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PAPER 65-22

THE CAREY FOSTER IN SITU SUSCEPTIBILITY METER

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P.J. Hood and D.F. Sangster

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DEPARTMENT OF MINES AND TECHNICAL SURVEYS

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ABSTRACT

Anomalies on aeromagnetic maps indicate varying intensity of magnetization of underlying rocks. The effective magnetization of a formation is the vector sum of two components, namely the induced and the remanent magnetization. Induced magnetization requires an ambient magnetic field, remanent magnetization does not. In weak fields, such as the earth's, intensity of induced magnetization is directly proportional to the applied field, and the constant of proportionality is called the susceptibility. In ground magnetic investigations it may be necessary to determine the susceptibility of a given formation. Most previous susceptibility meters were designed to measure the susceptibility of a hand specimen of the rock. However, magnetic susceptibility is a variable parameter and small samples may not be representative. A meter designed for use on the outcrop overcomes this difficulty and permits direct measurement at many locations.

The paper describes the in situ susceptibility meter (Model SM-4) built by Sharpe Instruments Limited for the Geological Survey of Canada using the Carey Foster bridge. Some field results from a geophysical study of the Briarcliffe Lake magnetite deposit in the Kapiho Iron Range, northern Ontario are presented, together with the results of calibration of the instrument using mixtures of sand and magnetite. The study shows that the in situ susceptibility meter is a much more reliable instrument for delineation of the highest tenor zones of magnetite iron-formation than the magnetometer because of the presence of remanent magnetism.

THE CAREY FOSTER IN SITU SUSCEPTIBILITY METER

INTRODUCTION

In the course of detailed geological and geophysical studies of magnetite iron-formation near Nakina, in northern Ontario, it became evident that high values of vertical magnetic intensity did not always occur over correspondingly high magnetite zones. Several large magnetic anomalies were recorded on outcrops of relatively low-grade iron-formation consisting of magnetite-quartz bands intercalated with quartz-biotite schist. Subsequent investigation showed that remanent magnetization predominates over the induced component in these areas. Because the intensity of the remanent component, unlike the induced component, is not a function of magnetite content, vertical magnetic intensity values cannot be used to estimate iron ore tenor.

Magnetic susceptibility, on the other hand, is dependent on magnetite content and could provide a semi-quantitative estimate of magnetite tenor. For this reason, a susceptibility meter rather than a magnetometer should be used to estimate relative ore grades.

Hand specimens collected in the field usually show a wide range of susceptibility values. This is partly due to the inhomogeneity of small specimens, especially in banded iron-formation, and it is therefore preferable to measure as large a sample as possible.

This paper describes a method of measuring the magnetic susceptibility of more than five cubic feet of rock using an in-situ susceptibility meter. This volume is equivalent to about 2,600 pounds of magnetite iron-formation.

CAREY FOSTER IN SITU SUSCEPTIBILITY METER

This instrument is basically the Carey Foster bridge (Carey Foster, 1887) which measures the mutual inductance between two coils. A susceptibility meter of this type has been described by Mooney (1952) and was subsequently used in a study of rock outcrops (Mooney and Bleifuss, 1953).

Sharpe Instruments of Canada Ltd. was commissioned to construct a transistorized model capable of being dismantled for easy transportation. The entire instrument breaks down into two 30-pound packs.

The in-situ susceptibility meter in operation on iron-formation is shown in Plate I. The effective measuring diameter is about 100 cm (about 3 feet) and effective depth of penetration about 40 cm (1.2 feet)(Mooney, 1952, p. 539). A 1.4-inch-diameter sample coil for the measurement of the susceptibility of short cylindrical specimens was also provided by the manufacturers.

