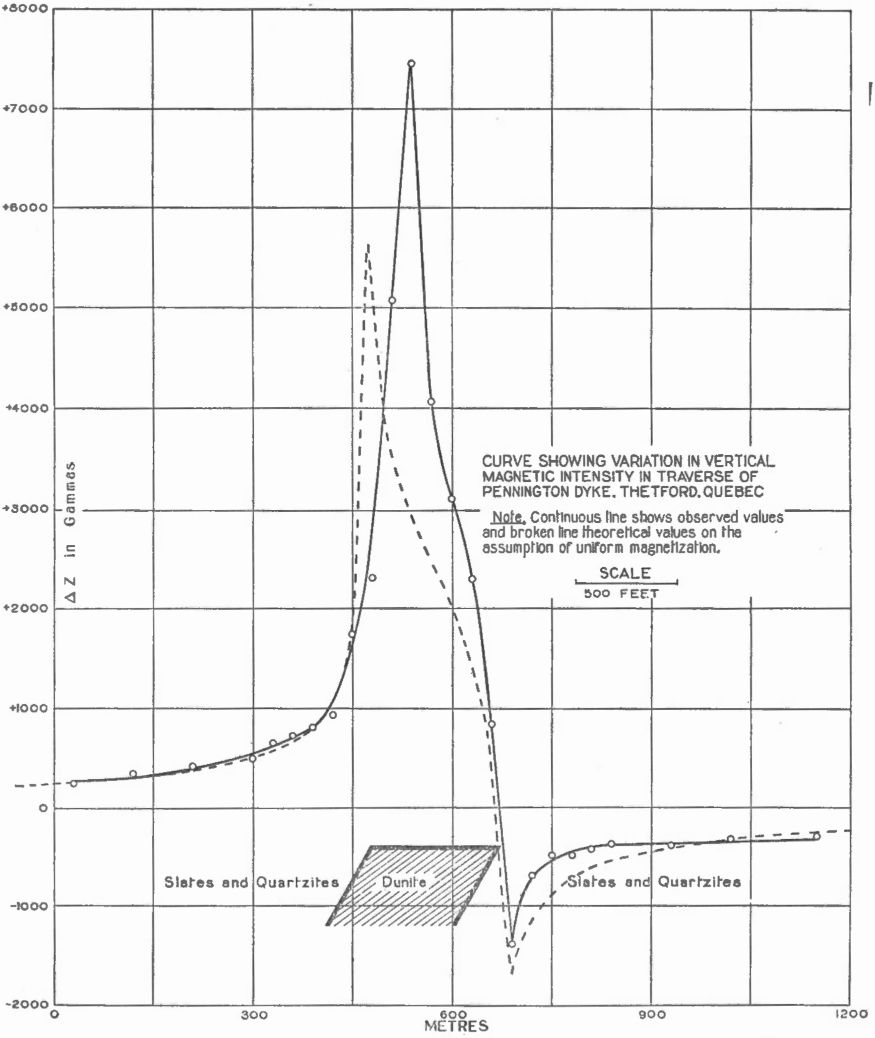

Figure 41. Curve showing variation in vertical magnetic intensity in traverse of Pennington dyke, Thetford, Quebec.

multiplied by the vertical intensity of the earth's magnetic field (=0·59) this value gives for the susceptibility of the dunite the approximate value 10,000 × 10^{-6} c.g.s. unit. If a dyke of this nature is supposed to be under a cover of drift equal to its width (in this case 600 feet) the effect to be expected in the case of the above susceptibility would be over 1,000 gammas which would be more than sufficient to locate the position of the dyke, especially as the magnetic field in the slates and quartzites seems to be very steady. Observations to test this were taken out to a distance of over a mile from the dyke in the slates and quartzites.

CONTACT OF SERPENTINE BELT WITH SLATES AND QUARTZITES

Following the survey of the dyke it was desired to make a further survey of a dyke or some similar structure under a considerable covering of drift, preferably where the structure was known. For this purpose the contact of the main body of the dunite with the slates and quartzites along the southerly projection of St. Alphonse street was selected and a traverse made of it. Along the traverse the depth of the drift is about 35 feet and the contact is well determined from extensive drilling in the

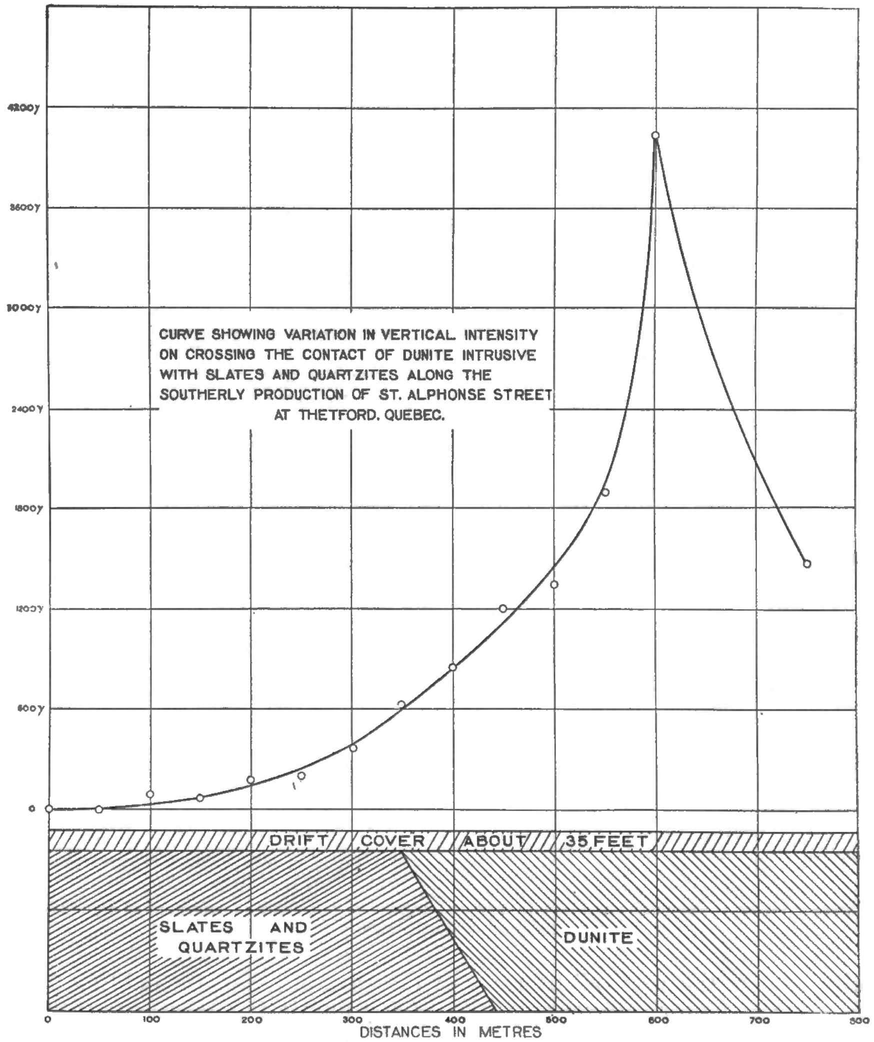

Figure 42. Curve showing variation in vertical intensity on crossing the contact of dunite intrusive with slates and quartzites along the southerly production of St. Alphonse street at Thetford, Que.

