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Abstract. This paper describes an astatic magnetometer designed for the measurement of weakly magnetized rock specimens with special reference to a magnetic control method as a means of improving both the performance and efficiency of the instrument.

In the first section, it is shown that for high sensitivity and rapid response, the two magnets should be long and thin, magnetized perpendicular to the long axis, and that the moment of inertia of each magnet should be 1/4 the moment of inertia of the whole suspended system. In general, magnetic materials of high coercive force give the best design.

The second section describes in detail the construction of an astatic magnetometer according to the above principles, including a method of astatizing without the use of trimmer magnets. Following a discussion on the size, shape and positioning of the rock specimen, a cylindrical specimen (height/diameter $=\pi^{1}/_{2}/2$) placed directly beneath the lower magnet is chosen. A specimen table and a method for accurate determination of the distance between specimen and magnetometer are described.

The third section describes the procedure for measuring three orthogonal components of magnetization of a specimen. When the instrument is operated in the conventional manner, that is with the restoring torque provided by the suspension fibre, with a period of 14 seconds the sensitivity is 1×10^{-8} oe/mm deflection on a scale 5 m distant. This sensitivity permits the measurement of specimens magnetized to an intensity of 1×10^{-6} e.m.u.

The fourth section describes the use of negative feedback to improve the performance and efficiency of the instrument. Here, in addition to the torque of the suspension, a magnetic restoring torque is provided by a small solenoid connected to a pair of photo resistors centred on the light beam. Measurements can be made in terms of current or voltage with a variety of electrical instruments. High sensitivity (0.56×10^{-9} oe/mv) can be obtained while maintaining a short period (5.1 sec). The sensitivity and the period can be lowered instantly through 11 steps down to 1.2×10^{-7} oe/mv and 1.2 sec. The quick response permits the direct measurement of the direction and total intensity of magnetization of the specimen, rather than computing them from three components. This eliminates much calculation and increases the accuracy, especially with weakly magnetized rocks. The range of the instrument provides for accurate measurement of specimens magnetized to an intensity of 1×10^{-7} to 5×10^{-3} e.m.u.; the time required for a measurement of direction and intensity is eight and three minutes, respectively. The period and damping of the system can be altered in many ways to suit particular conditions and requirements. Disturbances affecting the instrument and means of avoiding or reducing them are discussed.

Résumé. Les auteurs décrivent un magnétomètre astatique servant à mesurer l'intensité d'aimantation, généralement très faible, d'échantillons de roches; ils insistent tout particulièrement sur une méthode de contrôle par champ magnétique permettant d'améliorer la sensibilité et le rendement de l'appareil.

Dans la première partie, ils démontrent que, dans un système astatique à deux aimants, il est préférable d'utiliser des aimants longs et étroits aimantés perpendiculairement à leur axe longitudinal; en outre, le moment d'inertie de chaque aimant devrait être égal au 1/4 de celui de l'ensemble de l'équipage mobile. En général, ce sont les matériaux magnétiques à haute coercitivité qui répondent le mieux à ces conditions.

Dans la deuxième partie, les auteurs décrivent en détail la construction d'un magnétomètre astatique conçu suivant les principes énoncés précédemment, et la méthode employée pour le rendre astatique sans utiliser des aimants compensateurs. Après avoir discuté des dimensions, de la forme et du positionnement de l'échantillon, ils fixent leur choix sur un échantillon cylindrique (hauteur/diamètre = $\pi^{1}/_{2}/2$) placé directement sous l'aimant inférieur. Ils décrivent ensuite le porte-échantillon ainsi que la méthode permettant de déterminer avec précision la distance optimale entre échantillon et magnétomètre.

Dans la troisième partie, les auteurs énoncent la procédure à suivre pour mesurer trois composantes orthogonales de l'intensité d'aimantation d'un échantillon. Quand l'appareil fonctionne suivant le mode habituel, c'est-à-dire quand le couple de rappel du fil de torsion correspond à une période d'oscillation de 14 secondes, la sensibilité est de 1×10^{-8} oersted pour une déflection de 1 mm sur une mire graduée distante de 5 m. Cette sensibilité permet de mesurer l'intensité d'aimantation d'échantillons présentant des intensités aussi faibles que 1×10^{-6} gauss.

Dans la quatrième partie, les auteurs décrivent le procédé par lequel ils améliorent la sensibilité et le rendement de l'appareil à l'aide d'un système de rétroaction négative. On ajoute au couple de torsion du fil de suspension un couple de rappel électromagnétique fourni par un petit solénoïde connecté à deux photorésistances encadrant le faisceau lumineux. Les mesures se font en termes d'intensité ou de tension, à l'aide d'appareils électriques variés. Grâce à la méthode indiquée ci-dessus, on peut obtenir une haute sensibilité (0.56×10^{-9} oersted/millivolt), tout en conservant une courte période d'oscillation (5.1 sec.). On peut réduire instantanément la sensibilité et la période, en 11 étapes successives jusqu'à 1.2×10^{-7} oersted/millivolt et 1.2 seconde. Le temps de réponse très court ainsi obtenu permet la mesure directe de la direction et de l'intensité de l'aimantation de l'échantillon sans avoir à les calculer à partir de trois composantes. Ceci élimine une grande partie des calculs et améliore la précision, en particulier dans le cas des roches faiblement aimantées. L'appareil permet une mesure précise sur des échantillons dont l'intensité est comprise entre 1×10^{-7} et 5×10^{-3} gauss; il faut 8 et 3 minutes respectivement, pour mesurer la direction et l'intensité de l'aimantation. Il est possible de modifier à volonté la période et l'amortissement de l'équipage mobile pour répondre aux conditions et aux exigences particulières qui pourraient se présenter. Les auteurs examinent enfin les perturbations pouvant affecter l'appareil et indiquent la façon de les éviter ou d'en atténuer les conséquences.

Introduction

Astatic magnetometers have been used extensively for the measurements of the remanent magnetization of rock specimens since Blackett (1953) showed them to be well suited for measuring weak fields. Blackett's magnetometers were designed to measure the weakest field possible without regard to the time taken, and instrument periods were as long as 60 to 70 seconds. In paleomagnetic work, a large number of measurements are required and shorter period instruments are desirable. Various designs for maximum sensitivity at a limited period have been described (e.g. Collinson *et al.*, 1957; As, 1960; Collinson and Creer, 1960; Roy, 1963). Owing primarily to new manufacturing processes of magnetic materials, it has been possible over the last two decades to improve the design and consequently the performance of astatic magnetometers. The performance of a magnetometer constructed according to the design theory given by Roy (1963) and using Platinax II magnets shows that the instrument can accurately measure the components of magnetization of a rock specimen magnetized to an intensity of 1 x 10^{-6} e.m.u. with an acceptable response time of 14 seconds. With a change of the suspension fibre, the response time can be shortened to, say, 4 to 5 seconds; the corresponding reduced sensitivity (≈ a tenfold reduction) is still adequate to measure intensities of 1 x 10^{-5} e.m.u. These performances are obtained when using the conventional torsion control method of measuring (by means of lamp mirror and scale) the deflection produced by a magnetized specimen placed near the instrument. When using the instrument in this mode, the deflection of the magnet system should be entirely controlled by the torsion of the fibre. For this reason, by changing the suspension, the instrument can be made into a high sensitivity magnetometer *or* a quick-response magnetometer; however, the two characteristics (high sensitivity and quick response) cannot be combined because an increase of one is accompanied by a reduction of the other.

The range of intensities found in rock specimens is large (≈ 1 x 10^{-7} to 1 x 10^{-2} e.m.u.) and an instrument with multiple sensitivities is desirable for reasons of efficiency. Changing suspension fibres to attain this objective is most impractical. Because of the high risk of breaking the fibre, such changes are usually avoided. Furthermore, the time required for realignment of the system would defeat the purpose. An alternative would be to have several magnetometers of different sensitivities. However, because it is preferable to operate these instruments in field-free spaces, an array of such spaces far apart one from the other (to avoid interference) would be required. Such a proposition would be costly and not the most practical for obvious reasons, such as the time spent travelling from one instrument to the other.

Part IV describes a method by which the same instrument can be converted into a multiple sensitivities magnetometer. By using a feedback system, the sensitivity can be changed electrically to different preset values. In this way, the measuring range of the instrument can be expanded and, with the proper choice of sensitivities, the magnetometer can be operated at maximum efficiency whatever the intensity of the specimen. The performance (both sensitivity and speed of operation) can also be greatly improved. The sensitivity attainable with the present magnetometer is 10 times greater in the magnetic control mode than in the torsion control mode; at the same time the response is markedly quickened and kept below 6 seconds for all sensitivities. This rapid response permits the use of a direct-read method of determining the direction and total intensity of the magnetization of a rock specimen. Because two measuring procedures (three-component and direct-read) can be used with this instrument, both are described.

Part I — Theory of design

1. The magnet system

An astatic magnetometer consists essentially of two magnets fixed to a vertical rod which is suspended by a fibre or ribbon. The magnets of nearly equal moments are set with their directions of magnetization horizontal and antiparallel, and with one a distance L above the other. A mirror fixed to the rod permits one to measure the angular deflections of the suspended system about a vertical axis. To avoid susceptibility effects and to increase the sensitivity of the instrument, the magnetometer is usually placed in a quasi-zero field. The earth's field can be reduced by means of a magnetic-shielded room such as described by Patton (1967) or compensated for by means of a system of Helmholtz (or a similar type) coils. The choice of shielding or compensating coils does not alter the basic design but could possibly affect performance.

When a magnetized specimen is placed under the bottom magnet and oriented so that its direction of magnetization is not parallel to the axis of magnetization of the magnet, the deflection of the suspended system in a zero field is given by

$$\theta = \Delta HP/\sigma \quad \ldots . \ (1)$$

where ΔH is the vector subtraction of the fields produced at the bottom and upper magnets, P is the horizontal moment of a magnet and σ is the torsion constant of the fibre. The period is given by

$$T^2 = \frac{4\pi^2 I}{\sigma} = \frac{4\pi^2(2I_1 + I_2)}{\sigma} \quad \ldots . \ (2)$$

where I, I_1 and I_2 are the moments of inertia of the system, of one magnet and of the system without the magnets, respectively.