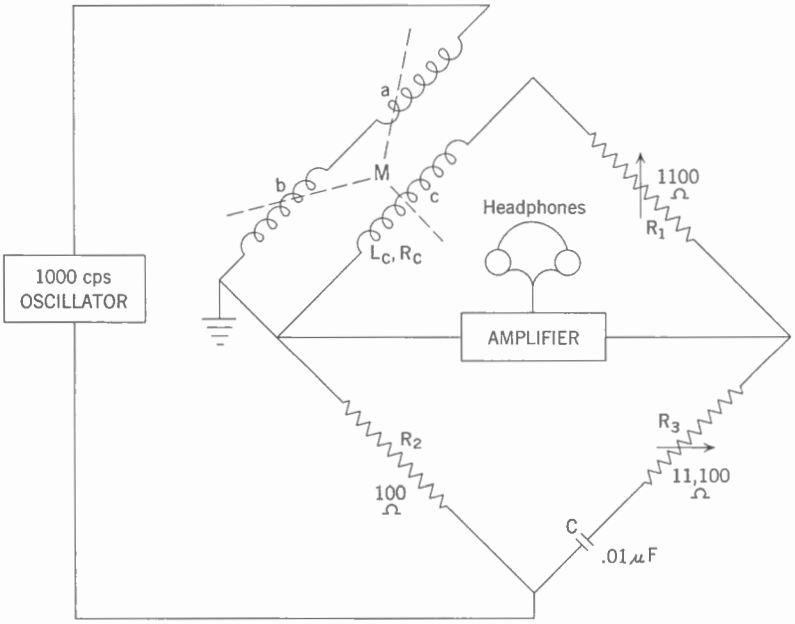

Figure 1. Carey Foster mutual-inductance bridge.

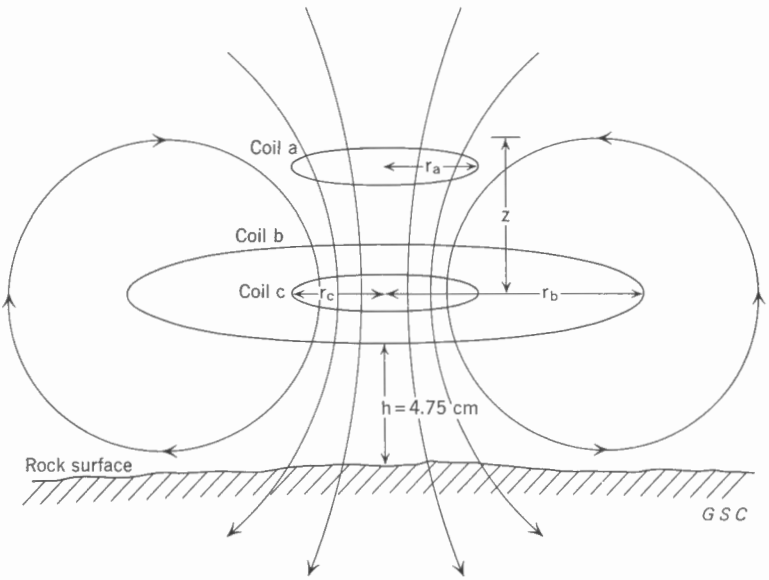

Figure 2. Schematic diagram of coil assembly.

Plate I. Sharpe in situ susceptibility meter in operation on magnetite iron-formation.

Principle of Operation

A diagram of the Carey Foster mutual-inductance bridge is shown in Figure 1. The basic theory of the bridge is to be found in a number of standard physics texts. Owen (1950, p. 21) gives the following balance conditions:

$$M = \frac{R_2 L_c}{R_2 + R_3} = CR_2(R_c + R_1) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where M = mutual inductance between the coils a, b, and c and L_c and R_c are the self inductance and resistance of coil c respectively.

$$\text{Hence } R_3 = \frac{R_2 (L_c - M)}{M} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Let ΔM and ΔL_c be the change in mutual and self inductance when the coils are placed on a rock surface of volume susceptibility k. Then from Equation (2),

$$R_3 + \Delta R_3 = \frac{R_2 (L_c + \Delta L_c - M - \Delta M)}{M + \Delta M} \quad \ldots\ldots\ldots\ldots \quad (3)$$

where ΔR_3 is the change in value of R_3 necessary to obtain a balance. The sign of ΔR_3 is always negative in practice because the increase in the mutual inductance between the coils is always greater than the increase in the self-inductance of coil c.

Mooney (1952) used the following notation:

$$\Delta M = \frac{G_1 k}{1 + 2\pi k} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

and

$$\Delta L_c = \frac{G_2 k}{1 + 2\pi k} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

where k is the volume susceptibility of the underlying rock.

