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APPARATUS FOR MEASURING MAGNETIC  
SUSCEPTIBILITY AND ITS ANISOTROPY

(Report and 4 figures)

K. W. Christie and D. T. A. Symons

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ABSTRACT

This apparatus was built to determine rapidly the magnetic susceptibility and/or its anisotropy in rock specimens in a low a. c. field ( $\approx 0.5$  oersteds). It accepts cubic or right cylindrical specimens up to 22 cc in volume. It consists of two accurately balanced a. c. transformers coupled to a commercial low-noise high-gain amplifier and digital voltmeter which allows volume susceptibilities as low as  $5 \times 10^{-8}$  emu(cgs) to be measured. To measure susceptibility only, the specimen is placed in the centre of one of the two identical sets of coaxial transformer coils with the amount of unbalance created being linearly related to the susceptibility. Alternatively, the susceptibility may be measured by placing the specimen in the air gap of the ferrite core in one of the two identical incomplete-toroid transformers; the susceptibility anisotropy is measured by moving a ferrite slug into the other air gap to balance the specimen's axial susceptibility and then rotating the specimen to measure the susceptibility difference for its other axes. It takes about 15 seconds per specimen to measure the susceptibility and a further 2 minutes to measure its anisotropy. The construction and calibration of the apparatus are discussed.



# APPARATUS FOR MEASURING MAGNETIC SUSCEPTIBILITY AND ITS ANISOTROPY

## INTRODUCTION

Magnetic susceptibility is defined by the ratio  $k = J/H$  where  $J$  is the intensity of magnetization or magnetic moment per unit volume induced by a magnetic field  $H$ . In natural rocks the value of  $J$  induced by a unit field  $H$  depends on the type, abundance, grain size and distribution of the minerals present especially the ferromagnetic minerals. Therefore the value of  $J$  is not easily estimated and must be measured. However, the value of  $J$  in rocks does vary almost linearly with  $H$  when  $H$  is low ( $< 1$  oersteds) which includes the range of the Earth's present magnetic field (0.25-0.5 oersteds) (Nagata, 1961). Low-field magnetic susceptibility is an important quantity to know for the interpretation of magnetic anomalies caused by rock formations having both induced and remanent magnetization, and more specifically in paleomagnetism for determining the Koenigsberger ratio  $Q$ .

Most rocks are not perfectly isotropic with magnetic grains randomly oriented and distributed. Therefore, the magnetic susceptibility is generally slightly to significantly anisotropic. Determination of the anisotropy of magnetic susceptibility is useful in petrofabric studies on many rock formations such as, for example, paleocurrent fabrics in sedimentary rocks (Rees, 1961), flow fabrics in extrusive and intrusive rocks (Symons, 1967), and stress fabrics in metamorphic rocks (Balsley and Buddington, 1960).

A number of instruments have been described in the literature to measure low-field magnetic susceptibility (Nagata, 1961; Collinson *et al.*, 1963; Graham, 1967) and its anisotropy (Granar, 1957; Girdler, 1961; King and Rees, 1962; Fuller, 1964; Stone, 1967). The apparatus described in this paper has been built in the Rock Magnetism Section of the Geological Survey of Canada during the past year to facilitate the routine measurement of these magnetic quantities for geologic studies. The apparatus has the advantage over others previously described in the literature in that it is sufficiently sensitive to study sedimentary rocks while retaining a rapid operation rate and having the main electronic components already available in most paleomagnetic laboratories from commercial sources.