vicinity. It may be of interest to state that the time required to complete the observations at the fifteen stations was less than two hours. The curve (Figure 42) shows again a steady field over the quartzites, increasing as the contact is reached. Although the contact is not shown quite definitely in the curve it does seem that the method would serve to outline approximately the position of the boundary of the intrusive. It is possible that further information might be obtained with a horizontal variometer which would serve to locate the boundary more definitely. At the place where this traverse was made the terrain is well suited for work with the torsion balance, and unless the subterranean topography is very much disturbed, it would perhaps prove the most precise method of all and might be expected to give information regarding the depth of cover and the dip of the intrusive that would be difficult or impossible to obtain from the magnetic results. In connexion with the last two surveys acknowledgment is due Mr. R. V. Hopper, geologist of the Asbestos Corporation, who first suggested the Pennington dyke for survey by the magnetometer and, following this, assisted in the selection of the site for the second survey (along St. Alphonse street).

CALDWELL PYRITE DEPOSIT

The results of the magnetic survey indicate that although the intensity is by no means uniform throughout the surrounding region, yet the very large anomalies are to be found only in the vicinity of the outcrops of the ore. These large anomalies are not due to the magnetic effect produced by the ore, but apparently to rock that is closely associated with the ore. It is clear that in the present case the magnetometer would be of value in locating approximately the position of the ore. It is to be remembered in this connexion, however, that for the most part the rocks producing the anomalies are probably either at or close to the surface.

HAZELDEAN FAULT

The results of all the magnetic measurements that were taken in connexion with the survey of the fault are shown in Figure 43. The strike of the fault is indicated approximately by the line of the maximum positive anomaly. The Precambrian rocks are evidently, as one would expect, more magnetic than the sedimentary strata. The curve showing the observed results across the main traverse *(See* Figure 44) is of the form to be expected if the Precambrian rocks were uniformly magnetized. However, the agreement between observed and theoretical values does not go much beyond this. The two curves were made to fit at the maximum, the maximum value from the formula being equated to the observed value. This equation gives for the susceptibility the value 988×10^{-6} c.g.s. unit, which may represent an average value of the susceptibility of the Precambrian. On the assumption of uniform magnetization that has been made, the observed curve (distance between maximum and minimum 1,500 feet) would indicate a throw of 3,000 feet, which is at least three times too great.

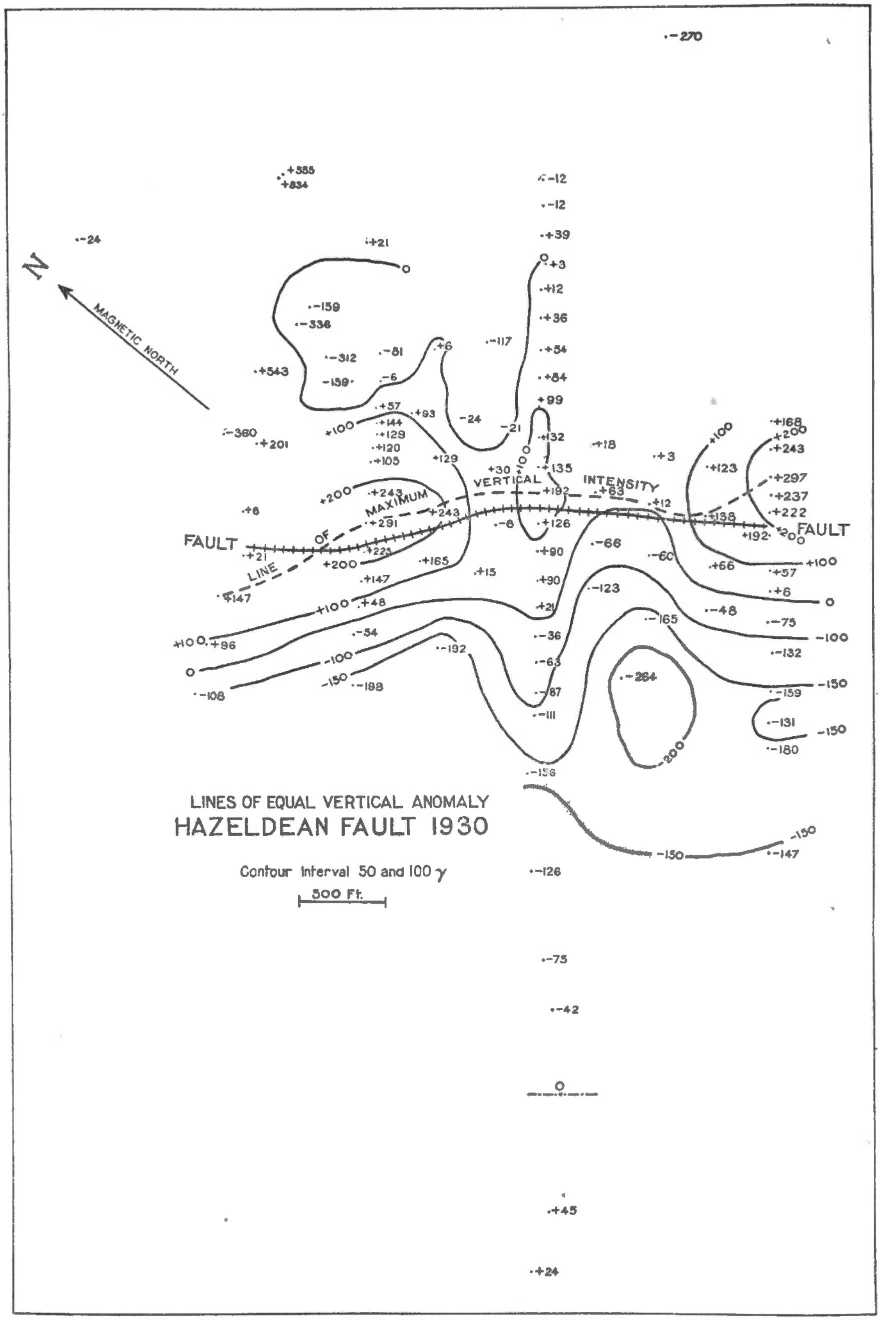

Figure 43. Lines of equal vertical anomaly, Hazeldean fault, 1930.

