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RELIABILITY OF SUSCEPTIBILITY MEASUREMENTS ON CONDUCTIVE SAMPLES - A COMPARISON OF COMMERCIALLY AVAILABLE INSTRUMENTS

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INTRODUCTION

The purpose of this investigation was to assess the accuracy of susceptibility measurements on conductive rock specimens for a number of commercially available instruments.

Because DC susceptibility is the parameter of interest in magnetic interpretation, it is desirable to measure susceptibility using as low an operating frequency as possible. However, except for highly magnetically viscous rocks, low-field susceptibility is frequency independent in the kiloHertz range (R.S. Bhathal and F.D. Stacey, Journal of Geophysical Research, v. 74 (1969), 2025-2027). The major consideration is therefore the effect of eddy currents induced in conductive specimens by an oscillating applied field. By Lenz's Law the field produced by the eddy currents will oppose the applied field and thus lower the apparent susceptibility. The eddy current effect is a function of the conductivity-frequency product, and therefore the lower the operating frequency of a susceptibility instrument, the higher the allowable conductivity of the rock on which reliable susceptibility measurements can be made.

The instruments used in this study were

1. The CSIRO balanced transformer bridge (211 Hz operating frequency)
2. Bison Magnetic Susceptibility System - Model 3101 (1 kHz)
3. Elliott Magnetic Susceptibility Meter - Model PP-2A (1 kHz)
4. Geoinstruments Magnetic Susceptibility Meter - Model JH-8 (1 kHz)
5. Minnitech Laboratories MS-3 Bridge (1 kHz)
6. Core Testing Unit CTU-2 (5 kHz)
7. Digico Bulk Susceptibility Unit (10 kHz)

Of these, the Elliott and Geoinstruments meters are essentially field instruments for which ease and rapidity of operation are more important than high precision of measurements, however their performance overall was comparable to the Bison and possibly better than that of the Minnitech. The manufacture of the Elliott meter has now been taken over by Scintrex.

THE CSIRO BRIDGE

The principles upon which this instrument has been based are described by Collinson et al. (J. Sci. Instrum., v. 40 (1963) 310-312). The instrument measures the unbalance signal due to insertion of a susceptible specimen in the air gap of one of the cores of an originally balanced transformer bridge. The design has been discussed by Ridley and Brown (ASEG Bulletin, v. 10, No 3 (1979), 192-193).

A theoretical analysis of the operation of the bridge shows that the observed susceptibility is controlled by a demagnetising factor dependent on the air gap between the poles and the specimen. If the specimen completely fills the gap, the true susceptibility is measured directly. For a standard size specimen 2.2 cm long in the 2.54 cm gap, we have

$$D_{SI} = 0.34/2.54 = 0.134 \qquad (1)$$

The emu demagnetising factor is 4π times larger, i.e. $D_{emu} = 1.682$. Therefore the apparent susceptibility is given by

$$k' = k/(1+Dk) \qquad (2)$$

$$\therefore \quad k = k'/(1-Dk') \qquad (3)$$

Equation (3) allows correction of the observed susceptibility for demagnetisation.

The response is linear in susceptibility at the low susceptibility end of its range and it has been absolutely calibrated to within 1% using paramagnetic salts as standards. Assuming negligible leakage flux and ideal transformer behaviour it can be shown that departures from linearity should be slight for even the most magnetic rock specimens. It is desirable however to test this with calibration samples of known, high susceptibility.

Because of the difficulty of obtaining homogeneous materials which have susceptibilities of the order of those in magnetic rocks and which could be used as calibration standards, a number of specimens consisting of varying proportions of magnetite powder dispersed in plaster of paris were fabricated. The magnetite was pure and came from Biggendon. After crushing, the magnetite powder was sieved and only particles less than 75 microns were used in the synthetic specimens. Details of the dispersed magnetite specimens are given in Table 1. Volume per cent magnetite contents range from 0.02% to 45%, covering most of the range found commonly in nature.

As expected, the measured susceptibility is proportional to the volume fraction of magnetite, for small magnetite contents. However, above about 4% magnetite by volume there is a departure from proportionality, and the susceptibility rises more rapidly than the relationship applicable at low magnetite contents, viz. $k = 0.276\ f$, where f is the volume fraction of magnetite. This behaviour is shown in Figure 1.

The explanation for the departure from linearity lies in grain interactions. As the magnetite content increases the individual grains no longer act in isolation and their response to an applied field is modified by the behaviour of their neighbours.

A simple theory of grain interactions will be given. The observed susceptibility of a volume fraction f of non-interacting grains of intrinsic susceptibility k_i is

$$k = k_i f/(1+N_o k_i) \qquad (4)$$

where N_o is the average self-demagnetising factor of the grains.