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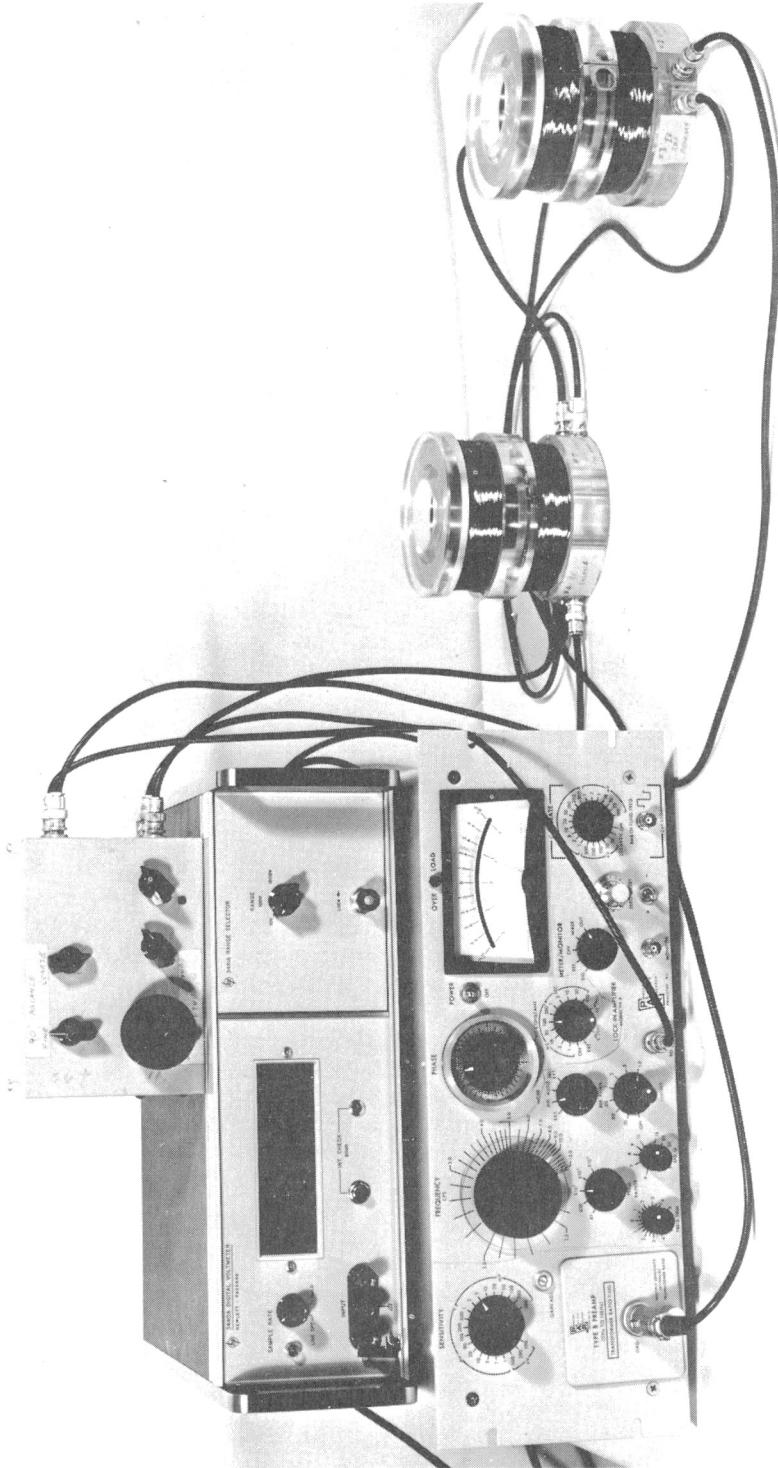


Figure 1. Solenoid transformer balance showing the operating layout with the amplifier unit on the left surmounted by the digital voltmeter, surmounted in turn by a box containing the variable resistor, variable capacitor and resonating capacitor. The transformers are on the right. (201113-B)

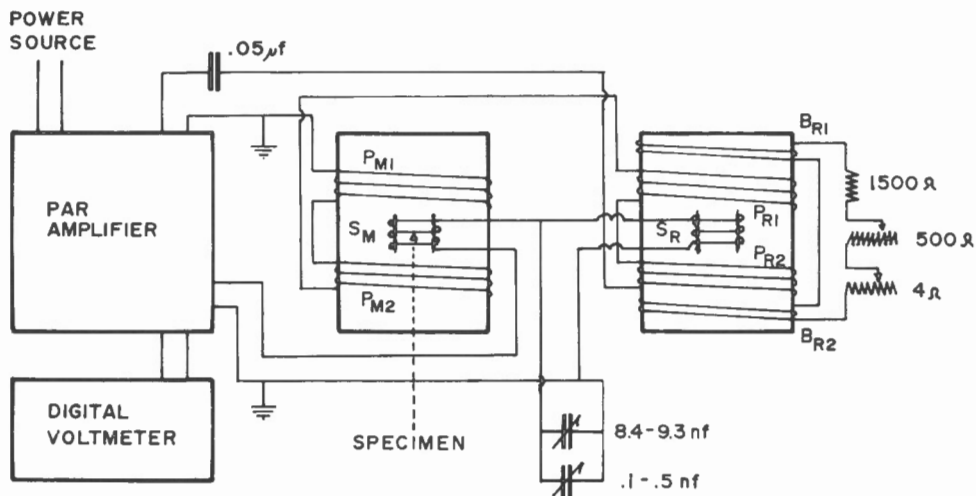


Figure 2. Block diagram for the solenoid transformer balance with the labels as noted in the text.