G_1 and G_2 are given by the following expressions:

$$G_1 = \frac{16\pi^2 n_a n_c \sqrt{r_a r_c}}{t_{ac}} \left[\left(1 - \frac{t_{ac}^2}{2}\right) K(t_{ac}) - E(t_{ac}) \right]$$

$$- \frac{16\pi^2 n_b n_c \sqrt{r_b r_c}}{t_{bc}} \left[\left(1 - \frac{t_{bc}^2}{2}\right) K(t_{bc}) - E(t_{bc}) \right] \qquad \ldots\ldots\ldots \quad (6)$$

where $t_{ac}^2 = \dfrac{4 r_a r_c}{(r_a + r_c)^2 + (z + 2h)^2}$

and $t_{bc}^2 = \dfrac{4 r_b r_c}{(r_b + r_c)^2 + 4h^2}$

Lastly

$$G_2 = \frac{16\pi^2 n_c^2 r_c}{t_{cc}} \left[\left(1 - \frac{t_{cc}^2}{2}\right) K(t_{cc}) - E(t_{cc}) \right], \qquad \ldots\ldots\ldots \quad (7)$$

where $t_{cc}^2 = \dfrac{r_c^2}{r_c^2 + h^2}$

K (t) and E (t) are complete elliptic integrals of the first and second kind and the subscripts refer to the coils a, b, and c. These are tabulated, for instance in the Handbook of Chemistry and Physics (1959).

Also r = radius (in cm.) of the coils,
n = number of turns in the appropriate coil,
h = the distance (in cm.) between the rock surface and coil b,
and z = the distance (in cm.) between coils a and c.

Figure 2 is a schematic diagram of the instrument; coil specifications are given in Table 1.

Table 1

Coil specifications

	Coil a	Coil b	Coil c
Radius r in cm.	9.8	31.1	9.8
Number of turns (n)	227	200	200

Equations 2, 3, 4, and 5 were manipulated to obtain the following formula which was then programmed for the IBM 1620 computer:

$$\Delta R_3 = \frac{(R_2+R_3)\left[R_2G_2 - G_1(R_2+R_3)\right]}{\left[L_cR_2(1/k + 2\pi) + G_1(R_2+R_3)\right]} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

A family of theoretical curves relating ΔR_3 to k for various values of Z (the distance between coils a and c) is given in Figure 3.

Calibration

A common difficulty in the construction and use of a susceptibility meter is an empirical calibration of the instrument. Measurements on materials of known susceptibility (e.g. $MnSO_4.4H_2O$, $Co(NO_3)_2.6H_2O$, $Ni(NO_3)_2.6H_2O$) would be desirable but the susceptibilities of metallic salts are generally too low (less than 200×10^{-6} emu/cc)[1] to calibrate an instrument for use on iron-formation. Another prohibiting factor is the large volume of material required for the in situ meter.

Theoretical calibration curves, relating ΔR_3 to susceptibility have already been presented (Fig. 3) but the instrument would be of greater use to industry if it were calibrated in per cent magnetite or per cent iron as well. One way to do this is

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1 Volume susceptibility is commonly expressed either in emu/cc or cgs units; the reader should note that these are identical.