From (1) and (2), we find the sensitivity is

$$\frac{\theta}{\Delta H} = \frac{T^2}{4\pi^2} \cdot \frac{P}{I} = \frac{T^2}{4\pi^2} \cdot \frac{P}{2I_1 + I_2} \quad \ldots . \ (3)$$

showing that the sensitivity can be increased by increasing the period and the ratio P/I.

2. Period limitations

Three considerations limit the increase of T. The first is the efficiency of the instrument. With critical damping, as is usually the case, the time taken for an observation may be taken as equal to the period. For routine measurements, because of the number of observations required (6 or 12 for each specimen), 30 seconds is normally regarded as the maximum period allowed.

The second limitation is due to the fact that a system cannot be made and remain truly astatic. The astaticism A is defined as the ratio of P/P' where P' is the residual moment of the system and can be written

$$A = P/P' = P/(P'^2_A + P'^2_S)^{1/2} \quad \ldots . (4)$$

where $P'_S = P_B - P_M$

$$P'_A = \alpha P_B = \alpha P_U$$

P_B and P_U being the dipole moments of the lower and upper magnets and α the angular departure from antiparallelism. Although an astaticism of 5,000 or even 10,000 can be obtained, it is unlikely to remain for any length of time owing to changes with time and temperature; changes which affect the whole system and particularly the magnetic properties of the magnets. For periods of months or years, it is more realistic to consider an astaticism of about 1,000. This is normally sufficient for accurate measurements on a magnetically quiet day. However, the error introduced in the readings owing to variations on disturbed days may be large and, for this reason, it is usually preferable to keep the period short. This source of error can be practically eliminated by using a negative feedback fluxgate system (Roy, 1963) which automatically detects and compensates for the diurnal variation.

The third limitation arises from the effect of changes in the dimensions and shape of any part of the apparatus, mainly of the compensating coils. These changes, which become more serious as the sensitivity is increased, may originate from different sources such as vibration and ambient temperature changes. Distortion or relative displacements of the compensating coils produce different field changes at the upper and lower magnets. Since the astaticism cannot reduce the effect of this type of disturbance, the drifts that occur might be considerable. This is exemplified in Part IV. These disturbances can be reduced by rigid construction of the coil system and good temperature control and their effect minimized with short periods.

3. Ratio P/I

This ratio which should be made as large as possible is given by

$$P/I = m\,J(\beta)\,/\,(2I_1 + I_2) \quad \ldots . (5)$$

where m is the mass of one magnet. $J(\beta)$ is the specific intensity of magnetization of a rectangular magnet of square cross section where $\beta = w/h$ = width/height.

Although the $J(\beta)$ of many materials increases asymptotically to a maximum value as β increases, it is found (Roy, 1963) that, because I_2 cannot be neglected (5), the maximum P/I is usually obtained for $\beta < 1$, that is, when the magnet is magnetized transversely or parallel to the short side. $J(\beta)$ is then ($0 < \beta < 1$) almost independent of shape (or β) and as a first approximation $J(\beta)$ can be treated as a constant. Under this condition, it can be shown that P/I is maximum for

$$I_1 = I_2/2 \quad \ldots . (6)$$

and from (5), we get

$$P/I = m\,J(\beta)/2I_2 \quad \ldots . (7)$$

I_2 should therefore be made as small as possible keeping in mind the necessity of a mirror large enough to provide a good light beam and a structure rigid enough to maintain high astaticism.

The dimensions of the magnet can be obtained from

$$I_2 = \rho\,hw^4/3 \quad \ldots . (8)$$

where ρ is the density of the magnetic material or from

$$I_2 = \pi\rho\,hd^4/16 \quad \ldots . (8a)$$

for an upright cylindrical magnet of diameter d.

From (7) and (8), one finds that P/I is inversely proportional to w^2 for rectangular magnets and to d^2 for cylindrical magnets indicating that the magnets be made high and thin. However, depending on the positioning of the specimen with respect to the magnet system, a practical limit of h usually has to be set. For example, when the specimen is placed under the bottom magnet, h should be small compared to the distance z between magnet and specimen; otherwise only part of the magnet would be reacting to a field produced by a nearby specimen. In general, h should be kept < 1 cm.

4. Magnetic materials

New manufacturing processes have made available magnetic materials well suited for astatic magnetometers; products of ceramic barium ferrite ($BaFe_{12}O_{19}$) such as Magnadur II, Magnadur III, Indox V and Arnox Va, and cobalt-platinum alloys such as Platinax II have very high coercive forces and their specific intensity of magnetization is almost independent of shape. The P/I curves of these materials are comparable and the performance of a magnet system built with any of these materials would be approximately the same (Deutsch *et al.*, 1967). Platinax II, however, is a very hard material that can be easily machined and is not as friable as the ceramic material. The Platinax II P/I curve is given in Figure 1 for different practical values of I_2. The I_2 of the system described next is $0.0019 \leqslant I_2 \leqslant 0.0025$ gm.cm^2. The uncertainty arises from the limits of error in calculating the moment of inertia of each component of the system. For this I_2, the maximum P/I requires 0.18 cm diameter magnets while ours are 0.2 cm. The reason for the discrepancy is that the exact value of I_2 cannot be determined in advance.

Part II — Experimental design

1. The magnet system (Figure 2)

The separation L (centre to centre) between the magnets (height = 0.8 cm) is 7.68 cm. The glass connecting rod (0.90 cm dia.) is inserted and cemented into the aluminum holder (wall thickness = 0.03

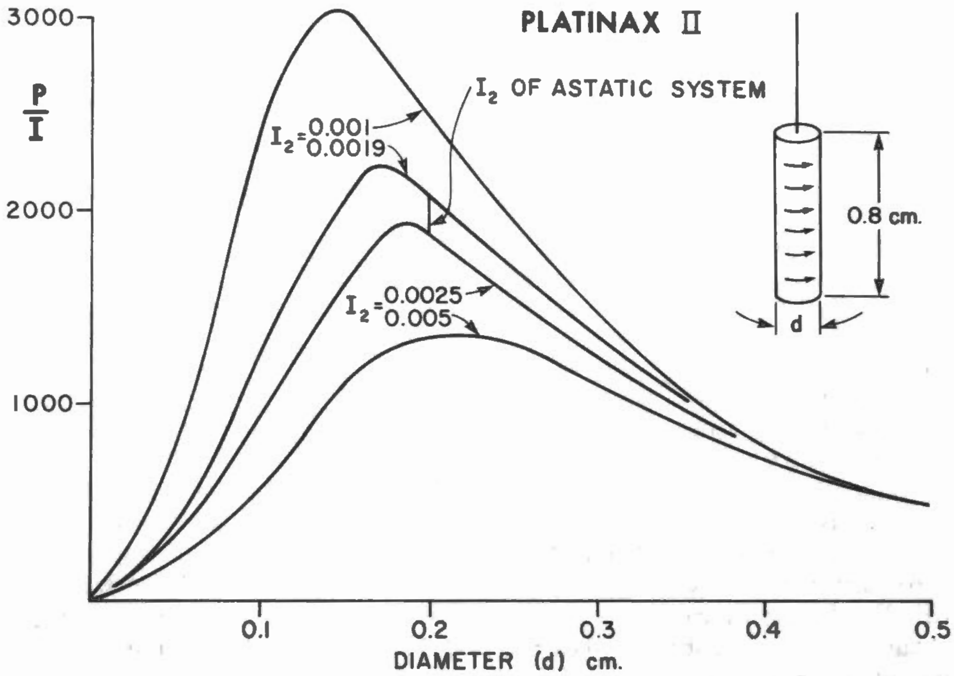

Figure 1. Values of P/I plotted against the diameter of transversely magnetized cylindrical magnets (height = 0.8 cm) for fixed I_2 and calculated from (7). ρ = 15.5. The calculated I_2 of the astatic system described in Part II is indicated.

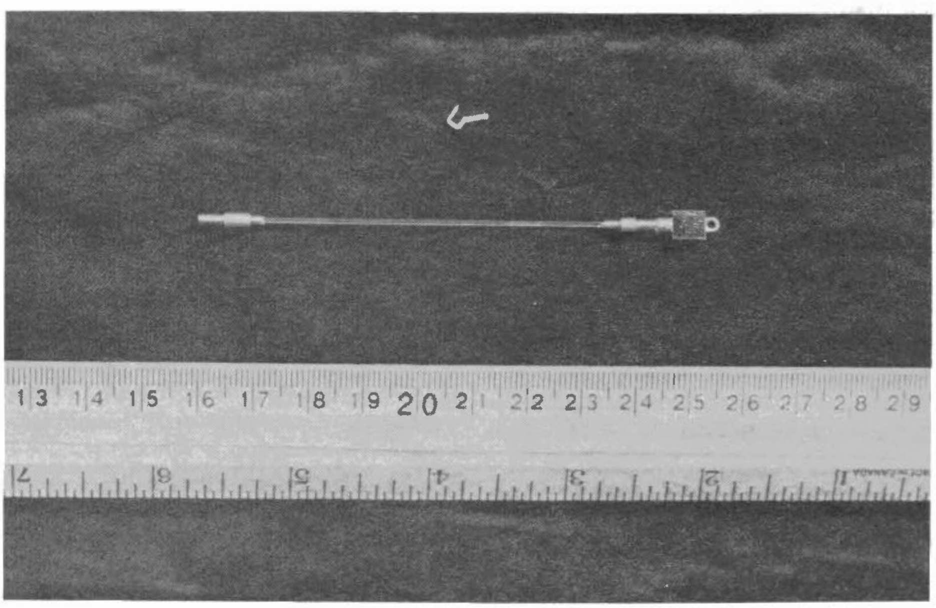

Figure 2. Astatic system of Platinax II magnets as described in Part II.

cm). The upper magnet is inserted and cemented into its holder (wall thickness = 0.025 cm). The mirror (side = 0.5 cm, thickness = 0.001 cm) is cemented into a depression of the top holder in order to maintain the dynamic balance of the system. The cross section of the bottom of the hook is of the knife edge type to avoid relative angular displacement between the magnet system and the suspension. The bottom magnet is pressure fitted into the slotted bottom holder so that with the aid of the rig described here it is possible to obtain high astaticism without the use of trimmer magnets that would add substantially to the moment of inertia. The magnets were first chosen out of a lot of 20 by comparing their magnetic moments using a commercial oerstedmeter. With repeat measurements at different distances from the probe, two magnets could be matched to better than 0.002 for an astaticism A_S ($=P/P'_S$; eq. 4) > 500. The final A_S (1000) was obtained by rubbing down the bottom magnet with an emery cloth. An azimuthal astaticism A_A ($=P/P'_A$; eq. 4) of 2200 was obtained with the following method. The bottom holder (with its magnet) is loosely clamped into an expansible hole (by means of a set screw) made at the end of a long pointer (25 cm). The pointer and the magnet system are placed onto a plate where an expansible hole receives the protruding bottom magnet which is then securely clamped. The pointer is moved in the required direction on a graduated scale drawn on the plate; in this way, the upper part of the system (carrying the upper magnet) can be accurately rotated while the bottom magnet is held in place. With such controlled rotations, a high astaticism can be obtained in a few (≈4) trials. A_A and A_S were determined by producing uniform fields parallel to (for A_A) and perpendicular to (for A_S) the direction of magnetization of the magnets. It is preferable to do both astaticisms at the same time as they become large. Unless the applied field is exactly parallel (or perpendicular) to the axis of magnetization of the upper magnet, and this usually is not the case when astatizing (because the system is taken in and out so often), the field will not be applied solely to P'_A or P'_S but to a component of each. If P'_S is much larger than P'_A, for example, part of it can easily be mistaken for a P'_A with the result that the magnet will be rotated the wrong way.