### DESCRIPTION

The apparatus is basically a transformer balance in which the internal oscillator of a Princeton Applied Research (PAR) lock-in amplifier (model HR-8 with a type B preamp for low impedance input) is used to excite in series the two primary coils ( $P_M$  and  $P_R$ ) of a measuring transformer and reference transformer respectively (Figs. 1 to 4). The net signal picked up by the two secondary coils ( $S_M$  and  $S_R$  respectively) connected in series opposition is returned to the amplifier input where it passes through a transformer, a linear amplifier, a narrow band filter, a phase sensitive detector for comparison with the output phase, and finally to a d. c. voltmeter for reading. The PAR amplifier is adjusted to suppress the out-of-phase component due to conductivity in the specimen and to give a positive (negative) reading for ferromagnetic or paramagnetic (diamagnetic) susceptibility. For easy and more precise reading, the result is displayed on a digital voltmeter (Hewlett-Packard, model 3440 A). All connections are made with single-wire shielded cable with the shielding grounded. Two pairs of transformers have been constructed of differing design and purpose. For simplicity, they are termed solenoid transformers and toroid transformers, and they will be described separately.

#### Solenoid Transformers

The solenoid transformer pair were designed for the rapid measurement of susceptibility along the longitudinal axis of a cylindrical core up to  $1 \frac{1}{4}$  inches in diameter.

The PAR amplifier output signal is set at an operating frequency of 1,000 Hz. It is fed through a  $0.05 \mu F$  resonating capacitor which was chosen to yield a maximum current into the primary coils of the two identical air-cored transformers. Each primary coil is in fact two coils ( $P_{M1}$  and  $P_{M2}$ ;  $P_{R1}$  and  $P_{R2}$ ) assembled in the form of modified Helmholtz coils similar to