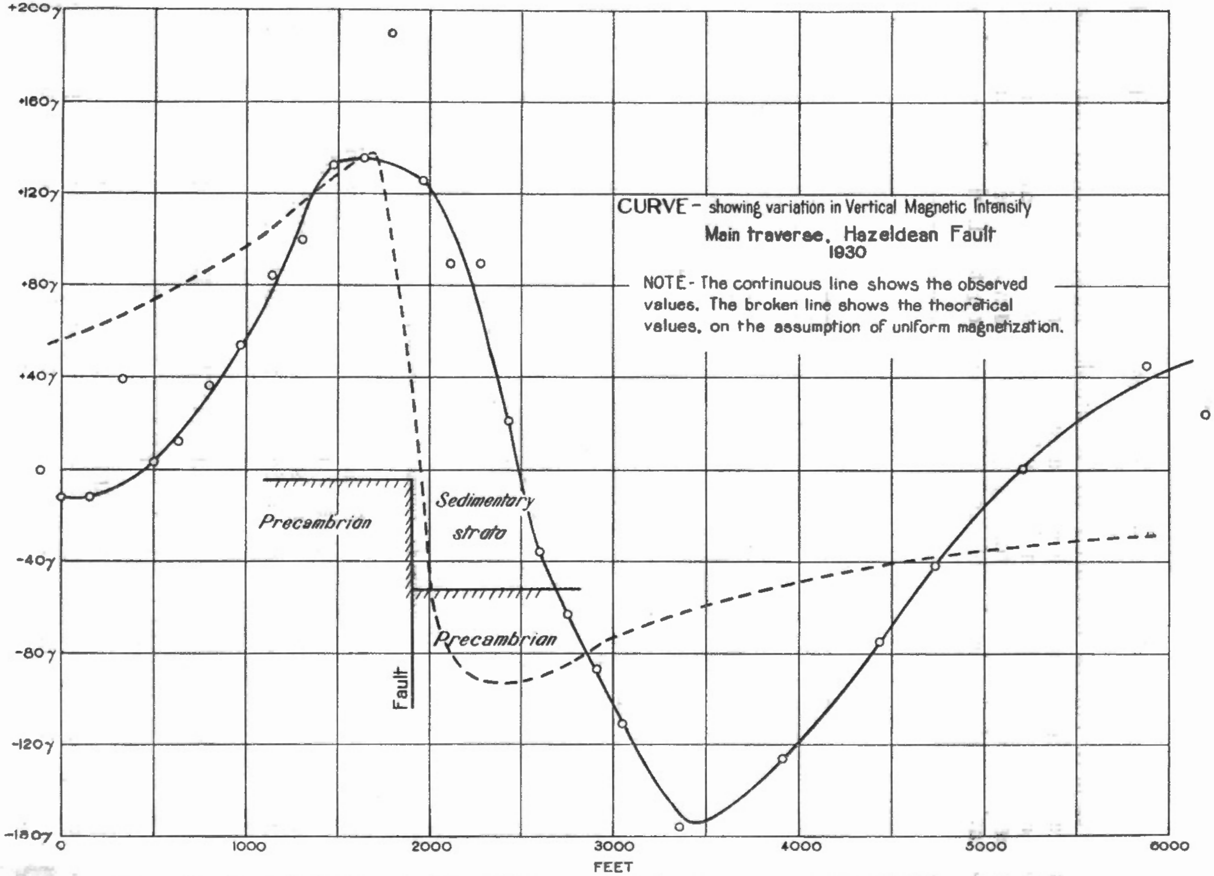

Figure 44. Curve showing variation in vertical magnetic intensity, main traverse, Hazeldean fault, 1930.

In the formulæ

$$\text{gradient} = 2\ G\ (\sigma_2 - \sigma_1)\ \log_e \frac{r_2}{r_1};\ \text{H.D.T.} = 2\ G$$

$(\sigma_2 - \sigma_1)\ \phi$; $\Delta Z = 2\ (\eta_1 \log_e \frac{r_2}{r_1} \pm \eta\phi)$, representing the gravitational and magnetic effects produced by a simple, ideal, vertical fault (*See* Figure 45), G represents the gravitational constant = $66 \cdot 7 \times 10^{-9}$ c.g.s. unit, $\sigma_2 - \sigma_1$ the difference in density between the strata, ΔZ the anomaly in the magnetic vertical intensity (on the assumption of uniform magnetization), η' the density of magnetic charge on the fault plane, and η

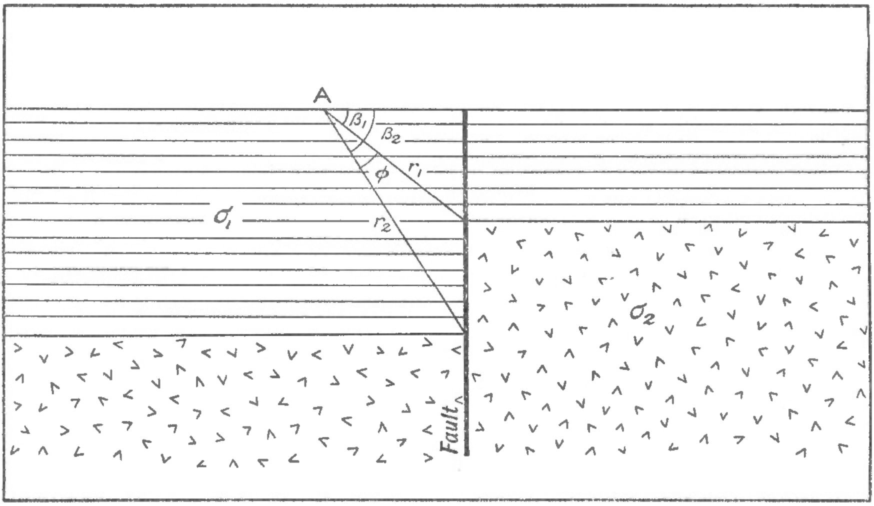

Figure 45. Illustrating a simple fault.

the density on the surface of the Precambrian. The surface density η is equal to κ (the susceptibility of the Precambrian) multiplied by Z (the vertical intensity of the earth's field), while η' is equal to κ multiplied by the component of the earth's field at right angles to the fault plane.

