KONINKLIJK NEDERLANDS METEOROLOGISCH INSTITUUT

MEDEDELINGEN EN VERHANDELINGEN

No. 78

J. A. AS

INSTRUMENTS AND MEASURING METHODS IN PALEOMAGNETIC RESEARCH

1960

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STAATSDRUKKERIJ- EN UITGEVERIJBEDRIJF / 'S-GRAVENHAGE

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VOORWOORD

Paleomagnetisch onderzoek schept de mogelijkheid het magneetveld van de aarde te bestuderen in de loop van de geologische historie. De belangrijkste conclusies, die uit het onderzoek van het remanente magnetisme van gesteenten worden getrokken, zijn volkomen afhankelijk van de nauwkeurigheid en de betrouwbaarheid der metingen.

De schrijver van deze publicatie, J. A. As, wetenschappelijk ambtenaar bij de geofysische afdeling van het Koninklijk Nederlands Meteorologisch Instituut, heeft onder leiding van Prof. Dr. J. Veldkamp, directeur van de afdeling, een astatische magnetometer en andere instrumenten voor paleomagnetisch onderzoek ontwikkeld. Deze instrumenten werden gebouwd door de Instrumentele Afdeling van het Instituut.

De publicatie bevat de theorie van de astatische magnetometer en beschrijft voorts de methoden die bij het paleomagnetisch onderzoek worden toegepast, zoals dit op het Koninklijk Nederlands Meteorologisch Instituut wordt uitgevoerd. Het tweede deel behandelt de "magnetische reiniging" van gesteenten door middel van wisselvelden.

De Hoofddirecteur van het

Koninklijk Nederlands Meteorologisch Instituut

IR. C. J. WARNERS

PREFACE

Paleomagnetic research gives the possibility to study the geomagnetic field through the whole geological history. The important conclusions which are drawn from the remanent magnetization of rocks are wholly dependent on the accuracy and reliability of the measurements.

The author of this paper, Mr. J. A. As, scientific collaborator of the Geophysical Division of the Royal Netherlands Meteorological Institute, has under supervision of Prof. Dr. J. Veldkamp, Director of the Division, developed an astatic magnetometer and other instruments for paleomagnetic research. The instruments have been constructed by the Instrumental Division of this Institute.

This paper presents the theory of the astatic magnetometer and describes the methods used in paleomagnetic research as carried out at the Institute. The second part of this paper deals with magnetic cleaning of rocks.

The Director in Chief

Royal Netherlands Meteorological Institute

IR. C. J. WARNERS

INTRODUCTION

The property of rocks of retaining their magnetization which was induced under the influence of the earth's magnetic field by a thermal, chemical, or other type of process, makes it possible to collect information on the magnetic field in the far distant past. This paleomagnetic research is of great importance to knowledge of the origin of the geomagnetic field and its behaviour over long periods.

It is confirmed by investigations on quarternary and tertiary rocks, that the magnetic field of the earth was a dipole field during those periods, the pole of which was in the vicinity of the present geographic pole.

In earlier geological periods the position of the magnetic pole calculated from the paleomagnetic measurements appears to differ from the present one. This polar wandering can be ascribed to continental movements.

For the geologist it will be possible to determine, with the aid of fossil rock magnetism, the age of rocks from the known field direction in the past. This will be of importance in those cases where the dating of intrusions, dykes etc. by geological methods is not, or is only very vaguely, possible.

Moreover paleomagnetism offers the geologist a method to observe the rotation of a formation since its depositing, by comparing the direction of the magnetization either with that of an undisturbed formation in the surroundings, or with the known magnetic field direction existing at the time of the formation of these rocks.

Much can be expected from the study of the wandering continents during geological periods with the aid of paleomagnetic research. Paleomagnetic information collected all over the world seems to indicate that great movements of the continents occurred in the past.

In paleomagnetic research orientated samples of rocks are investigated with respect to their remanent magnetization. The intensity varies greatly for various kinds of rocks. In general, basic vulcanic rocks have frequently a high intensity of the order of 10^{-3} to 10^{-2} gauss; sedimentary rocks on the other hand have a low intensity which a sometimes even of the order of 10^{-6} to 10^{-7} gauss.

A magnetometer must be able to measure the whole range of these intensities. For this purpose a magnetometer has been developed on the principle of an astatic system of magnets. The high sensitivity makes it possible to measure the weak magnetization of sedimentary rocks, whereas a strong magnetization can be measured by varying the distance between the sample and the magnetometer.