3a

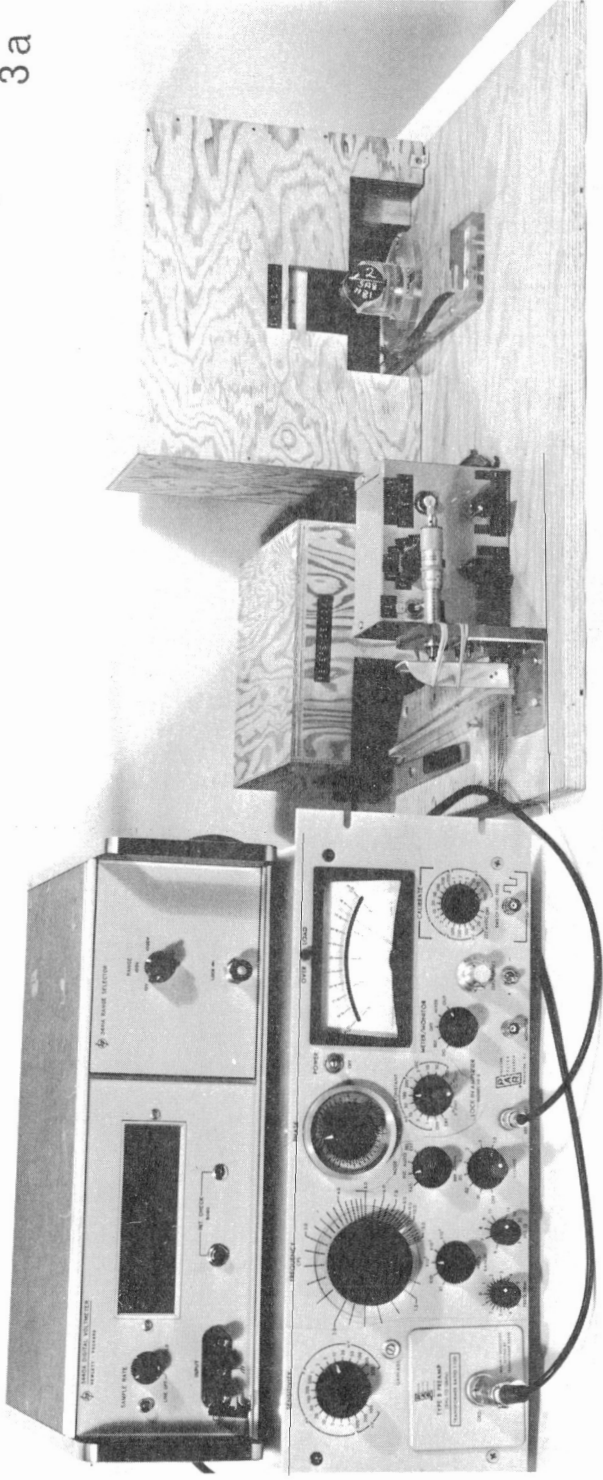
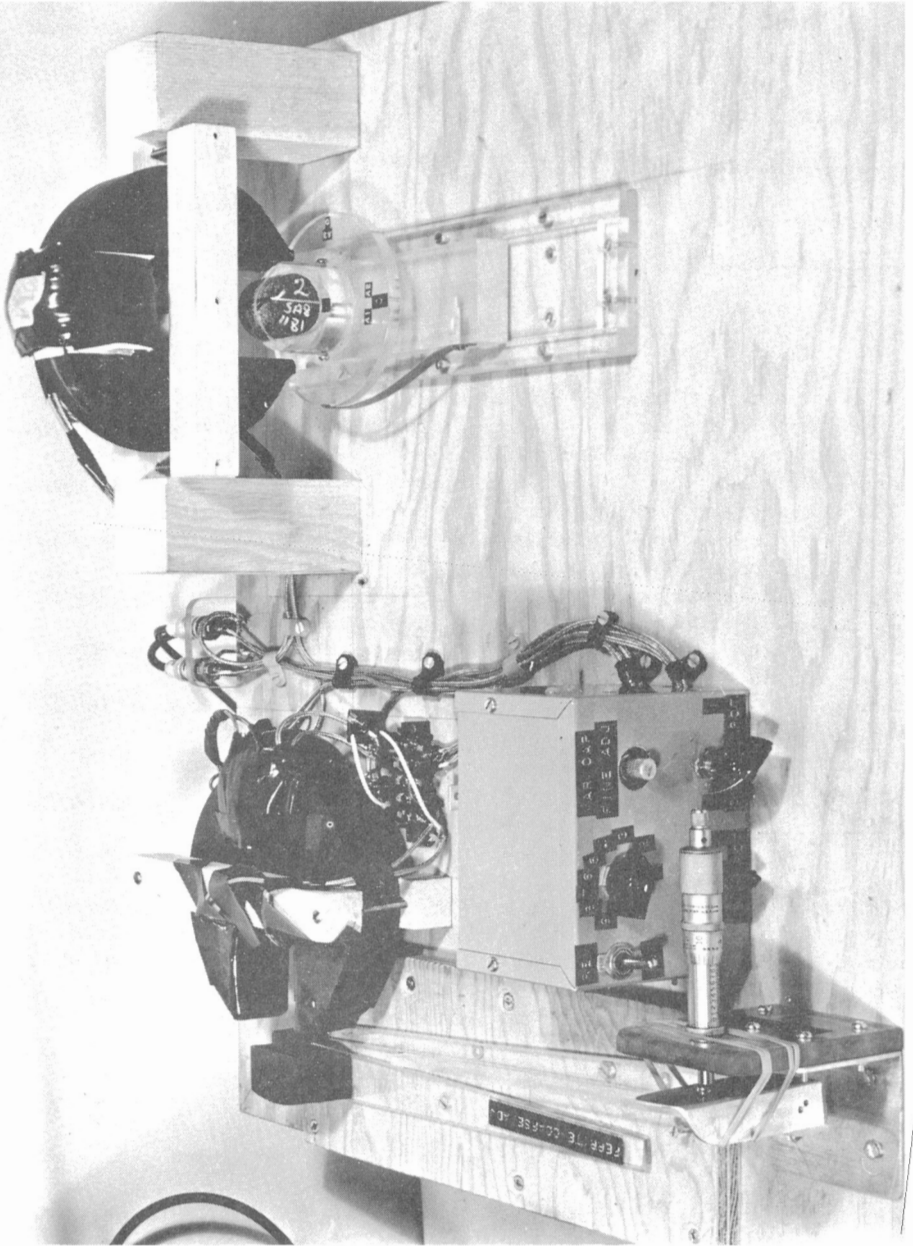