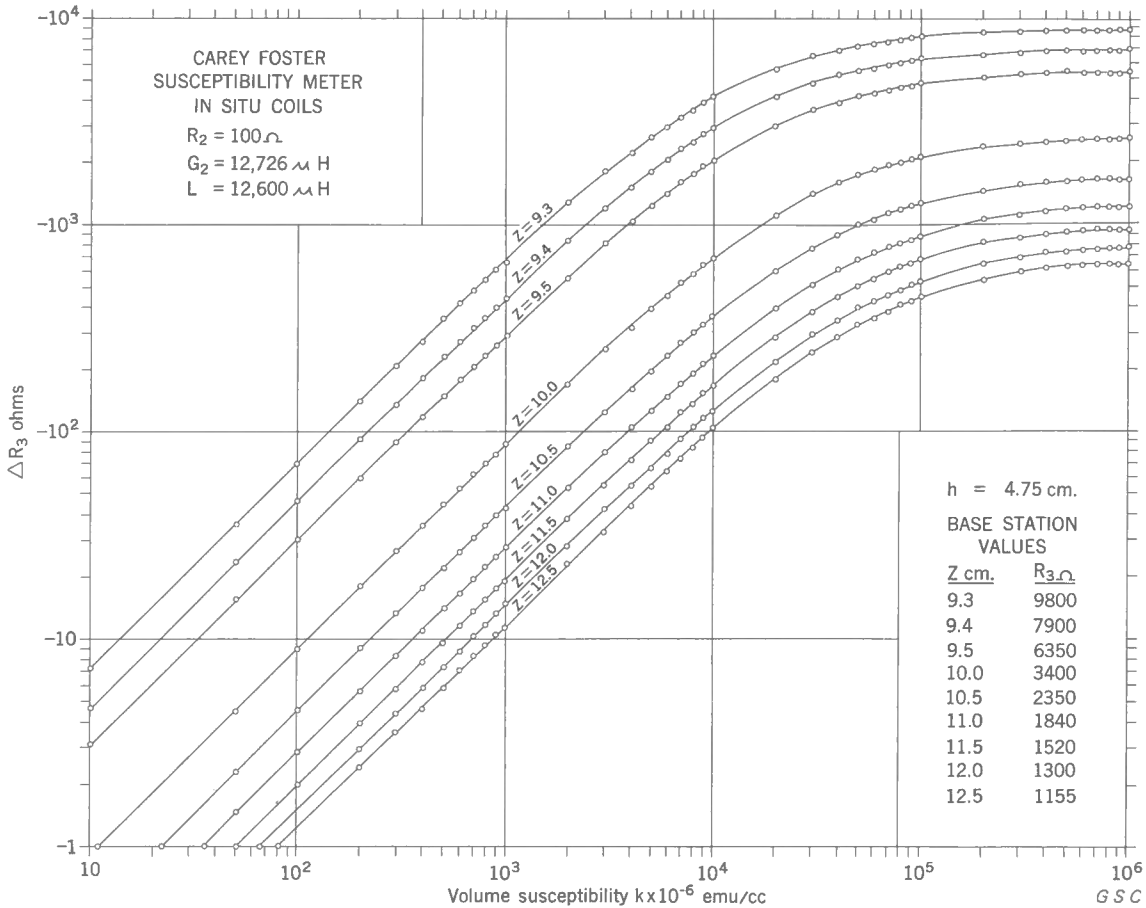

Figure 3. Theoretical calibration curves.