SURVEYS WITH THE TORSION BALANCE

CALDWELL PYRITE DEPOSIT

Surveys with the torsion balance began with a survey of the Caldwell pyrite deposit. This survey had a double purpose, in the first place to make an investigation of the effect produced by a heavy ore deposit and in the second place to obtain some first-hand knowledge of the sort of topography in which it becomes impracticable to work with the torsion balance. On the southern side of the ore-body the topography is not so rough, but on the northern side slopes of 20 degrees and, in certain places, more than this, are not uncommon. The difference in elevation between station 15 over the ore and station 38, the most northerly station (distant from one another, 1,000 feet), is approximately 250 feet. Owing to the fact that the effect of topography on the gradient decreases much more rapidly with the distance than it does in the case of the H.D.T., use was made of only the gradient results. In the field, levels were taken to a distance of 30 metres from each station for the purpose of computing the terrain correction. The elevations of most of the torsion balance stations were determined by levelling. Elevations of some of the more distant stations and numerous other distant points were determined by aneroid. Using these data in conjunction with M. E. Wilson's map (Publication No. 1798) of the deposit, a contour sketch of the area was made, and from this map topographical corrections out to a distance of 400 metres were made for each station. A further correction (very necessary in such a region) was made for the rock topography beneath the drift. At most stations the covering was shallow and could be determined by sounding with a thin steel rod, the soundings being made in the four cardinal directions to a distance of 10 metres.

Figure 46 shows the observed gradients corrected as explained above. As it stands it is difficult to make an interpretation of the results from this plan. However, it is apparent that the effect of the ore is influencing the results, because the gradients become large as the ore is approached from the south and decrease as it is passed. It is also apparent that due to some cause (possibly the dip and variation in density of the rock formation) there is a general regional tendency at all of the stations for the gradients to point in a definite direction, which is apparently a few degrees east of magnetic north. By taking the mean of the gradients for all the stations it was found that this effect was equivalent to a gradient of 58 Eötvös units in a direction 28 degrees east of magnetic north. Accordingly this quantity was subtracted from the observed values (corrected as already explained) and the residual anomalies were obtained and plotted in Figure 47. It is clear that these gradients are closely related to the presence of the ore. In fact they serve to outline the position of No. 2 ore-body. This is not so apparent in the case of No. 1 ore-body. The positions of the ore-bodies on this plan are the positions projected to the surface of the ground and were obtained from bore-hole sections supplied by the Grasselli Chemical Company. There are also shown on this plan the lines of equal gravity, or so-called isogams. These have been obtained by computation from the residual gradients. Gravity should have its greatest value over the largest and heaviest underground mass, which is indicated by the isogams to be in the vicinity of station 15. This agrees very well with the information to be obtained from the bore-holes.

Figure 48 shows the results obtained from a traverse across No. 2 ore-body compared with the values that would be produced were the ore deposited in the form of a dyke and greater in density than the surrounding rock by 1·7. The ore is not, of course, quite in the form of a dyke, but may be imagined to be so for the purpose of an approximate comparison. The left branch of the theoretical curve is approximately twice as high as the observed curve, whereas to the extreme right of the observed curve the actual values are somewhat greater negatively than the theoretical values. The discrepancy to the left could quite reasonably be explained