In the grain size range of interest $k_i \simeq 1.3$ (emu) and we obtain $N_o = 2.85$ from (4) and the relation $k = 0.276\ f$. Assuming random orientation of prolate particles, this value of N_o corresponds to an elongation ratio of 3.5:1. Isolated spherical grains have $N_o = 4\pi/3 = 4.19$.

Grain interactions lower the effective self-demagnetising factor of a particle. Néel (Comptes Rendues, v. 224 (1947), 1488 and 1550) gives the relationship

$$N = N_o(1-f) \qquad (5)$$

Therefore the observed susceptibility should be

$$k_{\text{Néel}} = k_i f/(1+k_i N_o(1-f)) = 0.276\ f\ (1+k_i N_o)/(1+K_i N_o(1-f) \qquad (6)$$

The measured susceptibilities, after correction for the demagnetisation factor of the bridge, agree very well with equation (6) (see Table 1).

This, together with the observation that the measured susceptibilities correspond well with those obtained elsewhere (e.g. Jahren, Geophysics, v.28 (1963), 756-766; Mooney and Bleifuss, Geophysics, v. 18 (1953), 383-393) suggests that the bridge calibration is fairly accurate in the high susceptibility range.

In the following sections it is assumed that the CSIRO bridge measures the true bulk susceptibility of rock specimens and the performance of all the other instruments is assessed with respect to the CSIRO bridge.

INSTRUMENT COMPARISON

Because the calibration of commercial susceptibility instruments is usually crude it was necessary to correct all instrument calibrations by normalising measurements on a standard sample. The standard sample chosen was a 2.5 cm diameter core consisting of a number of identical cylindrical synthetic specimens containing 5% magnetite by weight ($\simeq$1.1% by volume). The susceptibilities of the individual specimens were first measured on the CSIRO bridge and the Digico unit, and the specimens were then joined together into a long core for measurements with the other instruments. The measurements on the individual specimens indicate the core is magnetically homogeneous and isotropic, and thus is suitable for comparison of different instruments with differing geometrical relationships between sensors and samples.

Measurements of the susceptibilities of a variety of rock types were made with all the instruments. Data on the rock types used in this study are given in Table 2. The susceptibilities range from very low (<100 x 10^{-6} emu) to very high (>0.6 emu).

The results of all the measurements are summarised in Table 3. The calibration factors for the instruments are given and indicate that in most cases the commercially available instruments read a little low.

The conductivity values quoted are based on measurements made using the CTU-2 which inductively measures effective conductivity of a specimen at 100 kHz and 2.5 MHz. The method works best for non-magnetic samples and the conductivity measurements on pyrrhotite rich samples are considered to be only approximate.

The Geoinstruments meter is calibrated for use on a flat surface. Our measurements suggest that the appropriate factor for measurements made on one inch core is 3.37.

For most of the samples the different instruments agree reasonably well, and the scatter of measured values can be attributed to sample inhomogeneity and anisotropy, together with the fact that the sensor geometry varies from instrument to instrument.

The results for sample 10 suggest that the Elliott and Geoinstruments meters read very low for magnetite ores and that a large empirical correction factor is required for use on very magnetic rocks. The discrepancy between true and measured susceptibilities for these instruments is probably due to demagnetisation and gross departure of the frequency-susceptibility relationship from linearity.

The samples can be divided into non-conductive (samples 1-7 with $\sigma \lesssim 20$ mho/m) and conductive ore ($\sigma > 100$ mho/m, samples 8-12) categories. All the instruments are reasonably satisfactory for the non-conductive rock types, and can therefore be judged on cost, ease of measurement, etc. On these criteria the Minnetech instrument does not compare well with the others because of its low sensitivity, relatively small dynamic range, and the inconvenience of the audio null system.

However susceptibility values for the ore samples seem to be sometimes significantly lower when measured with the $\geq$ 1 kHz instruments than with the CSIRO bridge. The effect varies widely for different instruments and does not simply increase monotonically with frequency. The influence of eddy currents will depend on the geometry of the sensor-sample configuration and will be affected by conductivity inhomogeneities in the sample. From Tables 3 and 4 it is clear that the overall tendency is always for the conductive samples to measure low, even though the effect cannot be readily quantified in terms of frequency. This trend is clearly illustrated in Figure 2, which is a plot of the data in Table 4.

Although the conductivity-frequency effect appears on the basis of this data to lead to underestimation of true susceptibility, the resultant error is often smaller than the sampling error. For example at 1 kHz the susceptibility of the most conductive sample (No 12) appears to be about 30% low, which is probably acceptable. However some measurements with particular instruments may be more drastically affected. The measured susceptibility of sample 12 using the Geoinstruments meter, for instance, is over 60% low, and this sort of error could lead to a serious underestimation of the susceptibility of an ore body, particularly since the measurement is systematically biased low.