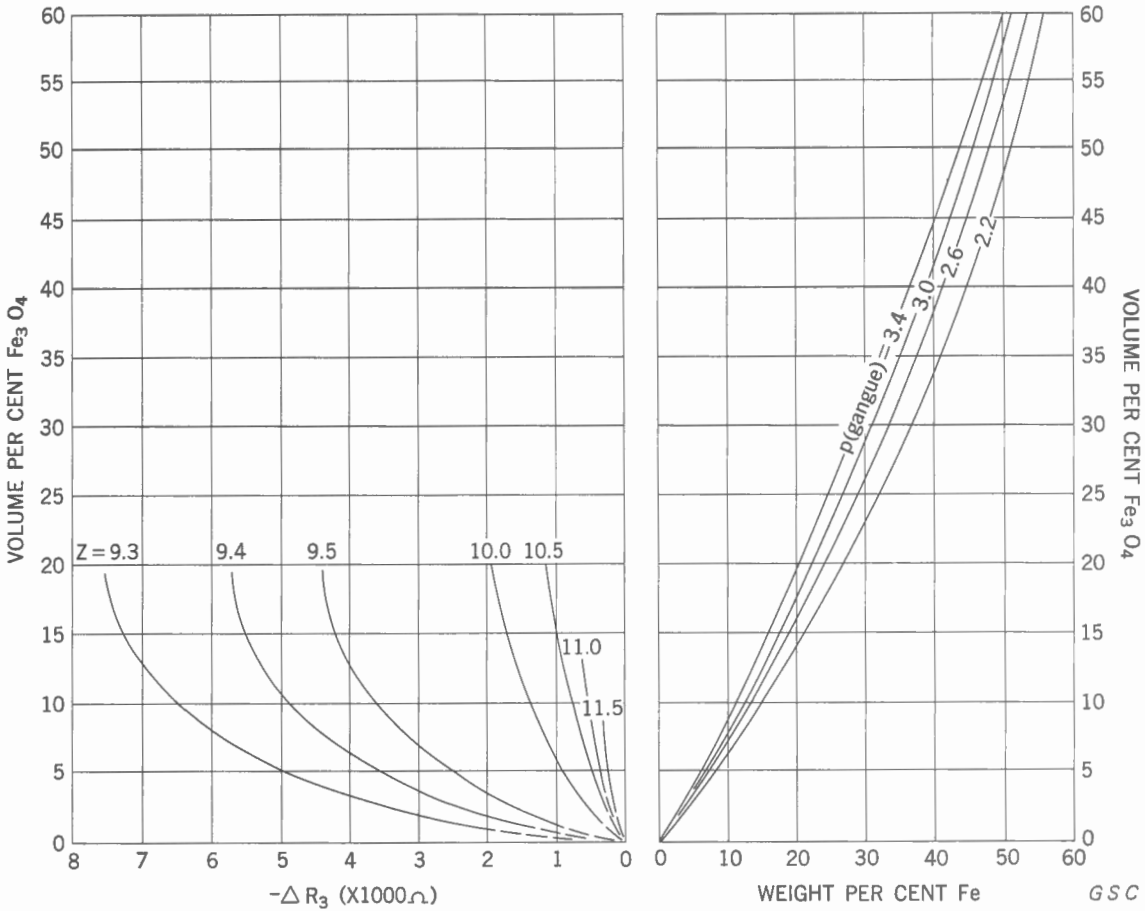

Figure 4. Experimental calibration curves.

to take measurements over mixtures of magnetite and a non-magnetic material such as quartz sand. Fortunately such material was available and the instrument was calibrated in the manner described below.

A plentiful supply of -325 mesh magnetite concentrate grading just over 70 per cent iron was made available by Anaconda Iron Ore (Ontario) Ltd. from its deposit north of Nakina, Ontario (Swensen, 1960; Lindberg, 1964). Assuming a specific gravity of 2.8 for the admixed gangue (mainly quartz with lesser amounts of hornblende, garnet, biotite, and specular hematite), a grade of 70% Fe is equivalent to 93.5 volume per cent magnetite.

Clean white glacial sand was collected from a beach on Hanover Lake 44 miles northwest of Nakina, Ont. The sand is well-sorted and composed essentially of rounded quartz and feldspar grains. Less than two per cent mafic minerals are present of which about 0.2 volume per cent is magnetic material.

A pit, measuring 3 x 3 x 3 feet, was dug in the beach, lined with a canvas tarpaulin, and then partially refilled with sand (Plate II), using an ordinary galvanized mop-bucket as a measuring standard. A total of 24 buckets of sand produced a layer about 1.5 feet deep on the pit floor. This depth is greater than the effective measuring depth (1.2 feet) of the susceptibility meter.

Coil a (Fig. 2) was adjusted so that Z = 9.3 cm. and the entire coil assembly placed on a four-foot non-metallic tripod situated several feet from the pit (Plate III). The bridge was then balanced, giving a value of R_3 at 9.3 cm. (Equation 1 and Fig. 1). The coils were then placed on the smoothed surface of the sand in the pit and the bridge re-balanced. The difference in the value of R_3 between the tripod and the pit is thus a measure of the volume susceptibility of the sand. This process was repeated for values of Z = 9.4, 9.5, 10.0, 10.5, and 11.0 cm. From the values of ΔR_3 obtained from each setting of Z, the volume susceptibility of the sand could be read directly from the curves shown in Figure 3. The average susceptibility of the pure sand was found to be 335 x 10^{-6} emu/cc.

Following determination of the "background" reading, one bucket of magnetite concentrate was added to the pit. The material was mixed until a uniform colour was attained. The pit now contained one volume of magnetite in 25 volumes of mixture. This is equivalent to 4 volume per cent magnetite and ΔR_3 values at Z = 9.3, 9.4, etc. were obtained over this mixture. For each new setting of Z, the value of R_3 on the tripod was read.

Another two buckets of magnetite were then added and mixed giving 3/27 x 100 = 11.1 volume per cent magnetite in the mixture. Values of ΔR_3 were again ascertained for this mixture and the process was repeated for various magnetite and sand ratios up to 40 volume per cent magnetite. In this manner, the instrument was calibrated for readings of ΔR_3 versus volume per cent Fe_3O_4 (Fig. 4).

In constructing these curves from the experimental data, the following corrections were necessary:

Plate II. Magnetite-quartz sand pit used for calibration of in situ Carey Foster susceptibility meter.

1. The magnetite concentrate contained only 93.5 volume per cent magnetite, calculated from mill assays reported as weight per cent iron and assuming a gangue density of 2.8.

2. The average porosity of the magnetite-sand mixtures was found to be 0.5 by the method described by Fraser (1935, p. 916). Therefore, the actual volume percentage of magnetite in the mixture is equal to:

$$\frac{\text{number of buckets magnetite} \times 0.935 \times 0.5 \times 100}{\text{total number of buckets mixture}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

The volume of magnetite in the beach sand (0.2%)was considered negligible and was ignored.