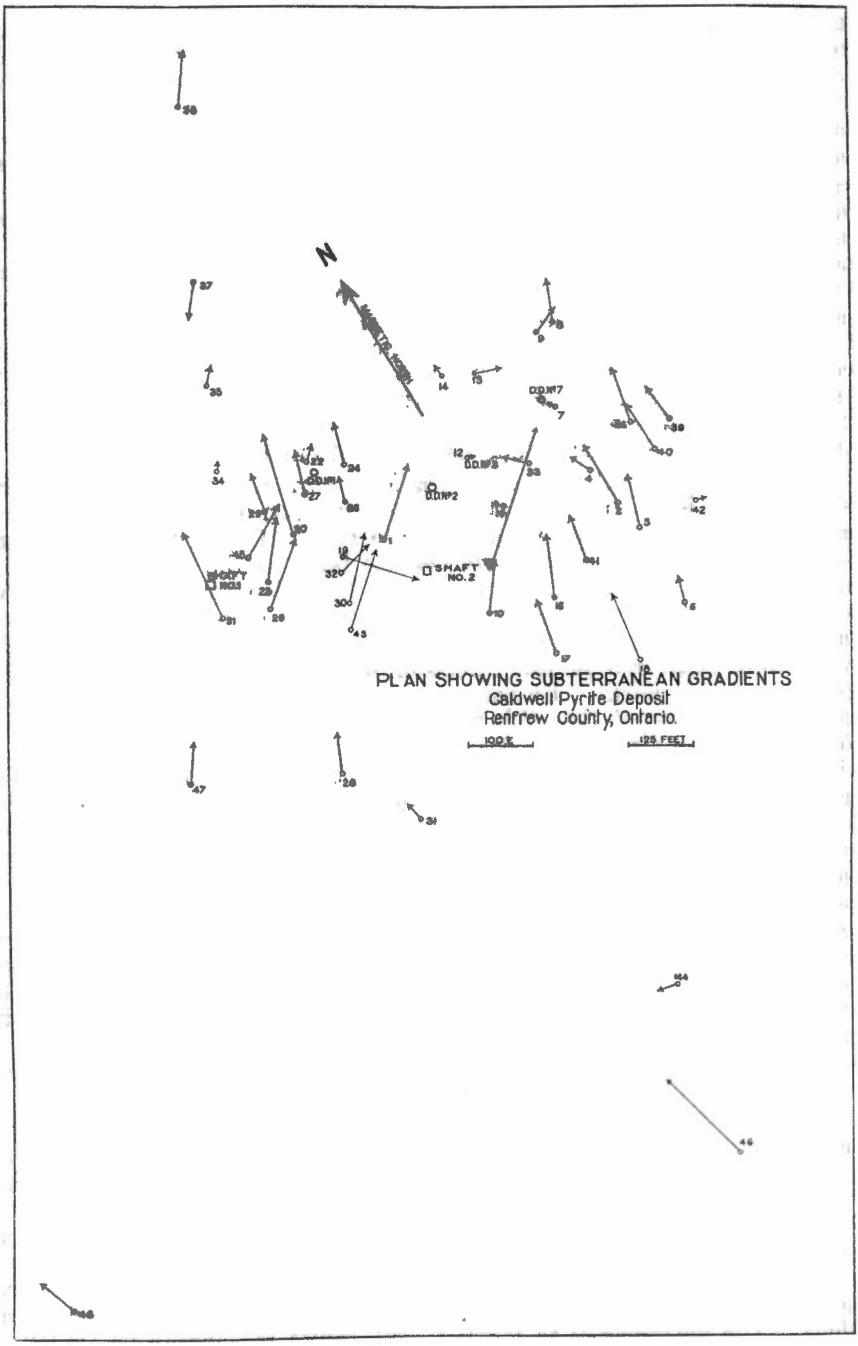

Figure 46. Plan showing subterranean gradients, Caldwell pyrite deposit, Renfrew county, Ontario.

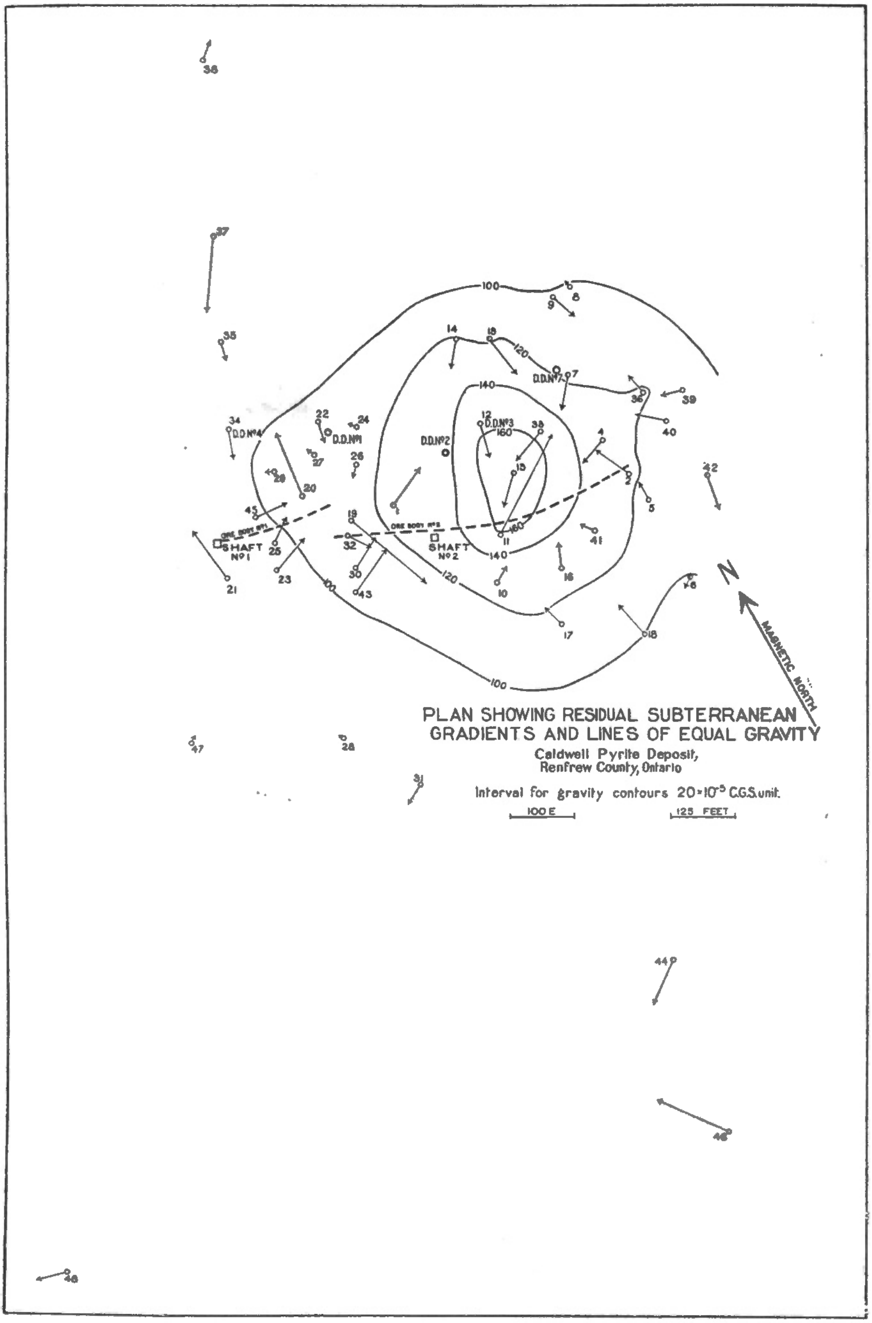

Figure 47. Plan showing residual subterranean gradients and lines of equal gravity, Caldwell pyrite deposit, Renfrew county, Ontario.

by the fact that the assumed density is probably considerably in excess of the average ore density as the value 1·7 (i.e. ore density 4·6) is based on a determination of a pure sample of the ore. If this is accepted then the gradient values for stations 13 and 14 are above normal, which is quite possibly the case.