The theory of the magnetometer has first been developed by Blackett (1952); further papers on various kinds of astatic magnetometers have been published by Collinson et al. (1957), Hellbart (1958), Kumagai (1953), Nagata (1953). In the first part of this paper the theory of the astatic magnetometer is given with some extensions.

In the second part attention will be paid to the magnetic cleaning of rocks. It is well known that not only remanent magnetism is present in the rocks, which was induced during the formation, but in many cases in recent times the geomagnetic field has induced an additional component to the remanent magnetization. As it is probable that the later induced magnetizations have properties different from the fossil magnetization we have to investigate these properties. One of the methods used here consists of the progressive demagnetization by alternating fields. In many cases it appears to be possible to remove the post-depositional induced magnetization. In part II some examples of this magnetic cleaning are shown.

THE ASTATIC MAGNETOMETER

SECTION I

THE SENSITIVITY OF THE ASTATIC SYSTEM

The astatic system is composed of two oppositely directed magnets, the magnetic moments of which are almost equal in strength. This system is suspended by a very thin wire.

We denote:

the torsion-coefficient of the wire by $\boldsymbol{\sigma}$,
the angle of torsion by φ,
the magnetic moments of the magnets by $\mathbf{p}$ and $\mathbf{p}'$,
the horizontal component of a constant magnetic field at the place of the magnet with moment $\mathbf{p}$ by $\mathbf{H}'$ and at the place of the magnet with moment $\mathbf{p}'$ by $\mathbf{H}$.

In equilibrium the torques acting on the system satisfy the equation

(1.1) $$\mathbf{p} \times \mathbf{H}' + \mathbf{p}' \times \mathbf{H} + \boldsymbol{\sigma}\varphi = 0\,,$$

when introducing $\Delta\mathbf{p} = \mathbf{p} + \mathbf{p}'$ and $\Delta\mathbf{H} = \mathbf{H}' - \mathbf{H}$,

equation (1.1) can be rewritten in the form

(1.2) $$\Delta\mathbf{p} \times \mathbf{H} + \mathbf{p} \times \Delta\mathbf{H} + \boldsymbol{\sigma}\varphi = 0\,,$$

or in non-vectorial notation

(1.3) $$\Delta p \cdot H \sin(\Delta p, H) + p \cdot \Delta H \sin(p, \Delta H) + \sigma\varphi = 0\,.$$

If a torque k is applied to the system, this system will deviate over a certain angle γ. Then the equation becomes

(1.4) $$\Delta p \cdot H \sin\{(\Delta p, H) + \gamma\} + p \cdot \Delta H \sin\{(p, \Delta H) + \gamma\} + \sigma(\varphi + \gamma) = k\,,$$

or

$$\cos\gamma\,\{\Delta p \cdot H \sin(\Delta p, H) + p \cdot \Delta H \sin(p, \Delta H)\} + \sigma\varphi +$$

$$+ \sin\gamma\,\{\Delta p \cdot H \cos(\Delta p, H) + p \cdot \Delta H \cos(p, \Delta H)\} + \sigma\gamma = k\,.$$

If the angle γ is small, then as a first approximation

(1.5) $$k = a\gamma\,,$$

with $a = \Delta p \cdot H \cos(\Delta p, H) + p \cdot \Delta H \cos(p, \Delta H) + \sigma$.

The torque a will be called the steering-torque. From the above equation it follows that when a torque acts on an astatic system, in first order the deviation varies linearly even when the magnetic field is not homogeneous.

If the torque k is produced by an applied field $\mathbf{F}$ with a gradient, as is the case when a sample of magnetic material is brought into the vicinity of the system, we have

(1.6) $$\mathbf{k} = \Delta\mathbf{p} \times \mathbf{F} + \mathbf{p} \times \Delta\mathbf{F}\,,$$

where the quantities $\mathbf{F}$, $\mathbf{F}'$ and $\Delta\mathbf{F}$ of the horizontal component of the applied field are defined in the same way as the quantities $\mathbf{H}$, $\mathbf{H}'$ and $\Delta\mathbf{H}$ of the constant field. The position of the sample of the magnetic material is so chosen, that $\Delta\mathbf{F}$ is orthogonal to $\mathbf{p}$, and supposing $\Delta p/p \ll \Delta F/F$, the torque then becomes $k = p \cdot \Delta F$; substitution into (1.5) gives simply

$$a\gamma = p \cdot \Delta F\,,$$

or

(1.7) $$\gamma = \eta \cdot \Delta F \quad \text{with} \quad \eta = p/a\,.$$

The quantity η will be called the sensitivity and is the angle of deviation for $\Delta F = 1$. According to (1.5) we have

$$\frac{1}{\eta} = H \cdot \frac{\Delta p}{p} \cos(\Delta p, H) + \Delta H \cos(p, \Delta H) + \frac{\sigma}{p}\,.$$