2. Magnet system housing (Figure 3)

The system is suspended by a 30-cm long phosphor bronze strip attached to a threaded rod passing through a circular plate which closes the upper end of an aluminum tube (length 23.5 cm; diameter 2.5 cm). The threaded rod and circular plate permit height adjustment of the magnet system. The tube is fixed to a 3-point aluminum plate resting on a wooden tripod. Levelling screws permit plumb adjustment of the tube. Under the plate, a rectangular box (height 18.7 cm; sides 7.6 and 3.2 cm) is attached. The short sides are made of aluminum and hold a nylon bottom plate. On the centre of this plate, a threaded holder carrying an aluminum disc (diameter 2.5 cm; thickness 0.15 cm) can be height adjusted for critical damping. The long sides are closed by detachable Perspex windows. The width of the box facilitates the installation and removal of the magnet system from the suspension hook. Two sides and the bottom are of nonmetallic materials to avoid eddy currents. Lenses of different focal lengths can be easily installed on the window facing west. The mirror has been set facing west so that the light beam is not in the direction of the operator.

3. Field compensation

The magnetometer is installed in the centre of a set of three orthogonal pairs of square (side = 244 cm) coils, which is part of an array of five identical sets (Roy *et al.*, 1969). The set (Figure 3) is located at the south end of a 3 x 12 meters building oriented along the magnetic meridian. Each component (vertical Z, horizontal along H_H and perpendicular to H_D the meridian) of the earth's field are compensated for by two circuits. Constant fields produced by constant currents compensate the mean field and a negative feedback fluxgate system compensates the diurnal variations. An additional winding on the coils is used to produce nearly uniform fields when astatizing the magnet system.

The system is oriented with the north pole of the bottom magnet pointing north. The effective compensation of the diurnal variations are 0.998 ± 0.0002 for H_H and 1.000 ± 0.0002 for H_D. Since the astaticisms are A_A = 2200 and A_S = 1000, the ratio of apparent uniform disturbing field is 10^{-6} for north-south and 2×10^{-7} for east-west disturbances.

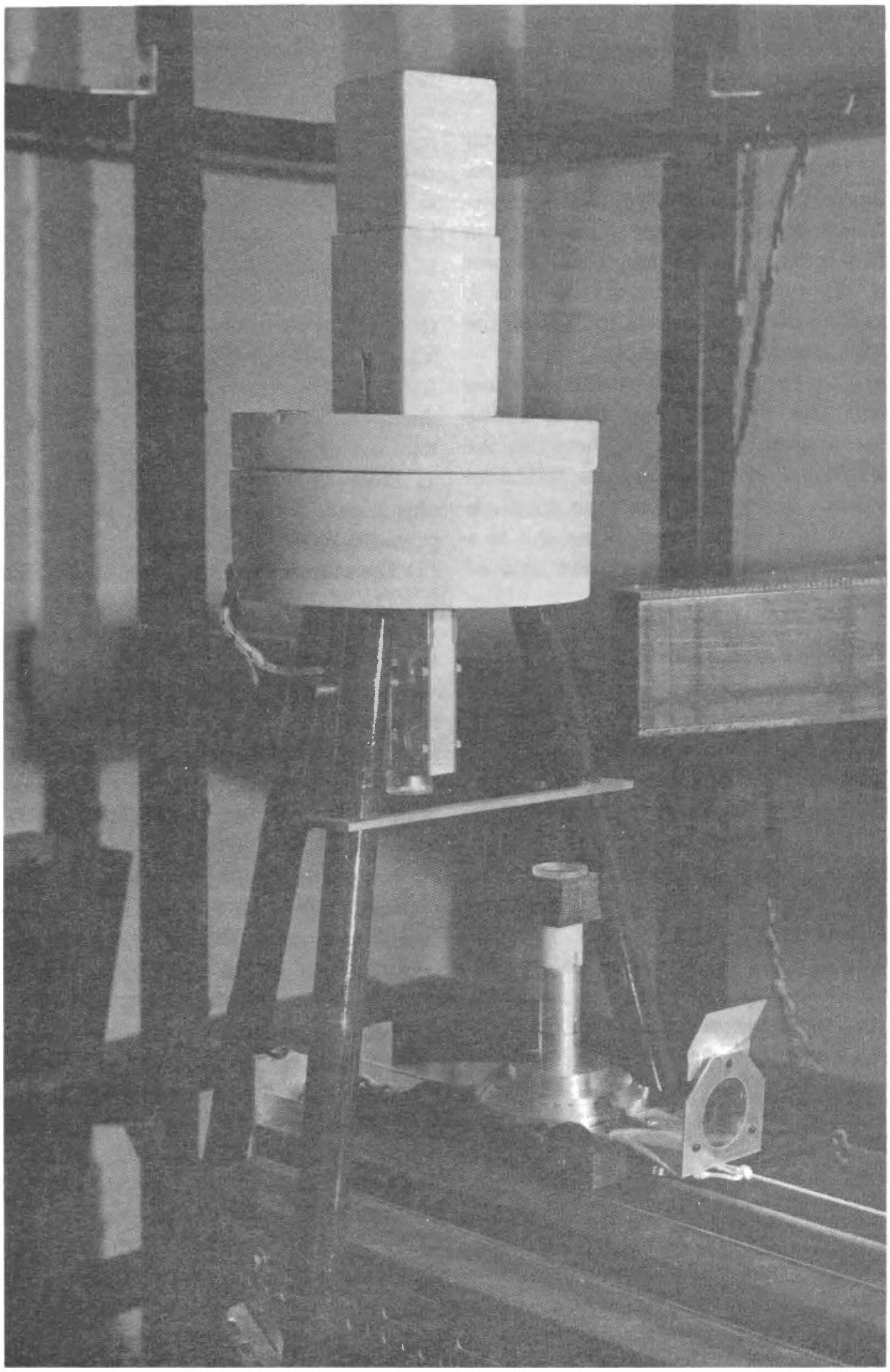

Figure 3. Astatic magnetometer with styrofoam head and specimen presentation table. Descriptions are given in Part II.

This means that for a change of say 100 γ in the north-south component, the deflection of the magnet system would correspond to a field of 10^{-9} Oe applied to the bottom magnet. At the location, the diurnal variations on a normal day are in the 60-70 γ range and on a disturbed day, they average about 200 γ. The instrument drift due to diurnal variations is therefore negligible.

4. Response of an astatic magnetometer

The amplitude of the angular deflection of the magnet system to the magnetization of a rock sample depends (1) on the positioning of the sample with respect to the system, (2) on the distance L between the two magnets and (3) on the shape and size of the sample.

(1) The sample can be positioned many ways (see Collinson and Creer, 1960). For a given distance (z) between the sample and one of the magnets, maximum response is obtained when the sample is placed in the horizontal plane and in a direction perpendicular to the axis of magnetization of the magnet (position A). Another position (B) is the placing of the sample on the axis of rotation of the system and below the lower magnet. The response of the instrument is about twice as large for position A as for position B. However, for practical considerations, position B is usually favoured. Technically, with a more sophisticated magnet system housing design, it is possible to make z as small for position A as for position B. However, because the presentation of the sample must be done by remote control (to avoid magnetic and other disturbances caused by the operator) safety devices to protect against accidentally hitting the instrument must be added. For position B, such devices (aluminum clamp on Figure 3) can be installed without increasing z since the sample and holder slide under the instrument. For position A, the sample has to be pushed toward or alongside the instrument. Since it is useful to be able to vary the distance (for measuring different intensities) the latter case should have a transverse motion. Therefore, in both cases, the sample has to be pushed toward the instrument and a protective screen must be installed, and z increased. Because the field reduces as the third power of the distance, a small increase of z will considerably reduce the instrument response. So, in practice, it is found that there is little to choose between the two positions. Position B was chosen because only one component (horizontal) of magnetization is measured in a single reading. In position A, the vertical component produced a field at the upper magnet; the deflection produced by this component is nulled by inverting the sample and averaging.

(2) The sensitivity of the instrument depends on L since the field produced at the oppositely magnetized upper magnet reduces the deflection. L should then be made large. On the other hand, the larger L is, the larger are the deflections produced by magnetic disturbances other than diurnal variations; disturbances such as those caused by a nearby magnetic object and distortion of the field compensating coils.

(3) The standard size specimen used in our laboratory is an upright cylinder of 2.5 cm diameter and 2.2 cm height for a ratio height/diameter = $\pi^{1/2}/2$. A larger ratio would increase the response of the magnetometer (Roy, 1967). However, since the specimen is of finite size and not a dipole point, corrections as calculated by Papapetrou (see Blackett, 1953) must be applied. When the specimen is cut according to the above ratio, the corrections are quite small (2% for $z = 3.6$ cm) and the same whether the specimen is upright or on its side (Roy, 1966); thereby, the errors due to shape are small and the computation of results simplified.