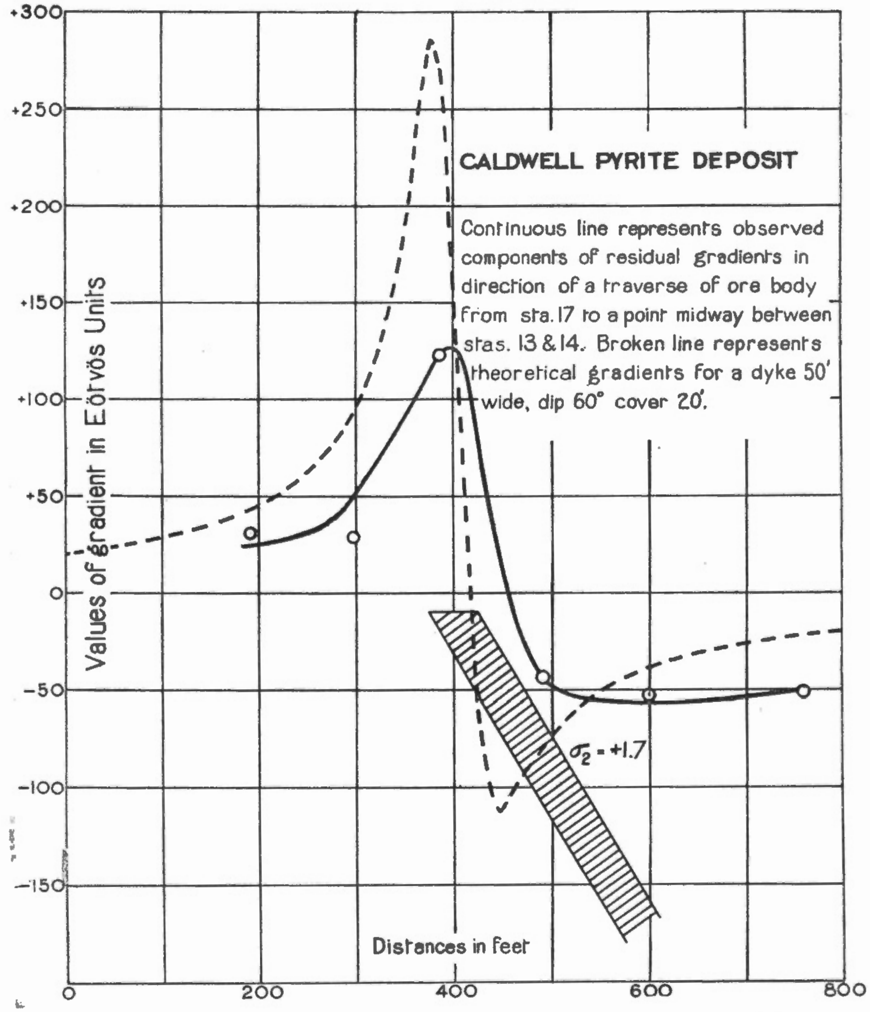

Figure 48. Gradient-graph, Caldwell pyrite deposit, Renfrew county, Ontario.

The dip of the ore to the north is indicated by the lack of symmetry in the observed curve. In this connexion at least one other station between stations 15 and 12 would be desirable, but on the ground this was impossible. The ratio maximum-to-minimum obtained from the observed curve as it stands is 2·2. In the case of a dyke this would indicate a dip of 65 degrees.

If the centre of gravity of the ore were known an estimate of its mass could be made from the anomaly in gravity which it produces.

In spite of the difficulties it is, therefore, apparent that a good deal of useful information relating to the ore either has been or could be obtained from the results of the survey. These difficulties were due mainly to two causes: (1) the roughness of the topography, and (2) the disturbances produced by the contact of the drift with the rock. Where the topographical correction is large the uncertainty in the value adopted for it also increases proportionately. In the present survey, owing to the dip and the location of the ore on the top of the side hill, the difficulty is accentuated because the correction becomes largest on the side of the deposit where the gravitational effect produced by it is smaller. With a small party unused to such work it was possible to prepare only a limited number of stations on the side hill, and these not altogether as one would like. Several stations immediately over and to the south of the ore were on the solid rock. This is, of course, the ideal situation. Other stations might have been selected where the rock could have been cleared to its surface without a great deal of expense, given the proper equipment and personnel for the purpose.

In conclusion, then, it would seem that with careful selection of the station positions with respect to the body to be investigated, and with attention to the station sites (which might involve cleaning the drift and in some cases even a certain amount of blasting), the torsion balance is capable of giving useful information in the survey of such large ore-bodies even in moderately rough terrain, and more certainly in cases where the topography and the relation of the drift to the country rock present less difficulties.

HAZELDEAN FAULT

The results of this survey are shown in Figures 49 and 50. The gradient and H.D.T., in both direction and magnitude for each station, are shown in Figure 49. The gradients in this plan are indicated by the arrows. With the partial exception of a single traverse to the north, where the conditions are complicated by an effect to be mentioned later, the strike of the fault, shown by the broken line, is indicated very clearly by the 90-degree change in the direction of the curvature. With the exception of the traverse already referred to (which includes stations 1 to 11) and the stations G_1 to G_3, the line determined by the curvature or H.D.T. is also the line (as it should be theoretically) of maximum gradients. The behaviour of the gradient and H.D.T. along stations 1 to 4 is an indication that the Precambrian dips sharply beneath the drift. The large values of the H.D.T. at stations G_2 and G_3, which are within the region of Precambrian exposures, are no doubt partly due to the drift-filled basin in which they lie and partly also to topographical effects, as the corrections are not complete for these particular stations. Smaller disturbances in both the gradient and H.D.T. are apparent in the results of the other stations on the Precambrian side of the fault and are no doubt due to the Precambrian topography beneath the drift, and also quite likely to the variation in density of the Precambrian, which certainly may vary from 2·6 to about 3·2 and possibly more than this according to the rock that may be present locally. To the south of the fault there is a well-defined disturbance over the sedimentary strata. It is more than likely that this is due to a drift-filled basin in these strata, the existence of which is apparent from a study of the isogams (*See* Figure 50) in conjunction with the plan of gradients and H.D.T's (Figure 49). In fact it is easier to interpret the results if one superimposes one plan upon the other. At the southern end of the bottom of the basin, that is along the main traverse, the curvature of the basin is such that it produces an H.D.T. which is parallel to the