CONCLUSIONS

1. The various commercially available field and laboratory susceptibility instruments appear to be satisfactory for use on non-conductive, moderately magnetic rocks.

2. The instruments need to be re-calibrated for use on very magnetic rocks such as magnetite ores.

3. Susceptibility measurements using operating frequencies of 1 kHz plus tend to underestimate the true susceptibility of conductive ore specimens. Except for highly conductive pyritic or pyrrhotitic ores, the commercial instruments are satisfactory, particularly when sampling problems are considered.

A low frequency instrument is recommended for detailed petrophysical studies on conductive ores.

TABLE 1

Specimen	Volume % magnetite	k'	k	$0.276f$	$k_{\text{Néel}}$
BS6	0.022	62	62	61	61
BS3	0.22	640	640	610	610
BS4	0.52	1,590	1,590	1,440	1,440
BS2	1.11	3,220	3,240	3,070	3,090
BN12	1.93	5,280	5,330	5,330	5,410
BN13	3.86	10,660	10,850	10,650	10,990
BN14	7.71	22,630	23,530	21,280	22,660
BN15	11.64	34,370	36,480	32,130	35,370
BN	45.0	147,500	196,200	124,200	192,400

k' = observed emu susceptibility x 10^6

k = emu susceptibility, corrected for demagnetisation
= $k'/(1-Dk')$ where $D = 1.682$

f = volume fraction of magnetite

$k_{\text{Néel}}$ = $0.276f\ (1+k_iN_o)/(1+k_iN_o(1-f)$

= susceptibility predicted by Néel's model of grain interactions

k_i = 1.3

N_o = 2.85

$k_i/(1+N_ok_i) = 0.276$

TABLE 2

SAMPLE No.	ROCK TYPE
1	Dispersed magnetite in gypsum (5 weight per cent magnetite)
2	Banded iron formation (Pilbara)
3	Basalt (Mt Jope)
4	Monzonite (Flemington)
5	Metabasalt (Mt Isa)
6	Metabasalt (Mt Isa)
7	Metabasalt (Mt Isa)
8	Massive sulphides (Cobar)
9	Pyrrhotitic ore (Elura)
10	Massive magnetite (Tennant Creek)
11	Massive (hexagonal) pyrrhotite (NW Tasmania)
12	Massive (monoclinic) pyrrhotite (Pine Creek)

TABLE 3

Sample No.	Conductivity (mho/m)	CSIRO Bridge (211 Hz)	Bison (1 kHz)	Elliott (1 kHz)	Geoinstruments (1 kHz)	Minnetech (1 kHz)	CTU-2 (5 kHz)	Digico (10 kHz)
Cal. factor		1.00	1.18	1.18	3.37*	1.26	1.45	1.00
1	~0	3,200	3,200	3,200	3,200	3,200	3,200	3,200
2	0.1	44	54	B	80	B	44	49
3	0.2	62	76	B	34	B	51	52
4	8	6,430	6,050	5,940	5,360	5,200	6,550	A
5	Low	53	45	B	44	B	-	-
6	Low	8,190	7,970	11,400	12,100	-	-	A
7	15	18,060	20,170	16,200	19,300	17,800	18,200	A
8	110	1,800	1,270	1,600	1,250	640	730	1,280
9	290	3,600	3,450	3,430	2,950	3,200	2,900	A
10	450	626,000	A	206,000	244,000	A	A	A
11	~10^4	360	350	400	320	B	330	330
12	~5×10^4	24,030	16,800	22,900	8,850	9,200	21,800	A

*includes geometry correction for 1 inch core. A. Signal off-scale. B. Signal below noise level

TABLE 4

Core	σ	211 Hz	1 kHz	5 kHz	10 kHz
1	0	3,200	3,200	3,200	3,200
2	0.1	44	67	44	49
3	0.2	62	55	51	52
4	8	6,430	5,780	6,550	-
5	Low	53	45	-	-
6	Low	8,190	10,500	-	-
7	15	18,060	18,600	18,200	-
8	110	1,800	1,370	730	1,280
9	290	3,600	3,280	2,900	-
10	450	626,000	$\sim$225,000	-	-
11	$\sim 10^4$	360	360	330	330
12	$\sim 5\times10^4$	24,030	16,200	21,800	-

Note: The susceptibility values quoted for 1 kHz measurement frequency represent the averages of the Bison, Elliott and Geoinstruments measurements. The Minnetech is omitted from the analysis due to its relative unreliability and lack of precision.