Plate III. Susceptibility coils mounted on non-metallic tripod to obtain base-station value of R_3

3. The tripod values of R_3 for a given Z were not the same for all mixtures used in the calibration. This was caused by small, unavoidable positioning errors in resetting Coil a for each mixture. The effect is only large for tripod values of R_3 obtained for Z values less than 10.0 cm. For example, the difference in R_3 between Z = 9.5 and 9.4 cm. is 1550 ohms i.e. 1550 ohms per millimetre. Consequently, small errors in repositioning Coil a would result in a considerable change in the value of R_3. The values of ΔR_3 presented in Figure 4 are therefore interpolated from those actually read during the calibration.

Also contained in Figure 4 is a family of curves relating volume per cent magnetite and weight per cent iron in magnetite for various densities (ρ) of gangue material. These parameters are related by the formula

$$\text{Wt. \% Fe} = \frac{72.4\,\rho_m v}{100\,\rho_g + v(\rho_m - \rho_g)}$$

where v = volume per cent Fe_3O_4

72.4 = weight per cent Fe in Fe_3O_4

ρ_m = density of magnetite = 5.17 g/cc

ρ_g = density of gangue

Figure 5 shows the relation between volume susceptibility and volume per cent magnetite calculated from the data of Figures 3 and 4. Linear extrapolation to at least 40 volume per cent magnetite is supported by Jahren's (1963) results from Minnesota taconites. The results appear to fall along the line

$$k = 0.001747 v^{1.2} \text{ emu/cc}$$

One factor which detracts from the accuracy of the calibration is the fact that -325 mesh i.e. less than 44 microns, magnetite was used. Gottschalk and Wartman (1935), and later Shandley and Bacon (1963), have shown that magnetic susceptibility falls off fairly rapidly below a grain size of 40 microns. This phenomenon may explain the fact that Jahren's (1963) curve is slightly above our experimental curve.

One of the factors that Jahren noted in his study of Minnesota iron-formations was the effect of layering on susceptibility determinations. He measured the magnetic susceptibility of cylindrical specimens (1 inch by 1 inch) which were placed in one of a pair of matched Helmholtz coils connected to an inductance comparison bridge. He found that with banded samples the susceptibility parallel to the bands was up to three times greater than the susceptibility measured at right angles to the bands. From Jahren's description of his susceptibility apparatus it is readily apparent that the alternating magnetic field applied to the cylindrical specimen is homogeneous and unidirectional at any instant of time. The geometry of the Carey Foster in situ susceptibility meter is quite different and the magnetic field is that due to a coil of wire, and consequently the magnetic field vector will be different at every point in the volume of influence. The situation is illustrated in Figure 2 using the lines-of-force concept. Thus the effect of banding will be minimized with the in situ meter.

Lastly no mention has been made of the possible effect of a 'demagnetization factor'. The derivation of the formula for the change of mutual inductance between two coils due to the presence of a semi-infinite plane of susceptibility k is a rigorous one, and the true susceptibility is obtained from the method. However the effective magnetic susceptibility (k_e) should be used in calculating the magnetic anomaly due to