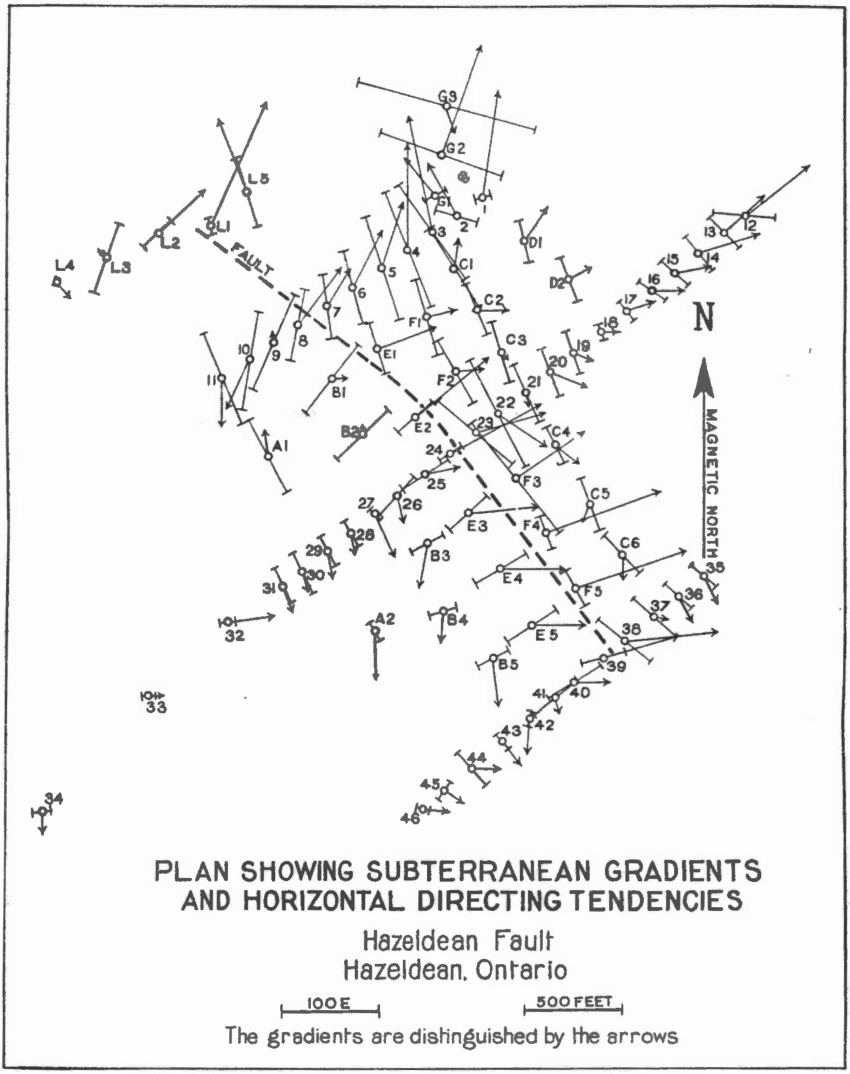

Figure 49. Plan showing subterranean gradients and horizontal directing tendencies, Hazeldean fault, Hazeldean, Ontario.

strike of the fault, thus having a tendency to increase the magnitude of the H.D.T. produced by the fault to the east of the fault and decreasing it to the west in accordance with the observed results. Along the traverse, including stations 1 to 11, the shape of the basin is such that it almost

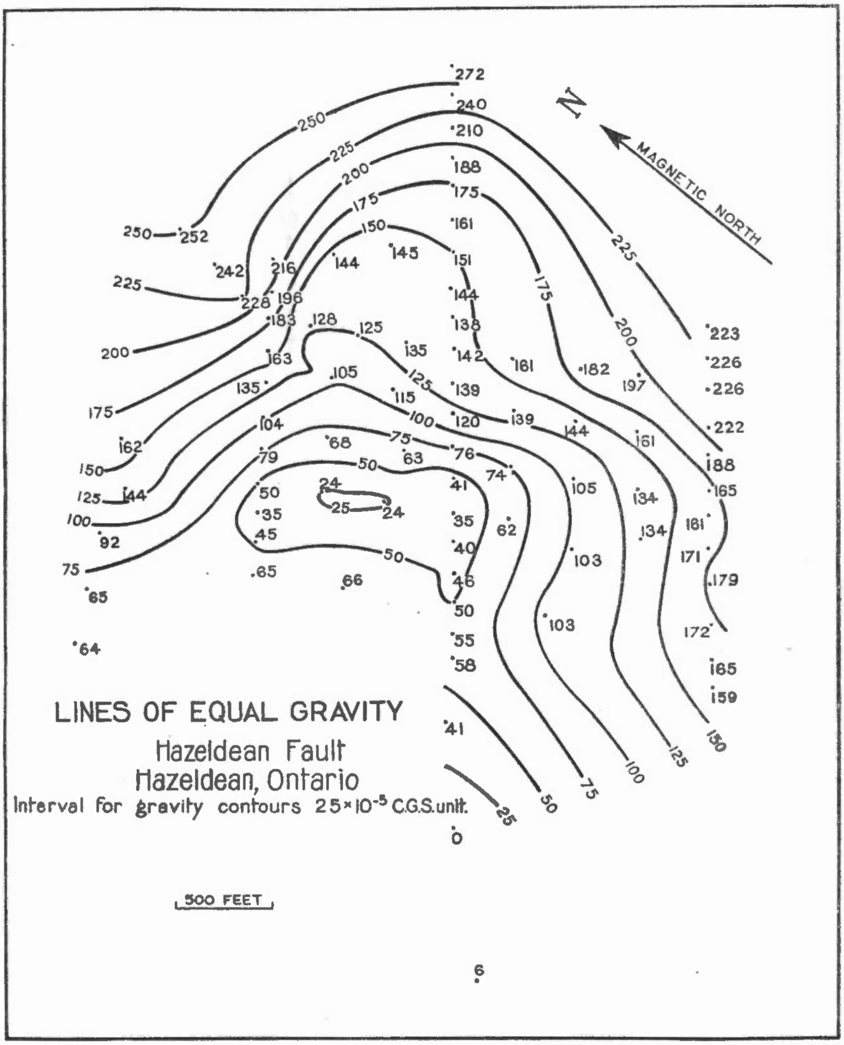

Figure 50. Lines of equal gravity, Hazeldean fault, Hazeldean, Ontario.

masks the effect produced by the fault, but the effects produced here by the basin, as for stations between the two traverses, are in accord with the shape of the basin outlined by the isogams.

As one proceeds westward along the main traverse a summit in the rock surface is evidently reached at a point between stations 31 and 32.

The presence of the basin is indicated in Figure 50 by the low values of gravity within the closed 50 and 25 gravity lines. A depth of about 60 feet in the limestone would be sufficient to account for the observed anomaly. The effect could be shown more clearly if the isogams were corrected for the effect produced by the fault.

As a matter of fact there are three distinct effects, each of which is evident in the influence it produces on the lines of equal gravity. (1) The effect already mentioned. (2) That produced by the fault, which would produce lines parallel to the strike of the fault and nearer to one another along the strike. (3) On the Precambrian side of the fault the rock outcrops along an arc which forms roughly a semicircle meeting the fault at points not far from the edges of the area covered by the survey. The region within the semicircle is drift covered. The isogams within this region of drift-covered Precambrian, therefore, owing to the greater density of the rock, have a tendency to become simicircular.