Figure 3a. Toroid transformer balance showing the operating layout with the amplifier unit on the left surmounted by the digital voltmeter, and the transformers on the right covered with draught shields. (201113E)

Figure 3b. Close-up view of the transformers. The reference transformer (upper left) is mounted so that the ferrite slugs (extreme upper left) can be moved in and out of its air gap using the micrometer (lower left) for fine adjustment. The measuring transformer (upper right) is mounted so that the specimen can be slid into the gap and rotated in its holder (middle right). The variable resistor, variable capacitor and resonating capacitor are in the box (middle left). (201113-A)

3 b



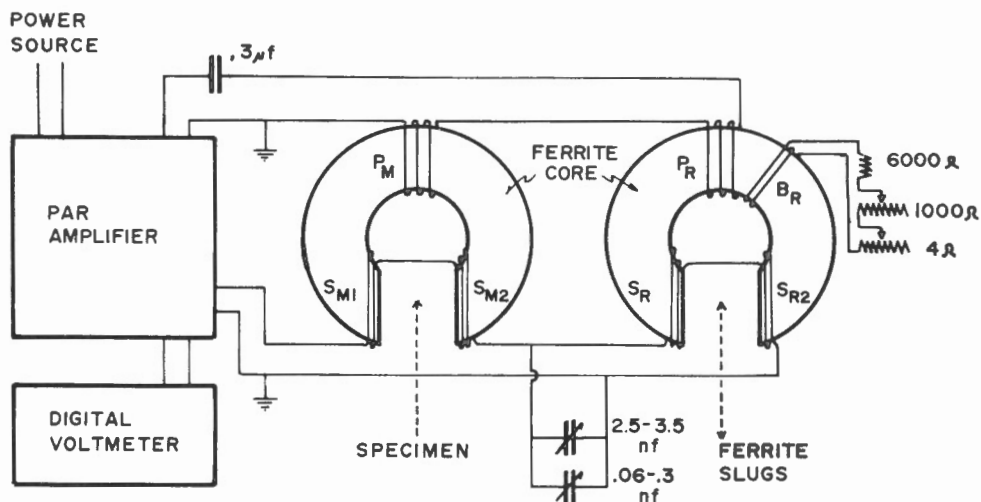


Figure 4. Block diagram for the toroid transformer balance.

that described by Graham (1967, and Figs. 1 and 2). Describing one transformer,  $P_{M1}$  and  $P_{M2}$  coils each contain 1,000 turns of ASA No. 22 enamelled copper wire with an inner diameter of 3 1/8 inches and a length of 1 1/8 inches, and with a coil separation of 1 inch. The secondary coil  $S_M$  is placed in the centre of and coaxial to the primary coils. It has 1,000 turns of ASA No. 29 enamelled copper wire with an inner diameter of 1 1/2 inches and a length of 1/2 inch. All the coils are rigidly held in a lucite mount. To achieve a better balance between the two transformers, an extra winding ( $B_{R1}$  and  $B_{R2}$ ) of 50 turns is added to each of the primary coils ( $P_{R1}$  and  $P_{R2}$ ) of the reference transformer. A variable resistor across the winding is used for the fine balancing of the conductive component. Also, a variable capacitor across one of the secondary coils (which one depends on where the unbalance between the two transformers exists) is used for the fine balancing of the inductive component.

### Toroid Transformers

The toroid transformer pair were designed for the rapid measurement of the anisotropy of susceptibility although the axial susceptibility of a specimen may also be readily determined. The general construction method is similar to that described by Collinson *et al.* (1963) and by Stone (1967).