A larger deflection would be obtained by using a larger specimen even if, for small z, the increase in deflection is not equal to the increase in volume. To make room for the larger specimen, z must be increased by $\Delta z = (V_x^{1/3} - V_s^{1/3})/2$ where V_s and V_x are the volumes of the standard and larger specimens respectively. The increase of the ratio deflection/volume varies with the increase in volume; for a typical $z = 3$ to 4 cms, the ratio increase would amount to 0.6 – 0.8 of a two- to four-fold increase in volume or about a 3-times larger deflection for a 4-times larger volume. There are many hindrances to using too large a specimen; for example, as the size is increased, the effects of inhomogeneity increase, larger coring equipment is required, etc. The main consideration is that, in rock magnetism, a specimen is often fitted into different apparatuses. Because other pieces of equipment such as alternating field demagnetizer favour small specimens, a medium-size specimen must be adopted as a standard.

5. Calibration

The system is calibrated by means of a coil suspended from the ceiling. The distances from the centre of the coil to the centres of the magnets are 122.27 and 129.95 cm. The 91 turns are tapped on the fifth turn to provide two field-producing sources for calibration of high (5 turns) and low (91 turns) sensitivities. The difference of field ΔH at the magnets is 1.010 x 10^{-8} Oe/ma for the 5 turns (diameter = 16.76 cm) and 0.6794 x 10^{-7} Oe/ma for the 91 turns (diameter = 15.98 cm).

6. Specimen table (Figure 3 and 4)

The specimen is placed in a graduated (10° spacing) Perspex cylinder which has been bored so that the specimen fits snugly. The cylinder fits into a rectangular piece of laminated wood veneer (permali). The dimensions of the cylinder and the wood holder are such that the distance between the centre of the specimen and all faces of the holder is constant so that z remains constant for all attitudes of the specimen. Holes in the bottom and two sides of the holder fit onto a pin in the centre of a small table for accurate centring of the specimen. Ridges on each side of the table maintain the orientation of the holder. The table is attached to a female tapered post which fits onto a male tapered post in the centre of a disc (diameter = 14 cm) whose perimeter is graduated in degrees. The assembly is installed on a three-wheeled carriage which is rolled under the magnetometer by means of string and pulleys. When the assembly is against its stop, gear coupling (ratio 4 to 1; 1 turn = 90°) permits rotating the assembly from a distance of two meters. The orientation

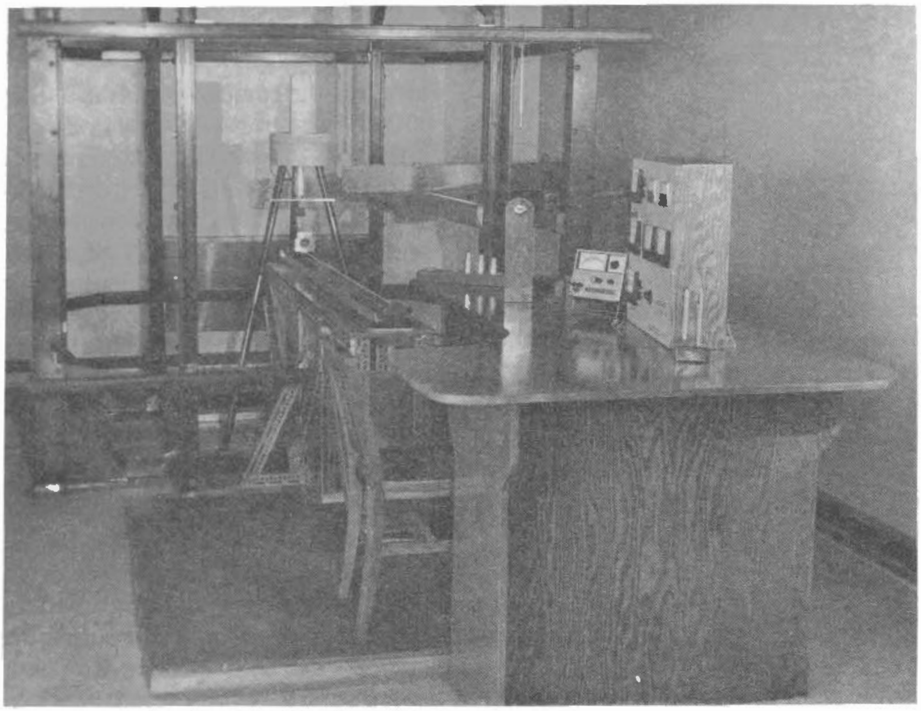

Figure 4. General view of astatic magnetometer and accessories.

of the specimen given by the graduated circle is read through a lens.

Centring and levelling of the holder table was accomplished by means of a small coil producing vertical fields. The carriage table is moved and tilted on the stationary table until the magnet system remains undeflected when a large field is applied in different azimuthal directions. A levelling to within 0.5° and a centring to within 0.3 mm could be obtained. Five different z's are provided by inserting tapered spacers (shown on the desk) under the holder table. The alignment of all parts is maintained by a slot and a pin at the bottom and top of the spacers. The distance z between each position and the bottom magnet is measured by means of magnetic fields; this is more accurate than direct readings of the distance. For each position a small two-turns coil (diameter = .503 cm) is placed with its axis perpendicular to the axis of magnetization of the magnet. A field is produced by passing a calibrated current through the coil. The difference of field ΔH at the bottom and upper magnets (for large A) is given by

$$\Delta H = \pi N i C_c r^2 \, 10^{-4} \times \left[\frac{C_B}{(r^2+z^2)^{3/2}} - \frac{C_U}{\{r^2(z+L)^2\}^{3/2}} \right] \quad \ldots \quad (9)$$

where i is the current in milliampere, N is the number of turns and r the radius of the coil. C_c, C_B and C_U are the corrections for the shape of the coil, bottom and upper magnets respectively. These corrections are to compensate for the differences between the physical and effective centres of coil and magnets; differences that are not negligible when z is comparable to the dimensions of these components.

The angular deflection θ of the system produced by ΔH is measured by the deflection (defl.) of the light spot reflected from the mirror. Using a scale at a distance D',

$$\Delta H = \frac{H_s \times \text{defl. (mm)}}{2 D' \theta} = S \times \text{defl. (mm)} \quad \ldots (10)$$

where S is the sensitivity expressed in Oe/mm defl. and is defined as the difference of field H_s required to deflect the light spot by 1 mm at a distance D'. From (9) and (10) we find that

$$\frac{C_c \, i}{\text{defl. (mm)}} \times \left[\frac{C_B}{[r^2+z^2]^{3/2}} - \frac{C_U}{\{r^2+(z+L)^2\}^{3/2}} \right] = C \quad \ldots (11)$$

where

$$C = \frac{10^4 S}{\pi N r^2} \quad \ldots (12)$$

Taking measurements at the different positions different i, z must be determined so that C in (11) is a constant. It is found that with precise measurements of i and defl. (the two large variables), z can be determined to within 0.3 mm. The method also provides an excellent check on the sensitivity (12) obtained from the calibration coil. The agreement between the two methods of calibrating is within 1 per cent.

The ratio of P/I can be checked experimentally. From (3) and (10), we get

$$P/I = 2\pi^2/D'ST^2 \quad \ldots .(13)$$

The P/I obtained by measuring T is 1975 and in agreement with the theoretical value (Figure 1).

Part III – Torsion method

1. Performance

The system was first tested by placing a graduated scale at $D' = 1.7$ meters. Using suspensions of different torsional constants, the following sensitivities and periods were determined

$S = 13.5 \times 10^{-8}$ Oe/mm defl. $T = 6.6$ sec.
$S = 3.37 \times 10^{-8}$ Oe/mm defl. $T = 13.2$ sec.
$S = 1.94 \times 10^{-8}$ Oe/mm defl. $T = 17.4$ sec.

On a scale at $D' = 5$ meters, the deflection would be about three times larger. The system could then be used as a moderately high sensitivity magnetometer (4.6×10^{-8} Oe/mm defl.) with a low period (6.6 sec) or as a high sensitivity (6.6×10^{-9} Oe/mm defl.) with a period of 17.4 sec.

2. Measurements

The magnetic moment of a specimen is often determined by measuring its three orthogonal components; p_x p_y and p_z. Since this measuring method can be used with the torsion and the magnetic control methods, a brief account of the procedure is given.

The specimen is placed upright with its orientation mark on 0° azimuth of the table to obtain p_x; p_y is obtained by rotating the table by 90°; p_z is obtained by placing the specimen on its side and with its axis perpendicular to the axis of magnetization of the bottom magnet. The components of magnetization are obtained (A being large) from

$$p_x = B_x S \left[\frac{E_{Bx}C_B}{z^3} - \frac{E_{Ux}C_U}{(z+L)^3}\right]^{-1} \quad \ldots .(14)$$

$$p_y = B_y S \left[\frac{E_{Bx}C_B}{z^3} - \frac{E_{Ux}C_U}{(z+L)^3}\right]^{-1} \quad \ldots .(15)$$

$$p_z = B_z S \left[\frac{E_{Bz}C_B}{z^3} - \frac{E_{Uz}C_U}{(z+L)^3}\right]^{-1} \quad \ldots .(16)$$

where E is a specimen shape correction which depends on the distances (z and $z+L$) to the bottom (E_B) and upper (E_U) magnets and on the presentation of the specimen: upright (E_x) or on its side (E_z). B_x, B_y and B_z are the scale deflections. For large L, E_U and C_U can be neglected and we have

$$p_x = B_x S z^3 \left[E_{Bx}C_B - \left(\frac{z}{z+L}\right)^3\right]^{-1} \quad \ldots (17)$$

$$p_z = B_y S z^3 \left[E_{Bx}C_B - \left(\frac{z}{z+L}\right)^3\right]^{-1} \quad \ldots (18)$$

$$p_z = B_z S z^3 \left[E_{Bz}C_B - \left(\frac{z}{z+L}\right)^3\right]^{-1} \quad \ldots (19)$$

Since z is constant, it is more convenient to determine the corrections in terms of the different positions used so that

$$p_x = B_x S\, C_x \quad \ldots .(20)$$

$$p_y = B_y S\, C_x \quad \ldots .(21)$$

$$p_z = B_z S\, C_z \quad \ldots .(22)$$

where all the corrections are included in C_x and C_z which can be readily obtained from tables. In a rock collection, most specimens are long enough to be cut to standard length (2.2 cm); z and the volume are then constant and $C_x = C_z$. The intensities (Int.) of each component are then given by

$$\text{Int}_x = B_x E \quad \ldots .(23)$$

$$\text{Int}_y = B_y E \quad \ldots .(24)$$

$$\text{Int}_z = B_z E \quad \ldots .(25)$$

where E is the constant correcting factor multiplied by the sensitivity and divided by the volume. The directions (D and I) and the total intensity of magnetization are determined from these components. The effects of inhomogeneity of magnetization are reduced by averaging readings 180° apart and also by averaging readings of upright and inverted positions of the specimen. In the side position (Int_z), the holder is rotated 180° about its axis.