In the case of this survey if any one of the quantities, mean density difference, depth of cover, or depth of sedimentary rocks, were known it would be a simple matter to calculate the other quantities from the results of the survey. (In the present case it is possible to do this as the depths are fairly well known.) Theoretically it is possible to determine the quantities independently from the torsion balance results alone. In the present case it is at least possible to assign limits to these quantities from the results of the survey. If we start with the fact (*See* Figure 45) that ϕ cannot exceed a right angle (for a vertical fault) at the point where the H.D.T. is a maximum, and take the average maximum H.D.T. effect produced by the fault to be about 65 Eötvös units, using the formula for the curvature shown on page 108, it follows that $(\sigma_2 - \sigma_1)$ must be greater than 0·3. Using this value of the differential density in conjunction with the formula for the gradient where it has its maximum value (about 130 Eötvös units), and that connecting the depth of cover (t) and the depth of the sedimentary rocks (T) on the one hand with the distance (equal to about 300 feet) of the maximum or minimum curvature from the fault ($\sqrt{Tt}$ = distance), it follows that the depth of cover must be greater than 59 feet and the thickness of the sedimentary strata less than 1,470 feet, which is no doubt a reasonable value for the drift cover, but apparently an over-estimate for the thickness of the rock strata.

HULL-GLOUCESTER FAULT

Further observations were taken at the site of the survey of 1929 as it was desired to investigate the condition in the vicinity of the limestone outcrop (*See* Figure 51) and in particular to determine if there was evidence of a fault to the northwest of the outcrop. There is no indication of one between the stations immediately to the north of the outcrop (stations 38 and A_2) and station A_{12} which is located at the end of the longest traverse. In the immediate vicinity of the outcrop if there is a fault on this side of the outcrop involving a material difference in density it certainly does not extend as far to the north as the traverse indicated by the letter L. In the interpretation of the results here it is to be remembered that the stations 2AA and 38A are on the axis of the outcrop, on what is in effect a sharp

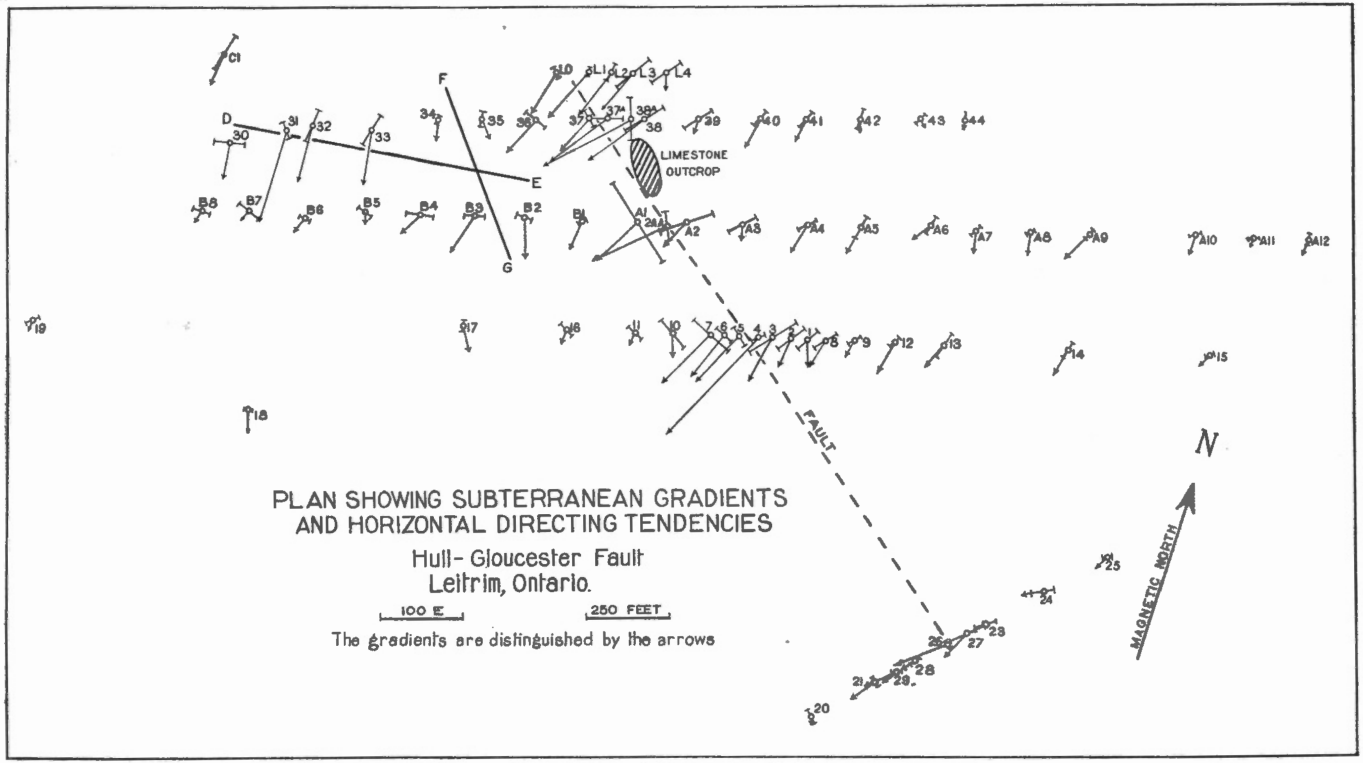

Figure 51. Plan showing subterranean gradients and horizontal directing tendencies, Hull-Gloucester fault, Leitrim, Ontario.

anticline with lighter drift to each side which tends to turn the H.D.T. in a direction parallel to the axis. Consequently, in interpreting the general conditions the local effects at these stations are better neglected. From last year's results it was concluded that the fault ran from station 26 to a point between stations 4 and 5. From the results of this year's work it is possible to trace the fault along as far as station L_0. In addition there is evidence of either a fault or a scarp along the line DE. By establishing a number of stations in a traverse across this line it might be possible to distinguish between a scarp and a fault if the strata involved in each case were known. From the behaviour of the gradient and the curvature at the stations immediately on each side of the line FG there is evidence of a hollow running in the direction of the line. It is quite possibly in the uppermost rock surface. Along the traverse which includes stations 15 to 19 and along which the results are least affected by influences apart from that caused by the faulting, it is apparent from the symmetry in the effects on the gradient and the H.D.T. that they are due to a fault that is either vertical or very nearly so.

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