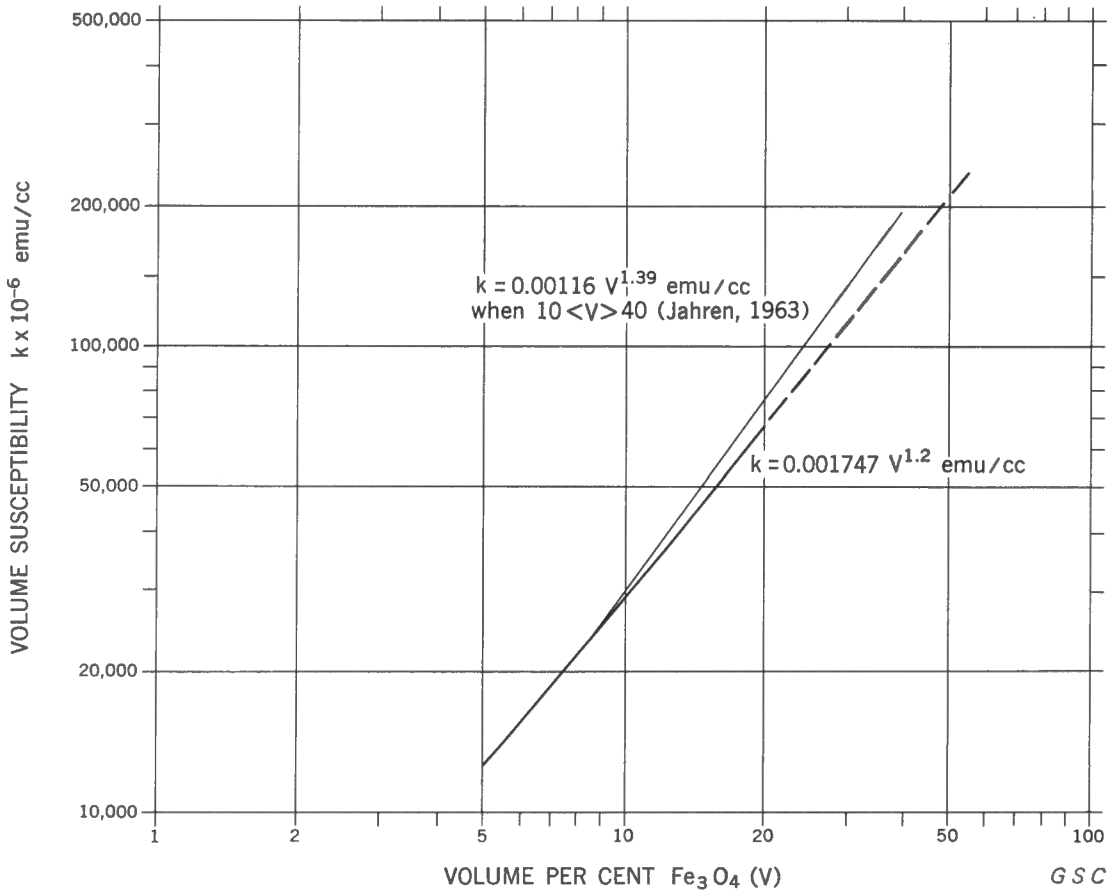

Figure 5. Calibration curves of susceptibility (k) versus volume per cent Fe_3O_4.

a given causative body. For the infinite plane this is related to the true magnetic susceptibility by the formula

$$k_e = \frac{k}{1 + 2\pi k}$$

Other geometries have been discussed in the literature by Werner (1945, 1953), Vogel (1962, 1963), Bath (1962), Gay (1963), and Jahren (1963).

FIELD RESULTS

Survey Procedure

1. The susceptibility meter and tripod are assembled at the outcrop making sure that the various screws are tight, and that there is no play in the coils. The separation (Z) between coils a and c is set using the scale provided by the manufacturer. A typical value would be Z = 9.4 cm.

2. The susceptibility meter is placed on the plastic tripod (see Plate III) which preferably should be located on a relatively low-magnetic rock outcrop such as pegmatite or granite. The bridge is then balanced by adjusting the values of the resistances R_1 and R_3 for minimum sound in the headphones. It is a good idea to initially reduce the volume of sound heard to a bearable level using the amplifier gain control provided, and gradually increase the gain as the balance point is approached until the maximum gain available is being used at the null point.

3. The value of R_3 is written in the notebook. It will be emphasized that care should be used in obtaining this value because it enters into all subsequent calculations.

4. The in situ susceptibility meter is now ready for use and it is placed on the outcrop (see Plate I) at the points where the susceptibility is to be determined. The bridge is then rebalanced for minimum sound in the headphones and the value of the resistance R_3 is noted. It should always be less than the base station value of R_3.

5. The difference between the base station and the survey station value of R_3 gives ΔR_3. The volume susceptibility of the material underlying the survey station may then be obtained from Figure 3 using the appropriate value of Z.

Care should be taken that no large pieces of loose rock are in close proximity to the coils because the mutual inductance between the coils will be increased. Needless to say the rock surface should be as flat as possible although Mooney (1952) has shown that the coil configuration is not very sensitive to irregularities in the rock surface. The presence of overburden should be noted in the survey fieldbook by a suitable notation (such as the letter O), together with other observations which would be useful in interpreting the results.

Survey of the Briarcliffe Lake magnetite deposit

The in situ susceptibility was used during a combined geological and geophysical study of the Briarcliffe Lake magnetite deposit in the Kapiko Iron Range, northern Ontario. The property is owned by Anaconda Iron Ore (Ontario) Ltd.