Part IV – Magnetic control method

The performance and efficiency of a torsion-controlled astatic system can be improved by using magnetic fields to control and measure the deflection. This is illustrated by using as an example the previously described system, two photo resistors and an electrical circuit which provides an automatic negative feedback. The circuit (Figure 5) has been designed to suit specific conditions that will be discussed. However, it can be easily modified for different conditions and requirements, and great freedom is left to the designer.

By comparing the two methods, the magnetic control is preferred. For example, it permits, while maintaining short periods, sensitivities not possible with the torsion method since the period would then be too long to meet the requirements. As opposed to the torsion method where the sensitivity and period are set by the suspension fibre, the magnetic control method allows quick switching among several different sensitivities and associated periods. This increases the working range and efficiency of the magnetometer since the more strongly magnetized specimens can be measured at much lower period and therefore in less time. Because of the quick response, the system can be used as a null detector and the direction of magnetization can be determined directly. The direct-read method in turn allows taking full advantage of the flexibility of the instrument, thereby increasing the accuracy of results achieved with the three-component method. Problems arising as the sensitivity is increased and precautions to be taken will be discussed.

1. Principle of operation

When the horizontal field is equal at the upper and lower magnets ($\Delta H = O$), the light spot (diameter 2.1 cm) illuminates equally two photo resistors (diameter 2.5 cm) placed side by side at a distance of 90 cm from the magnet system. The current through each photo resistor is 6 ma, the lower branch of the circuit (Figure 5) is in balance, and no current flows in the upper branch. When a magnetized specimen is brought under the magnet system ($\Delta H \neq O$), the spot is deflected, the resistance of one photo resistor decreases, the resistance of the other increases, and a current flows through the upper part of the circuit and one of the seven solenoids, depending on the switch position. The solenoid is located near the upper magnet and in the same horizontal plane (Figures 3 and 4) with its axis perpendicular to the axis of magnetization of the magnet. It is wired so that the torque it produces on the upper magnet tends to reduce the deflection. If, in a particular switch position, the circuit gives a current through the solenoid of K_1 ma/radian deflection, and the solenoid produces a field of K_2 Oe/ma at the upper magnet, the feedback torque for a small deflection θ is $PK_1K_2\theta$. When the system has come to rest

$$P\Delta H = PK_1K_2\theta + \sigma\theta \qquad \ldots .(26)$$

writing

$$PK_1K_2/\sigma = G \qquad \ldots .(27)$$

where G is the (magnetic/torsion) control ratio

$$\Delta H = K_1K_2\left(1 + \frac{1}{G}\right)\theta \qquad \ldots .(28)$$

The deflection θ is determined by taking the reading n in millivolts as measured across a precision resistor R inserted in the feedback circuit and is given by

$$n\,(\text{mv}) = K_1R\theta \qquad \ldots .(29)$$

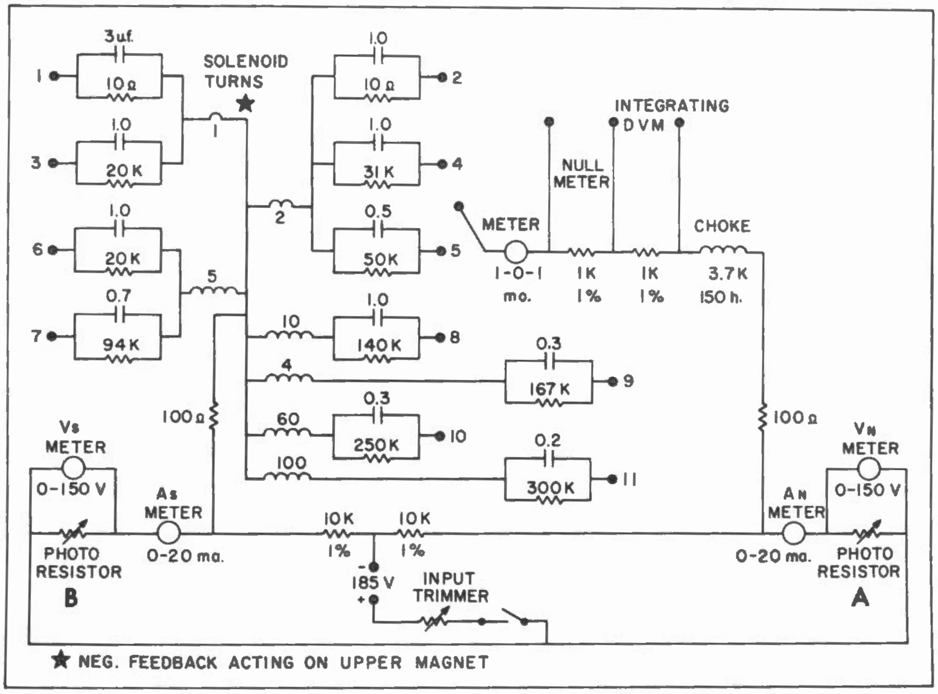

Figure 5. Circuit used to provide negative feedback from signal picked up by the photo resistors.

and from (28)

$$n\,(\text{mv}) = \frac{R\Delta H}{K_2\left(1 + \frac{1}{G}\right)} \qquad \ldots .(30)$$

The sensitivity S in oersted per millivolt is then given by

$$S\,(\text{Oe/mv}) = \frac{\Delta H}{n} = \frac{K_2\left(1 + \frac{1}{G}\right)}{R} \qquad \ldots .(31)$$

The factor K_2 can be calculated from the geometry:

$$K_2 = \frac{\pi N\, 10^{-4}}{l} \times \left[\frac{x+l}{\{(x+l)^2 + r^2\}^{1/2}} - \frac{x-l}{\{(x-l)^2 + r^2\}^{1/2}}\right] \qquad \ldots .(32)$$

where l is the half-length of the solenoid, r its radius, x its distance from the magnet, and N the number of turns.

The control ratio G can be determined by comparing the deflection produced by a given ΔH with and without feedback. However, it is difficult to obtain an accurate estimate in this way, and it is preferable to measure the sensitivity first by means of the calibration coil (III, 5), and then derive G from (31):

$$G = \left[\frac{RS}{K_2} - 1\right]^{-1} \qquad \ldots .(33)$$

The sensitivity can be accurately determined by measuring in mv the deflection caused when a ΔH is applied. The application of progressively higher ΔH permits one to determine the operating range of the photo resistors and the accuracy of the readings (i.e. the near linearity of the curve $\Delta H/n$) within that range.

The period of the undamped system is

$$T_c = 2\pi\left[\frac{I}{\sigma + K_1K_2P}\right]^{1/2} = 2\pi\left[\frac{I}{\sigma(G+1)}\right]^{1/2} \qquad \ldots .(34)$$

by analogy to (2). Both the aluminum damping disc (II, 2) and the capacitors shown in Figure 5 are used for damping the system. The damping disc is adjusted for critical damping at a period T_c of 5 sec. The additional damping provided by the capacitors reduces both the time required to take a reading and the oscillations of the magnet system caused by vibrations of the ground. The frequency of these oscillations varies (about a 4 cycles/sec frequency) depending on the disturbing conditions. Without electrical damping, oscillations would occasionally build up (especially when operating the instrument at lower sensitivities where the magnetic control is large and T_c short $\cong$ 2 to 3 sec) until the light spot was driven out of the range of the photo resistors. The values of the capacitors were determined empirically, and a variety of time constants provided to meet different conditions.

2. Characteristics of the system

The light source is a Pye (W.G. Pye Co. Ltd.) lamp outfit (#8122). The light bulb (4V-1A) and the optical system is placed at 1.1 m from the magnetometer. The transformer (117/4V) is magnetic and placed 10 meters away. A lens (1 m focal length) is placed at 1.6 cm from the mirror. The light beam is received on two cadmium sulphide photo resistors (NSL 4972; Dwg 5472; National Semi-conductors Ltd.) mounted on a brass carriage (at D' = 90 cm) that can be remotely displaced (± 3 cm) in a horizontal direction perpendicular to the direction of the light beam. The photo resistors are housed in a tapered rectangular box which projects to within 25 cm of the magnet system; the inside of the box has been painted black and the instrument can be operated in a lighted room. The photo resistors (shown on the table; Figure 6) were specially manufactured without a metal case and the magnetization of the pins produces a negligible field at the magnet system. Their rated characteristics are max power = 1 watt, max voltage = 420V, resistance at 100 foot-candles = 140 ohms and in darkness = 2.3 meg ohms. In the system described, when the light spot is directed on one photo resistor, the resistance is 2.1 K on the lighted photo resistor and