The frequency of the PAR amplifier output signal is selected to yield a maximum current, and for this transformer pair, it is about 800 Hz. The signal is fed through a 0.3  $\mu$ F resonating capacitor and into the primary coils ( $P_M$  and  $P_R$ ) which each contain 4,000 turns of ASA No. 30 enamelled copper wire (Figs. 3 and 4).  $P_M$  and  $P_R$  are each wound on a ferrite core with each core constructed by cementing two disc 'toroids' together with epoxy and sawing out a 2-inch-wide air gap. The disc 'toroids' are made by Indiana General Corporation (part CF-125; material Q-1; outer diameter 5.8 inches; inner diameter 2.5 inches; thickness 0.625 inch and they have a

high initial permeability ( $\mu_{\text{init}} = 125$ ), a suitable mechanical rigidity, a low temperature coefficient ( $0.1\%/^{\circ}\text{C}$ ), a high Curie point ( $350^{\circ}\text{C}$ ), and a suitable frequency range (10 M Hz). Each transformer has two secondary coils wound on either side of the air gap ( $S_{M1}$  and  $S_{M2}$ ;  $S_{R1}$  and  $S_{R2}$ ) with each coil composed of 150 turns of ASA No. 34 enamelled copper wire and connected in series. As before, provision was made to achieve a better balance using a variable resistor with an additional 100 primary windings and a variable capacitor in conjunction with the reference transformer, however, the improvement proved marginal. Two ferrite slugs are used to balance the reference transformer by moving them in or out of the air gap; one is large and used for coarse adjustment, and the second is much smaller and used for fine adjustment in conjunction with a stainless steel micrometer (Tumico, model 1760). All the components are fixed solidly to a heavy plywood base and covered with draught shields in such a way as to reduce noise from electrical, seismic and thermal sources.

## OPERATION

### Specimen Considerations

Both transformer pairs are designed to operate with cylindrical core specimens of 1 1/4 inch diameter and 1 3/32 inch height which is the standard size used in our laboratory and the optimum configuration for our automated biastatic magnetometer (Larochelle and Christie, 1967; Larochelle and Pearce, 1969). Tests on artificial specimens of magnetite powder of various dimensions confirmed that such specimens are an optimum configuration for the toroid transformer balance. Thus significant distortion of the ellipsoid of anisotropy of magnetic susceptibility resulting from specimen shape or inhomogeneity is minimized (Stacey, 1960; Stacey *et al.*, 1960; King and Rees, 1962). Other specimen sizes such as smaller cores or cubes may readily be used with appropriate specimen holders, calibration constants and correction factors.

### Measurement

In both transformer pairs the axial susceptibility is determined by balancing the transformer pair, then inserting the specimen into the air core or gap of the measuring transformer which changes its reluctance and unbalances the circuit. The amount of unbalance is directly related to the susceptibility or induced component because the conductive component - which is relatively much smaller in most specimens in any case - is rejected by the phase-sensitive detector. The axial susceptibility is then determined by multiplying the voltmeter reading by the calibration constant. The time required to measure a single specimen is about 15 seconds.

To gain sensitivity to measure the anisotropy of susceptibility, the toroid transformer pair is balanced with the specimen inserted so that by rotating the specimen the difference in susceptibility along different axes is measured. By measuring along axes 45 degrees apart in three mutually perpendicular planes and by noting that the anisotropy satisfies a second-order tensor, the orientation and magnitude of the principal axes of the anisotropy

ellipsoid can be calculated (Granar, 1957; Nye, 1957; Girdler, 1961; King and Rees, 1962; and Stone, 1963). A computer program has been written to perform this calculation. The time required to measure the susceptibility of a single specimen along the required directions is about 2 minutes.

### Calibration

Both transformer pairs were calibrated using several specimens whose susceptibilities were determined using the electronically-calibratedd biastatic magnetometer with known inducing fields. The noise level is  $2 \times 10^{-8}$  emu (cgs) so that the minimum measurable volume susceptibility in both transformer pairs is  $5 \times 10^{-8}$  emu for the standard specimen size. Thus sediments which commonly have small diamagnetic susceptibility components of about  $-5 \times 10^{-7}$  emu with superimposed ferromagnetic components of lesser magnitude can be measured successfully. Under normal operation, the maximum measurable volume susceptibility is about 0.2 emu excluding the demagnetizing effect which increasingly exceeds 1 per cent over  $2.4 \times 10^{-3}$  emu. Susceptibilities of greater magnitude than  $5 \times 10^{-2}$  emu are relatively rare in natural rocks other than iron ores, but such specimens or artificial specimens could be measured by further attenuation of the input or output signal and by correcting for the demagnetizing effect.