Assuming that the torsion-coefficient of the suspending wire is small, so that we have

$$\sigma \ll H \cdot \Delta p\,,$$

and supposing that the homogeneity of the horizontal field satisfies the relation

$$\frac{\Delta H}{H} \ll \frac{\Delta p}{p}\,,$$

then according to the equations (1.8) and (1.3) the angle $(\Delta p, H)$ must be small, and the sensitivity is determined by

$$\eta = \frac{\lambda}{H} \qquad \text{with} \qquad \lambda = \frac{p}{\Delta p}.$$

λ, which will be called the factor of astatism, is defined by the ratio between the magnetic moment of one magnet and the difference of the magnetic moments of both magnets. Hence, under the presumed conditions, a high sensitivity can be obtained firstly by a high factor of astatism and secondly by reduction of the horizontal field H.

There is yet a third method for obtaining a high sensitivity, as the condition $\Delta H/H \ll \Delta p/p$ is not absolutely necessary. One may equally well use the gradient of a field to increase or to decrease the sensitivity. If one applies a gradient ΔH with the aid of an auxiliary magnet and if one chooses the position of this magnet so that either $\cos(p, \Delta H) = 1$ or $\cos(p, \Delta H) = -1$, in order to increase or to decrease the sensitivity, then evidently η is given respectively by

(1.10)
$$\eta = \frac{\lambda}{H - \Delta H \cdot \lambda},$$

and

(1.11)
$$\eta = \frac{\lambda}{H + \Delta H \cdot \lambda}.$$

SECTION II

THE QUALITY OF THE ASTATIC SYSTEM

The conditions necessary to obtain a high sensitivity have been discussed in the first section. However, when developing an astatic system one has to pay attention to the period of the system. An instrument is required of high sensitivity combined with a short period. As the period of the system is

$$\tau = 2\pi \sqrt{\frac{I}{a}}$$

and the sensitivity $\eta = p/a$, one can eliminate a by which a relation is obtained in the form

$$\tau = 2\pi \sqrt{\frac{I}{p}\,\eta}\,, \tag{2.1}$$

in which I is the moment of inertia of the system.

The quantities I and p are technical constants depending on the properties of the material and on the dimensions of the system. Therefore we introduce a quality factor Q, which is by definition the magnetic moment of one magnet divided by the moment of inertia of the system:

$$Q = \frac{p}{I}\,, \tag{2.2}$$

so that

$$Q = 4\pi^2 \frac{\eta}{\tau^2}\,. \tag{2.3}$$

Now the requirement for a high sensitivity of a system with a given period as well as the requirement of a low period for a system with given sensitivity both result in the demand for a high quality factor Q.

The moment of inertia I of the total system is composed of the moments of inertia of both magnets (I_p) and of the moment of inertia of axis plus mirror (I_o):

(2.4) $$I = 2I_p + I_o\,,$$

With

(2.5) $$\delta = 2 + \frac{I_o}{I_p}$$

(2.2) is transformed into

(2.6) $$Q = \frac{1}{\delta}\frac{p}{I_p}\,.$$

In order to apply the theory it is assumed that both magnets are cylindrical. In this case two possibilities can be distinguished.

1. The axis of the cylinder and the direction of the magnetization are parallel (longitudinal magnetization)
2. The axis of the cylinder is orthogonal to the direction of the magnetization (transversal magnetization)

In the case of longitudinal magnetization we have

(2.7a) $$I_{pl} = \frac{m}{4}\left(\frac{d^2}{4} + \frac{l^2}{3}\right),$$

and in the case of transversal magnetization

(2.7b) $$I_{ptr} = \frac{m}{4}\left(\frac{d^2}{2}\right).$$

In these equations d is the diameter, l is the length and m the mass of the magnet. Introducing the density ρ, the volume V and the ratio $\beta = l/d$ we have

(2.8) $$I_p = V^{5/3} \cdot \rho \cdot f(\beta)\,,$$

where $f(\beta)$ has the following forms:
for longitudinal magnetization

(2.9a) $$f_l(\beta) = \left(\frac{1}{2\pi}\right)^{2/3}\left(\frac{1}{4\beta^{2/3}} + \frac{\beta^{4/3}}{3}\right),$$

and for transversal magnetization

(2.9b) $$f_{tr}(\beta) = \left(\frac{1}{2\pi}\right)^{2/3} \left(\frac{1}{2\beta^{2/3}}\right).$$