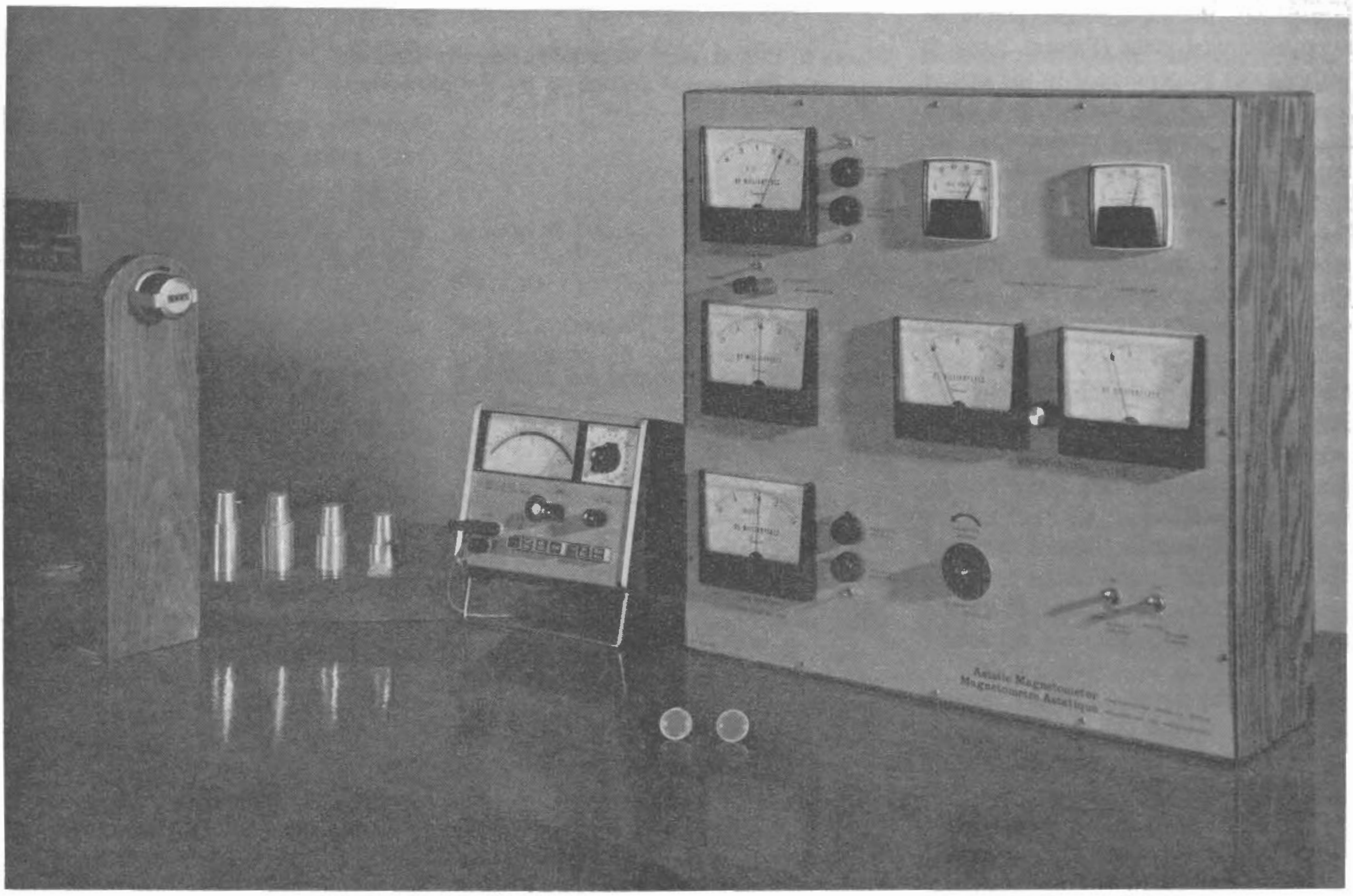

Figure 6. Control panel as described in Part IV. The deflection shown has been obtained by passing a current through the calibration coil. The dial indicating the alignment of the magnet system is shown on the left. The aluminum spacers used to obtain different distances are also shown. On the table are photo resistors of the type used.

200 K on the other giving a max/min ratio of about 100. Among several types of photo resistors tested, this type gave the highest ratio. Since the deflection ratio mv/mm increases with this ratio, the photo resistors should be chosen accordingly. When the spot is equally split onto the two photo resistors, the resistance of each is about 17 K.

A 185-volts power source is trimmed so that on zero deflection of the magnetic system a current of 6 ma (base current) flows through the photo resistors. Owing to long term changes in the circuit and light intensity changes due to voltage variations and dirt on the lenses, the input voltage might have to be changed slightly to obtain the right base current. This is done by trimming down a constant voltage source set slightly higher than required, and which is placed at the other end of the room because of its magnetic properties. The voltage across and the power through the photo resistors are about 100 volts and 0.6 watt. With a rated power of 1 watt, the current (and sensitivity) could be increased by 25 per cent if necessary. However, as a precaution and for longer life of the photo resistors, all calibrations have been performed on the 6 ma base current and therefore hereafter parameters such as D, G and working range, which depend on the base current, are given on this basis.

The negative feedback can be switched to one of the seven solenoids (radius = 0.4 cm). Their number of turns with the mean distance (given in cm in brackets) from the upper magnet are in descending order of sensitivity 1(7.6), 2(7.6), 5(7.5), 10(7.2), 4(3.7), 60(6.1) and 100(4.6). The deflections are measured in mv across a 1-K resistor by means of a DC null voltmeter (Hewlett Packard; 419A) and/or an integrating digital voltmeter (H.P. 2401-C).

Different spacings between the photo resistors were tried. As the spacing is increased (from 0.2 to 1 cm from side to side) the sensitivity increases slightly (5-10%) and the overall working range remains about the same; the portion of the range, where $\Delta H/n$ is almost linear, decreases. In practice, the feedback current increases with the angular deflection until the spot is fully (or centred) on one of the photo resistors. However, for the feedback current to be practically linear with respect to the deflection, i.e. ratio (current/deflection) constant, the spot must be on *both* photo resistors. Once the spot has left one photo resistor but keeps moving onto the other the ratio (current/deflection) becomes smaller and smaller (from 100% to 90%) resulting in a decrease in sensitivity. Therefore, in order to minimize the sensitivity variations within a given range, the photo resistors have been placed as close as possible to each other, that is 0.2 cm for these caseless photo resistors.

3. Sensitivities

Without magnetic control, and with a suspension giving $\sigma = 5.5 \times 10^{-3}$ dyne cm/radian, the period of the system is 6.6 sec and the sensitivity is 2.55×10^{-7} Oe/mm at $D' - 90$ cm. Table I gives the eleven sensitivities (S 1 to S 11) available with the magnetic control. They were measured with the aid of the calibration coil over a range of ΔH values (IV, 1), and the table shows the range of output readings for each switch position within which the sensitivity is constant to 3 per cent and 1 per cent respectively.

Table I also gives the factor G, calculated from (33), the ratio

$$f_c = 1/(1 + \frac{1}{G}) \quad \dots (35)$$

which is the fraction of ΔH measured by magnetic control, and the period of the system T_c, calculated from (34).

S 1, S 2, S 6, S 8, S 9, S 10 and S 11 are regarded as the primary sensitivities, and are generally used, because of their larger G and f_c values, and smaller T_c. The instrument can measure (on S 11) fields as large as 3×10^{-5} Oe and it can detect (on S 1) fields as low as the disturbing conditions at the location permit. The disturbances affecting the instrument are discussed in (IV, 6); under the best conditions at the site, magnetizations producing fields as small as 2×10^{-9} Oe at the lower magnet can be detected. One advantage of the photoelectric system can be seen from the following comparison. To obtain a sensitivity of 0.56×10^{-9} Oe/mm deflection on a scale at a distance D' of 5 meters, the system without feedback would have a period of 60 seconds, which would be impractical because of disturbance problems.

The control panel is shown in Figure 6. The meters on the right-hand side indicate at all times the voltages across and the currents through the photo resistors. On zero deflection a large change in voltage from 100 volts would be indicative of a lighting or photo resistor problem. The input current trimmer is located between the two milliammeters and is the only adjustment required for

Table I. Particulars of the system for each of the 11 circuits shown in Figure 5.

	Sensitivity $\times 10^{-9}$ Oe/mv	G	f_c	T_c (sec)	RANGE LIMIT (mv.) 3 per cent accuracy	3 per cent accuracy
S 1	0.56	0.64	0.40	5.1	3000	2500
S 2	0.68	1.50	0.60	4.2	2400	2000
S 3	0.88	0.35	0.26	5.7	1500	1200
S 4	1.17	0.58	0.36	5.2	1200	900
S 5	1.48	0.42	0.30	5.5	1000	700
S 6	1.77	2.00	0.67	3.9	1500	1250
S 7	3.15	0.58	0.37	5.2	550	450
S 8	5.30	1.03	0.51	4.6	450	350
S 9	13.30	2.78	0.69	3.4	400	325
S 10	29.40	9.10	0.90	2.1	300	275
S 11	120.00	28.50	0.97	1.2	275	250

G is the control ratio (magnetic/torsion) given by (33).
f_c is the fraction of ΔH measured (35).
Without magnetic control, the period of the magnetometer is 6.6 seconds.

intensity measurements (no adjustments are required for direction determinations). The milliammeter in the upper left-hand corner is used for calibration. In this photograph, a current is applied to the calibration coil to deflect the system off zero. A digital ammeter of high resolution can be used by switching to the terminals below the meter. The high or low sensitivity calibration coil can be selected by a switch. The milliammeter (centre left) indicates the deflection of the magnet system during measurement and is useful because its response is quicker (no damping) than that of the nullmeter shown on the left of the panel. For direction finding, the milliammeter is used to find an approximate zero and fine zeroing is accomplished using the nullmeter which has a large scale and is easier to read. The other meter (bottom left) is an indicator for the zeroing procedure (when $\Delta H = 0$) that will be explained later.

4. Design variations

Under this heading, we consider the possibility of extending the measuring range of a magnetically controlled astatic magnetometer beyond the limits imposed by the present requirements and the disturbing conditions (described in IV, 6) existing at this particular site.

The upper limit has been set so that, with the present specimen table and specimen size, most weakly magnetized (intensity $\leqslant 4 \times 10^{-3}$ e.m.u.) rock specimens can be measured; the direction and intensity of specimens of larger intensity are quickly measured by means of a fluxgate magnetometer especially adapted for this purpose. Thus, in this instance, the largest field (3×10^{-5} Oe) the instrument can measure is adequate; however, for other applications or with a different setting, it might be desirable to design an instrument which could measure higher fields. The upper limit can easily be raised and it is not necessary to open the housing (III, 2) of the magnetometer.

When the instrument is operated at lower sensitivities, G is large (Table I), and (31) shows that S is then almost independent of G and proportional to K_2. Therefore, the sensitivity can be reduced (more Oe per mv) by simply adding turns to the solenoid or reducing the distance between the solenoid and the upper magnet. From (27), (31) and (34), it is found that the reduction of T_c^2 is then almost proportional to the reduction of S. Thus, without changing the suspension, the measuring range can be extended upwards so that the instrument can also be used as a low sensitivity and short period magnetometer.