Archaean iron-formation lies within a belt of quartz-biotite schist surrounded by younger granite and gneisses. Magnetite and quartz occur in bands a few inches to several tens of feet thick intercalated with schist. The main magnetite zone is a band about 50 feet thick averaging 20-30 per cent iron. The main gangue material is quartz (S. G. = 2.6) but also present in minor quantities are specular hematite (5.3), garnet (3.5), hornblende (3.2), and biotite (3.0). In calculating weight per cent iron from volume per cent magnetite, an average gangue density of 2.8 g/cc was used.

The formation strikes N70° E and dips are vertical or steep to the north and south. Relict graded bedding in the schist indicates the major structure is an overturned isoclinal syncline. The plunge of microstructures and mineral lineation in both schist and magnetite shows that this structure plunges about 60 degrees to the east. Isoclinal folding has thickened the main magnetite zone from 50 to over 250 feet in the area of the survey.

Quartz-feldspar-muscovite pegmatite intrudes the iron-formation as dykes, sills, or irregular bodies. A twenty-foot survey grid was laid out over the most easterly outcrop in the Briarcliffe Lake deposit using wooden survey pegs or, where no overburden existed, the station was marked by paint directly on the rock surface. Vertical-force fluxgate magnetometer (ΔZ) and susceptibility (k) readings were obtained at 2.5 feet intervals along north-south survey lines spaced 5 feet apart using a rope survey chain to interpolate between the stations. Figure 6 shows four diagrams of this strip of outcrop; (1) geology, (2) vertical force, (3) susceptibility, (4) tenor of ore calculated from susceptibility measurements.

The weight per cent Fe results have been obtained from the empirical calibration previously described but values above 26 weight per cent Fe (20 volume per cent Fe_3O_4) were obtained by extrapolation of the calibration results.

There are a number of points of interest on these maps. The first is that the highest vertical-force magnetic values do not necessarily occur over the best grade of magnetite. For instance, at survey peg 116N/007E, ΔZ = 200,000 gammas and k = 100,000 x 10^{-6} emu/cc. This is the highest vertical-force anomaly occurring in the strip, whereas the highest susceptibility reading occurs at survey peg 155N/015E, where ΔZ = 96,000 gammas and k = 250,000 x 10^{-6} emu/cc. These cases refer to approximately 30% Fe and 52.8% Fe by weight respectively.

The geologic contacts between the magnetite and country rock are sharply defined by the susceptibility results whereas the gradient of the magnetic field over the contacts is much less steep. The presence of a few inches of overburden, however, causes the susceptibility readings to be lower than is actually the case, whereas the

magnetometer readings are relatively unaffected.

A field check on the accuracy of the weight per cent Fe values in the outcrop was available from a 200 x 25 x 5 foot bulk sample trench located a few feet west of line 000E. An average of 34 readings on the outcrop along 000E gave a value of 26.5% Fe by weight. The mill assay for the trench gave 24.6% Fe by weight.

SUMMARY AND CONCLUSIONS

The in situ Carey Foster susceptibility meter would appear to be a useful instrument in the ground follow-up of aeromagnetic anomalies. The advantages of measuring susceptibility in situ include the fact that a large sample is measured which means that the results are more representative of the whole outcrop. No sample is actually collected so that drilling or subsequent crushing of rock samples is unnecessary.

The study has also demonstrated that the in situ susceptibility meter may be used to delineate the higher tenor zones of magnetite iron-formation. It is probably advisable to calibrate the instrument for the particular iron property being investigated because it is well-known (see for example Werner, 1945) that there is an appreciable scatter in the susceptibility/magnetite relationship. This is due, in part, to grain size and the presence of impurities. The possible presence of hematite will, of course, cause the estimated % Fe by weight to be lower than the true value because hematite has negligible susceptibility compared with magnetite (Birch, Schairer, and Spicer, 1942). The banding of the iron-formation will also cause some effect, but this is minimized by the coil system.

ACKNOWLEDGMENTS

The cooperation of the president of Anaconda Iron Ore (Ontario) Limited, J. B. Knaebel is acknowledged in extending various courtesies. V. Burda and H. Gross of Sharpe Instruments of Canada Limited, manufacturer of the instrument, were most helpful. G. A. Gross of the Geological Survey with whom the project was a joint endeavour has reviewed this publication and offered a number of useful suggestions. Wilfrid Rivard and Walter Born, technical officer and student assistant respectively, during the 1964 field season, performed their duties conscientiously and made a significant contribution to the success of the project. D. J. McClure programmed the IBM 1620 computer to obtain the theoretical susceptibility values.

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