The magnetic moment p is given by

(2.10) $$p = V \cdot J\,.$$

J, the magnetization per unit of volume, is a quantity which is dependent on the material and is closely related to the shape of the magnet. This quantity J is deduced from the following equations

(2.11) $$B = H + 4\pi J\,;$$

(2.12) $$H = H_{ex} - H_d\,;$$

(2.13) $$H_d = 4\pi DJ\,.$$

B is the magnetic induction,
H is the magnetic field inside the magnet,
H_{ex} is the external applied field,
H_d is the field caused by the polarization of the magnet,
D is the demagnetization factor.

If the external field H_{ex} is zero, one has

$$H = -D\,(4\pi J) = -D\,(B - H) = \frac{-D}{1-D}\,B\,,$$ or

(2.14) $$\frac{H}{B} = \frac{-D}{1-D}\,,$$ and

(2.15) $$J = \frac{1}{4\pi}\,\frac{-H}{D} = \frac{1}{4\pi}\,\frac{B}{1-D}\,.$$

In a first approximation one can use the well-known demagnetization factors (see Stoner, 1945) for ellipsoides, which are, in the case of longitudinal magnetization,

(2.16a) $$D_l = \frac{1}{\beta^2 - 1}\left\{\frac{\beta}{\sqrt{\beta^2 - 1}}\ln\left(\beta + \sqrt{\beta^2 - 1}\right) - 1\right\},$$

and for transversal magnetization

(2.16b) $$D_{tr} = \tfrac{1}{2}\left\{\frac{\beta}{\sqrt{\beta^2 - 1}} - \frac{1}{\beta^2 - 1}\ln\left(\beta + \sqrt{\beta^2 - 1}\right)\right\}.$$

The magnetic induction B as a function of H is, for various magnetic materials, shown in figure 1.

In the graph of B versus H the straight lines

$$\frac{H}{B} = \frac{-D}{1 - D}$$

are drawn; the value of D is obtained from (2.16) for a given value of β.

At the point of intersection B or H is read and J is calculated as a function of β by means of formula (2.15).

According to equation (2.10) $p = V \cdot J(\beta)$ and using (2.8) and (2.9) this becomes

(2.17) $$p = I_p^{3/5} \cdot \Phi(\beta) \qquad \text{with} \qquad \Phi(\beta) = \{\rho^{-3/5} \cdot f(\beta)^{-3/5} \cdot J(\beta)\}.$$

Now it is possible to express the quality factor Q into the moment of inertia and the quantity β. According to (2.6) hence

(2.18) $$Q = \frac{\Phi(\beta)}{\delta I_p^{2/5}}.$$

Using β and I_p as independent variables the largest value of Q will be obtained if $\Phi(\beta)$ is at its maximum [1]), whereas at the same time the nominator has its minimum value.

The second condition means, that

(2.19) $$2I_p^{2/5} + I_o I_p^{-3/5}$$

should be a minimum.

If I_o has a given value, the minimum will be reached when

(2.20) $$I_p = \tfrac{3}{4}\, I_o\,,$$

and then $\delta = 3\tfrac{1}{3}$.

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1) The function $G_s(\beta)$ used by Blackett is equal to $\{\rho\Phi(\beta)\}^{-5/6}$.

Summarizing, it may be stated that the highest quality of an astatic system is obtained when

1st Material and form are chosen so that $\Phi(\beta)$ is a maximum.

2nd The moment of inertia I_0 of axis plus mirror has its technical minimum value.

3rd The moment of inertia of each magnet is $\frac{3}{4}$ of the moment of inertia of the axis plus mirror.

SECTION III

THE BROWNIAN MOVEMENT OF AN ASTATIC SYSTEM

It is unnecessary to increase the level of the sensitivity of an astatic system when the unrest of the system, if observable, is proportionally increased at the same time.

Therefore we have to investigate how the Brownian movement limits the sensitivity and the measuring range of the instrument.

In equation (1.7) we have found the relation between the gradient of the applied horizontal field and the angle of deviation of the system. If γ_o is the smallest angle observable, then the smallest measurable gradient is

$$\Delta F\,(\min) = \frac{\gamma_o}{\eta}. \tag{3.1}$$

When the mean deviation γ_b caused by the Brownian movement is greater than γ_o, the smallest measurable gradient will be

$$\Delta F\,(\min) = \frac{\gamma_b}{\eta}. \tag{3.2}$$

The theory of the Brownian movement yields the relation

$$a\gamma_b^2 = kT, \tag{3.3}$$

k is Boltzmann's constant,
T the absolute temperature,
a the steering torque.