Under the present disturbing conditions discussed in IV, 6, the measuring range of this particular instrument cannot be extended downwards. Higher sensitivities would not increase the performance unless the disturbances or their source (mainly temperature changes) can be better controlled or damped. However, under the assumption that this can be done and as a matter of interest to people designing a magnetometer for operation under more favourable conditions, the extension of the measuring range downwards is now considered.

Equations (27) and (31) show that higher sensitivities (less oersted per mv) can be obtained by reducing either K_2 or σ. However, because, at high sensitivity, G is usually small, the change of S obtained by changing K_2 *or* σ is not readily visualized from the equations and may be illustrated by an example. Using S 1 of Table I as a base for comparison, the calculated sensitivities (S_x) and periods (T_x) obtained by changing K_2 and σ to arbitrary K_x and σ_x are given in Table II. In the calculations, f_c has been kept equal or larger than 0.20 so that a reasonable fraction of ΔH is measured. The table shows that a small improvement in sensitivity can be optionally obtained by reducing K_2 or σ; changes of suspension can therefore be avoided by using a different solenoid to change the sensitivity. Table II also shows that to obtain a large increase of S_x, both K_2 and σ must then be reduced. In Nos. 6, 7 and 8 where G_x is kept constant, the increase of both S_x and T_x is proportional to the reduction of K_x.

The sensitivity could also be increased by increasing K_1. An increase of K_1 would increase the control ratio K_1 (27) which in turn would increase S (31). K_1 could be increased in a number of ways, e.g. light beam of stronger intensity and photo resistors with a higher power rating. The use of a stronger magnet cannot increase the sensitivity and, as in the torsion method, the magnet system must be designed according to the theory given in Part I. From (27), (31) and (34), we find

$$S = \frac{1}{RK_1}\left(\frac{2\pi}{T_c}\right)^2 \cdot \frac{I}{P} \qquad \ldots .(36)$$

showing that the sensitivity increases as P/I increases.

5. Measuring method (direct read)

Because of the quick response, the instrument is used to read directly the

Table II. Calculated periods (T_x) and sensitivities (S_x) obtained by changing G, K_2, σ and f_c of S 1 (Table I) to arbitrary G_x, K_x, σ_x and f_x. See Part IV – 4. Design variations.

NO	G_x/G	K_x/K_2	σ_x/σ	G_x	f_x	T_x sec	S_x $\times 10^{-9}$ Oe/mv.
S 1	1.	1.	1.	0.64	0.39	5.1	0.56
1	3.00	3.00	1.00	1.92	0.65	3.8	1.02
2	3.00	1.00	0.33	1.92	0.65	6.6	0.34
3	2.00	1.00	0.50	1.28	0.56	6.1	0.40
4	0.39	0.39	1.00	0.25	0.20	5.8	0.43
5	0.39	1.00	2.56	0.25	0.20	3.6	1.09
6	1.00	0.67	0.67	0.64	0.39	6.3	0.37
7	1.00	0.50	0.50	0.64	0.39	7.3	0.28
8	1.00	0.33	0.33	0.64	0.39	8.8	0.19

direction of magnetization. The specimen is placed in the holder so that its orientation mark is towards the 0° azimuth on the graduated circle and the assembly is rolled under the instrument (as in Figure 4). It is then rotated until a zero deflection is obtained on the nullmeter. This occurs when the mean direction of the horizontal component of magnetization is parallel to the axis of magnetization of the bottom magnet. The angle D_1 between this direction and the mark is read directly on the graduated circle. The assembly is then rotated until a second zero giving D_2 is encountered at approximately (D_1 + 180°). Averaging of the two readings reduces the effect of inhomogeneity. With weakly magnetized specimens, the first reading is usually repeated (and used for averaging) for eventual drift. The sense of the direction is obtained from the positive or negative reading on 0° azimuth. The same procedure is followed with the specimen in an inverted position. The declination D is obtained by averaging the four readings. The graduated Perspex cylinder containing the specimen is rotated in its wooden holder so that, when the specimen is placed on its side, the horizontal component of magnetization lies in the horizontal plane. The assembly is then rotated until a zero reading is obtained on the nullmeter; this occurs when the mean direction of (the total) magnetization is parallel to the axis of magnetization of the bottom magnet. The angular reading on the graduated circle is that of the direction of magnetization with respect to the axis of the specimen, i.e. the inclination I'. I'' is obtained at about 180° from I' and the average of the two readings gives I_1. The assembly is rotated to $I_1 - 90°$ and then $I_1 + 90°$ so that the direction of total magnetization is at right angle to the axis of magnetization of the bottom magnet and two intensity readings are measured on the integrating DVM (not shown). The holder is then rotated 180° about its horizontal axis and the procedure is repeated; I_2 is obtained and $I_2 - 90°$ and $I_2 + 90°$ are measured. I_1 and I_2 are averaged to obtain I and the four intensity readings averaged to get the total intensity (Int.). Whether I is positive or negative is determined from the direction of the deflection on 0° azimuth.

Using the spacers (Figure 5), the specimen can be placed at five different distances (z = 3.58; 4.08; 5.08; 6.08; 11.08 cms) from the bottom magnet. These five positions (Pos. 5 to Pos. 1) and the 11 sensitivities permit to measure specimens of different intensities. From (19) the intensity is given by

$$\text{Int.} = S \text{ defl. (mv) } z^3 / [E_{Bz}C_B - (\frac{z}{z+L})^3]\, V \quad \ldots (37)$$

where V is the volume of the specimen. Writing

$$K = S z^3/[E_{Bz}C_B - (\frac{z}{z+L})^3]\,V \quad \ldots (38)$$

where the constant K is determined for each Pos. and S we get

$$\text{Int.} = K \times \text{defl. (mv)} \quad \ldots (39)$$

For convenience, the 55 different K are tabled on the measuring sheet (Pos. vs S).

When a specimen is not of standard height (≠ 2.2 cm), a correction must be added to the intensity measurements. This correction depends on the volume of the specimen and on the inclination I and, for a given Pos., is given by

$$C'_Z = \frac{[E_{Bz}C_B - (\frac{z}{z+L})^3]\,V}{[C_I C_B - (\frac{z}{z+L})^3]\,V'} \quad \ldots (40)$$

where C is the correction owing to the shape and orientation of the specimen and V' is the volume of the (non-standard) specimen. For $z > 3$ and L much larger than z, the effect of $(z/z + L)^3$ is negligibly small and we can write

$$C'_Z = \frac{C_s V}{C_I V'} \quad \ldots (41)$$

where C_s is written for E_{Bz}, the correction applicable to a standard specimen. C_I is obtained from

$$C_I = \{C_V^2 \sin^2 I + C_W^2 \cos^2 I\}^{1/2} \ldots (42)$$

where C_V is the correction to be applied when $I = 90°$; the axis of the specimen is then horizontal and perpendicular to the axis of magnetization of the bottom magnet. C_W is the correction when $I = 0°$; the small dimension (height) is then parallel to the axis of magnetization of the magnet and no additional correction is required so that $C_W = C_s$. Since the volume ratio V/V' = 2.2 cm/height, the correction is then given by

$$C'_Z = 2.2/\text{height}\,\{(C_V \sin I/C_s)^2 + \cos^2 I\}^{1/2} \quad \ldots (43)$$

The intensity of a non-standard specimen is obtained from

$$\text{Int. (n.s.)} = K\, C'_Z \times \text{defl. (mv)} \quad \ldots (44)$$

C'_Z has been tabled (h vs I) for the 5 Pos.

The largest value on the K table is 1975 x 10^{-8} Oe/mv. Since the range at S 11 is ± 250 mv (1% accuracy; Table I), intensities up to 4.9 x 10^{-3} e.m.u. can be measured. The smallest K is 0.261 x 10^{-8} Oe/mv which means that an intensity of magnetization (of a standard specimen) = 1 x 10^{-7} e.m.u. will produce a deflection (at S 1) of 38 mv. The accuracy of the reading is discussed in IV, 6.

6. Disturbances

Certain precautions must be taken when working at high sensitivities (S 1 to S 5 to measure intensities of 1 to 10 x 10^{-7} e.m.u.). Otherwise, vibrations and temperature changes may cause noise and drift large enough to render the instrument useless for measuring intensities $<10^{-6}$ e.m.u. Seismic vibrations of 4 cycles/sec cause the magnet system to oscillate about its axis at the same frequency. The instrument is set on an anti-vibration pier which was built at the same time as the building. It consists of a concrete slab (1.05 x 1.05 x 0.15 meter) resting on crushed stone and sand to a depth of 1.5 meters. It is detached from the floor of the building. Measurements (by F. Lombardo of the Seismology Division) taken on the floor and on the pier show that the amplitudes are 3 times smaller on the pier. The transmission of these low frequency oscillations to the electrical circuit can be controlled to a certain extent by the filters but cannot be cancelled. It is then difficult to measure directly the current passing through the negative feedback solenoids and much easier to measure the voltage across a precision resistor. The zero deflections (for D and I) are measured by means of the DC nullvoltmeter which is normally left on the 100 mv range. The input resistance is high (100 MΩ) and the response time is less than 1 sec. The remaining small oscillations are not a serious problem. Indeed, since the deflection must be zero, it is relatively easy to rotate the specimen until the oscillations are equally divided on both sides of the scale centre. The intensities are measured on the integrating DVM which is normally set on a 2-sec integrating time.

The room temperature must be carefully controlled, especially when working at high sensitivity. The magnetometer head is quite sensitive to any temperature change. Such changes will cause expansion of the aluminum plate and vertical tube supporting the suspension; large drifts will then occur. To prevent this, a styrofoam cover (Figure 3) was made and at least 5 cm of insulation protects any part of the head. The shape of the compensating coils system is temperature dependent. As the room temperature changes, the coil system is either distorted or tilted. Although the distortion (or tilt) may be small, the changes in fields at the upper and bottom magnets are different and a drift will occur; a drift that may be large since the astaticism is of little help against this type of disturbance. The amplitude of the drift depends on the source of heat and on the location of this source with respect to the coil system.