The calculated peak field in the air cores of the solenoid transformer pair is 0.5 oersteds, and the measured field using a Hall probe is 0.3 oersteds. The measured peak field in the air gaps of the toroid transformer pair is 0.6 oersteds. Therefore the inducing field in both transformer pairs can be classified as a 'low field' comparable to the Earth's magnetic field. Further, there is a linear relationship between the voltmeter reading and the magnitude of the susceptibility of the calibrating specimens in the range from  $1 \times 10^{-6}$  emu to  $2 \times 10^{-3}$  emu.

### CONCLUSION

The described apparatus has proven suitable for the rapid routine measurement of low-field magnetic susceptibility and/or its anisotropy in specimens of all rock types of common paleomagnetic interest. The major electronic components - the amplifier and digital voltmeter - are commonly available in most paleomagnetic laboratories, so that the transformer pairs and fine balance electronics described can be built in a few days at a modest cost (< \$200.00 Cdn.).

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REFERENCES

- Balsley, J. R., and Buddington, A. F.  
1960: Magnetic susceptibility anisotropy and fabric of some Adirondack granites and orthogneisses; Am. J. Sci., vol. 258-A, pp. 6-20.
- Collinson, D. W., Molyneux, L., and Stone, D. B.  
1963: A total and anisotropic magnetic susceptibility meter; J. Sci. Instr., vol. 40, pp. 310-312.
- Fuller, M. D.  
1964: AC bridge methods for the measurement of susceptibility anisotropy; in Instruments and Techniques for Rock Magnetism, T. Nagata and K. Kobayashi, Edit., Univ. Pittsburgh, 13 pp.
- Girdler, R. W.  
1961: The measurement and computation of anisotropy of magnetic susceptibility of rocks; Geophys. J. Roy. Astr. Soc., vol. 5, pp. 34-44.
- Graham, J. W.  
1967: Preliminary account of a refined technique for magnetic susceptibility anisotropy measurement of rocks; in Methods in Paleomagnetism; D. W. Collinson et al., Edit., Elsevier, Amsterdam, pp. 409-424.
- Granar, L.  
1957: Magnetic measurements on Swedish varved sediments; Ark. Geofysik., vol. 3, pp. 1-40.
- King, R. F., and Rees, A. I.  
1962: The measurement of the anisotropy of magnetic susceptibility of rocks by the torque method; J. Geophys. Res., vol. 67, pp. 1565-1572.
- Larochelle, A., and Christie, K. W.  
1967: An automatic 3-magnet or biastatic magnetometer; Geol. Surv. Can., Paper 67-28.
- Larochelle, A., and Pearce, G. W.  
1969: A possible source of error in determining the remanent magnetization of cylindrical rock specimens with a biastatic magnetometer; Geol. Surv. Can., Paper 68-62.
- Nagata, T.  
1961: Rock magnetism; revised edition; Maruzen, Tokyo, 350 pp.
- Nye, J. F.  
1957: Physical properties of crystals; Clarendon Press, Oxford, 322 pp.

Rees, A. I.

- 1961: The effect of water currents on the magnetic remanence and anisotropy of susceptibility of some sediments; Geophys. J. Roy. Astr. Soc., vol. 5, pp. 235-251.

Stacey, F. D.

- 1960: Magnetic anisotropy of igneous rocks; J. Geophys. Res., vol. 65, pp. 2429-2442.

Stacey, F. D., Joplin, G., and Lindsay, J.

- 1960: Magnetic anisotropy and fabric of some foliated rocks from S. E. Australia; Geofis. Pura Appl., vol. 47, pp. 30-40.

Stone, D. B.

- 1963: Anisotropic magnetic susceptibility measurements on a phonolite and on a folded metamorphic rock; Geophys. J. Roy. Astr. Soc., vol. 7, pp. 375-390.

- 1967: An anisotropy meter; in Methods in Paleomagnetism; D. W. Collinson et al., Edit., Elsevier, Amsterdam, pp. 372-380.

Symons, D. T. A.

- 1967: The magnetic and petrologic properties of a basalt column; Geophys. J. Roy. Astr. Soc., vol. 12, pp. 473-490.