The room is heated by 5 electric radiant heaters (2000 watts) controlled by 3 thermostats: (1) 2 heaters (1 thermostat) at the south end of the building; (2) 1 heater in the middle of the west wall and 1 at the north end of the building (1 thermostat); (3) 1 heater (1 thermostat) in a vestibule. About 20 minutes after switching on any of these groups, an irregular but oscillating drift starts. Recordings show the zero drifting one way for about 6 sec, then regressing by 70 per cent in 5 seconds before drifting again in the original direction by the same amount; this fairly regular pattern repeats until about 20 minutes after switching off this group of heaters. The amplitude of the drift (in one peak-to-peak oscillation) depends on the source or group that is switched on: (1) 2×10^{-7} Oe; (2) 6×10^{-8} Oe; (3) 4×10^{-9} Oe. These values correspond to the field required at the bottom magnet to reproduce the drift recorded.

When the building is allowed to cool with the heaters off, the oscillating drift disappears and a regular drift of about 2×10^{-7} Oe/°C takes place. Therefore, it seems reasonable to assume that the oscillating drift is caused by heat convection currents around the compensating coil system thereby producing shape changes. It is intended to install additional bracing in an attempt to reduce the oscillating drift. The drifts would probably be smaller for a smaller L and they would not occur if a magnetic-shielded room was used.

However, by taking certain precautions the instrument can still be used at full sensitivity. Since the amplitude of the drift is dependent on the location of the source, and 3 heaters are sufficient to maintain the room temperature constant, source (1) is never used. When measuring on S 1 to S 8, source (2) is switched off and when measuring on S 1 to S 5, source (3) is also switched off. The maximum decrease of temperature in winter without heat is 4°C/hour (in general it is 1 to 2°C/hour). The drift is then 8×10^{-7} Oe/hr or 1.3×10^{-8}/min. Since a set of three readings (D_1, D_2, D_1) can be taken in 30 seconds, it is estimated that the error introduced in the mean by drift and noise is probably not much greater than 3×10^{-9} Oe. This amounts to 5-6 mv on S 1. The estimate agrees with experimental results such as C84A (Table III) where the individual directions (of a 0.37×10^{-6} e.m.u. intensity) are all within 3° of the mean.

The magnetization of the specimen holder should be thoroughly checked. It should not produce fields larger than 1 to 2×10^{-9} Oe at the bottom magnet. The permali holder used can easily be contaminated and it must often be washed with soap or alcohol and magnetically cleaned in alternating fields of 3000 Oe. Another prevention against drift is to insulate the damping disc; otherwise, specimen and holder which are not at room temperature because of previous warm up (by handholding for example) will produce a temperature change at the bottom magnet resulting in a drift. To prevent this, a Perspex cup (Figure 3) has been glued to the damping disc (the rest of the case bottom is of nylon).

7. Zeroing

The instrument can be zeroed in two ways: mechanical and electrical. The photo resistor carriage can be displaced by remote control and its position is indicated on a dial (Figure 6; on the left). The alignment of the magnet system with respect to the 0° azimuth of the specimen holder is indicated by this dial. When the dial reads 000.0, the two are aligned to within 0.002° of arc; a reading of 001.0 corresponds to a misalignment of 0.2′ of arc. The dial is normally kept between 950.0 and 050.0 so that the misalignment of the magnet system is ⩽ 10′ of arc.

The electrical zeroing is accomplished by passing a calibrated current in a 2-turns coil on the feedback solenoid holder. No misalignment of the magnet system occurs when this method of zeroing is used. A meter (Figure 6; bottom left) graduated (1° – 0° – 1°) indicates the angular displacement if no electrical compensation was used.

8. Performance

Table III gives the results of routine measurements taken from different rock collections. It is divided into two parts. The first part shows the results of progressive thermal or chemical demagnetization. To check the accuracy of the direction determination, specimens with stable magnetizations are chosen to avoid large direction changes inherent to the specimen. Small direction changes between different demagnetization steps may be owing to real changes of directions or to measurement errors. However, the regularity of the changes

Table III. (a) Measurements taken on the same specimen after each thermal (at x°C) or chemical (during x hours immersion in Hcl) demagnetization.

	H 134B		H 2A		H 2B	
°C	D,I	INT. X 10^{-6} e.m.u.	D,I	INT. X 10^{-6} e.m.u.	D,I	INT. X 10^{-6} e.m.u.
20	168,−34	4.5	184,+05	9.6	191,+08	9.3
100	168,−35	4.5	185,+01	9.0	186,+02	9.6
300	168,−35	3.8	185,+00	8.7	187,+01	9.0
400	169,−34	3.4	185,+00	6.3	187,+01	7.1
500	169,−32	2.7	188,+00	4.9	190,−01	5.4
550	169,−33	2.5	189,−05	2.2	196,+01	3.9
600	168,−33	1.9	I.M.		198,−01	2.4
650	168,−33	1.2			I.M.	

I.M. = Large instantaneous magnetizations, acquired when the specimen is subjected to the field (0.20e) of the magnetometer, render the readings meaningless.

	C 23 B		C 34 B		C 54 B	
Hours	D,I	INT. X 10^{-6} e.m.u.	D,I	INT. X 10^{-6} e.m.u.	D,I	INT. X 10^{-6} e.m.u.
00	037,+67	13.0	075,+57	4.9	045,+43	19.1
29	037,+66	9.5	080,+55	1.8	045,+40	15.1
100	040,+70	6.3	073,+60	1.2	046,+45	10.9
241	046,+69	2.7	076,+63	0.8	050,+48	4.8
423	042,+73	1.5	070,+72	0.9	045,+54	3.3
790	054,+79	1.3	073,+73	0.9	048,+55	3.2

(b) Repeat measurements taken on inhomogeneously magnetized specimens. The measurements are often taken at different distances as indicated by Pos.

Specimen	D,I	INT. X 10^{-6} e.m.u.	POS.	Specimen	D,I	INT. X 10^{-6} e.m.u.	POS.
C84A	143,+00	0.35	4	H152A	147,+00	1.6	4
	145,+05	0.37	4		145,+00	1.5	3
	147,+03	0.38	4	H166	261,+36	5.2	2
	145,+04	0.36	4		260,+36	5.0	3
	142,+02	0.37	4	690371	162,+34	11.7	2
H8A	115,+33	5.8	3		160,+35	12.8	3
	118,+33	5.9	2		162,+34	13.3	3
H9A	318,+13	4.7	4	690372	184,+23	20.2	2
	320,+13	4.7	3		185,+23	20.2	3
H108*	074,+68	1.7	4	690373	181,+16	54.6	2
	074,+69	1.9	4		181,+16	54.4	3
H151	128,−26	2.2	4	690082	050,+37	46.3	3
	128,−26	2.2	4		049,+37	44.9	2
					048,+35	46.8	1

*Non standard specimens – height = 1.2 cm

between 100°C and 600°C for H2B for example, suggests that most of the changes can be attributed to direction changes.

The second part consists of repeat measurements taken on the same specimen because the magnetization was very inhomogeneous and the two directions (D_1 and D_2) of a set of readings were far from 180° apart. In such cases, intensity permitting, the repeat measurements are taken at different distances and the position is indicated. Only specimens of low intensities are listed. Repeat measurements on specimens of intensities > 10^{-4} e.m.u. normally agree to 1°; readings are taken to the closest degree. Results indicate that the direction of intensity = 1 x 10^{-7} e.m.u. can be determined to within 9° on S 1 as estimated from the ratio noise/deflection = 6 mv/38 mv, and the direction of intensity of 3 x 10^{-7} e.m.u. (such as C 84 A) to within 3°. The direction of 1 x 10^{-6} e.m.u. intensities can be determined on S 6 to within 2°. These values can, of course, be improved upon by taking repeat measurements.

For intensities < 10^{-6} e.m.u., about 8 specimens can be measured in an hour; this includes repeat measurements that may be required because of intermittent increases in the disturbance level. About 12 specimens of intensities in the 10^{-6} e.m.u. range can be measured per hour. When the intensities are > 10^{-4} e.m.u. the measurements can be done on S 10 and S 11 and because of the quick response, 15 to 20 specimens are normally measured in an hour. It is found that about 2/3 of the time is spent in handling the specimens, changing spacers and working out the averages of *D*, *I* and Int. so that for weakly magnetized specimens repeat measurements can be taken without unduly increasing the total time.

The system could be used to measure three orthogonal components of magnetization. However, for many reasons, it is preferable to measure *D*, *I* and Int. as described. Time is saved by eliminating the necessity of computing the results as required in the three-component method. Accuracy obtained with the direct method is greater; in the three-component method, each determination is performed on a fraction of the total intensity while in the direct method *I* and Int. are determined from the total intensity. The determination of *D* is obtained from the total horizontal intensity and its accuracy can be further improved by reducing the distance used for *I* and Int. or by using a higher sensitivity. Indeed, since only Int. depends on *K*, both Pos. and *S* can be changed at any time for the determination of *D* and *I*. A change of distance (or Pos.) is usually avoided in the three-component method because of complications in computation; different *z* and shape correcting factors must then be used for p_x and p_y and p_z.

The direct method also provides an instant estimate of the inhomogeneity of magnetization. The direction readings (D_1, D_2) of an inhomogeneously magnetized specimen will not be 180° apart. However, measurements taken at different distances show that the mean reading (upright and inverted) is representative of the mean direction of magnetization.

It should be noted that the *mean* direction of magnetization is not necessarily parallel to the direction of the magnetizing field. For example, if a change of direction or polarity of the field occurs while a sedimentary formation is gradually deposited and consolidated, the direction of magnetization of the upper part of a specimen (2.2 cm thickness formed during that change) is different from that of the lower part. Such an occurrence is readily determined by the inequality of D_1 and D_2 since D_1 (upright position) is then biased towards the direction of the latter field and D_2 (inverted position) towards the direction of the former. In paleomagnetic work, it is normally assumed that the field at the time of magnetization was a dipole field and that the direction of magnetization obtained after adequate cleaning is representative of the direction of the earth's field at that time. However, if a specimen is highly inhomogeneously magnetized, the mean direction and intensity of magnetization measured may be the resultant vector of two magnetizations acquired in two different fields and therefore that vector is non-representative of a particular field. By comparing D_1 and D_2, and I_1 and I_2, the direct read method of measuring provides means of assessing if during magnetization the direction of the field remained in the same direction with respect to the orientation and attitude of the specimen. The method has been used successfully to detect the presence of a composite magnetization of the Seal Lake and Croteau Groups sediments (Roy and Fahrig; in preparation).

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