It is desirable to express the quantities a, I, I_p, Q, η, $\Delta F\,(\min)$ into γ_b, δ, τ, $\Phi(\beta)$, because the latter quantities are in one way or another restricted. We then find for the steering-torque a:

$$a = \frac{kT}{\gamma_b^2} \qquad \text{(from equation (3.3))}, \tag{3.4}$$

the moment of inertia of the total system I:

(3.5) $$I = \frac{kT}{\gamma_b^2} \cdot \frac{\tau^2}{4\pi^2} \quad \text{(from equations (2.1) and (3.4))},$$

the moment of inertia of one magnet I_p:

(3.6) $$I_p = \frac{1}{\delta} \frac{kT}{\gamma_b^2} \frac{\tau^2}{4\pi^2} \quad \text{(from equations (2,4), (2,5), (3.5))},$$

the factor of quality Q:

(3.7) $$Q = \Phi(\beta) \left\{ \frac{16\pi^4 \gamma_b^4}{\delta^3 \tau^4 (kT)^2} \right\}^{1/5} \quad \text{(from equations (2.18) and (3.6))},$$

the sensitivity η:

(3.8) $$\eta = \frac{\Phi(\beta)}{2\pi} \left\{ \frac{\gamma_b^4 \tau^6}{2\pi \delta^3 (kT)^2} \right\}^{1/5} \quad \text{(from equations (2.3) and (3.7))},$$

and the lower limit ΔF:

(3.9) $$\Delta F\,(\text{min}) = \frac{2\pi}{\Phi(\beta)} \left\{ \frac{2\pi \delta^3 (kT)^2 \gamma_b}{\tau^6} \right\}^{1/5} \quad \text{(from equations (3.2) and (3.8))}.$$

The formula (3.9) gives the extreme value of the quantity ΔF involved, by substituting the limits of γ_b, δ, τ, $\Phi(\beta)$ as follows:

a) the lower limit of γ_b is γ_o according to (3.2),
b) the lower limit of δ is 2 when $I_o \ll I_p$ approximately,
c) the period τ of the system has an upper limit of about 30 seconds, as a system with a greater period is for practical reasons undesirable, and
d) the maximum value of $\Phi(\beta)$ depends on the magnetic material and on the shape of the magnets.

Introducing the above limits of the quantities δ, γ_b, τ and $\Phi(\beta)$, the absolute smallest value of ΔF which can be measured is expressed by

(3.10) $$\Delta F\,(\text{min}) = \frac{2\pi}{\Phi(\beta)\,(\text{max})} \left\{ \frac{2^4 \pi (kT)^2 \gamma_o}{\tau^6\,(\text{max})} \right\}^{1/5}.$$

SECTION IV

THE INFLUENCE OF FLUCTUATIONS OF THE GEOMAGNETIC FIELD

The most important disturbances of the astatic system are caused by the fluctuations of the earth's magnetic field. Even on magnetically quiet days magnetic fluctuations occur, and fluctuations of at least 1γ mut be taken into account in our calculations.

Let us define the horizontal component of these fluctuations by $\mathbf{H}_v'$, $\mathbf{H}_v$ and $\Delta\mathbf{H}_v$ corresponding to $\mathbf{H}'$, $\mathbf{H}$ and $\Delta\mathbf{H}$ of the constant field as introduced in section I; then the variable torque a_v working on the system is given by

$$\boldsymbol{a}_v = \Delta\mathbf{p} \times \mathbf{H}_v + \mathbf{p} \times \Delta\mathbf{H}_v \,. \tag{4.1}$$

The deviation γ_v of the system exerted by this variable torque is given by (1.5)

$$\gamma_v = \frac{a_v}{a} \,. \tag{4.2}$$

If γ_v becomes greater than γ_o, then the fluctuations influence the lower limit of $\varDelta F$, which follows from (3.2)

$$\varDelta F\,(\min) = \frac{\gamma_v}{\eta} = \frac{a_v}{p} \,, \tag{4.3}$$

or with (4.1)

$$\varDelta F\,(\min) = H_v \cdot \frac{\varDelta p}{p} \sin\,(\varDelta p, H_v) + \varDelta H_v \cdot \sin\,(p, \varDelta H_v) \,.$$

The quantity $\varDelta H_v$ appears only when the variable field is not homogeneous. If the variable field is homogeneous we have

$$\varDelta H_v \ll H_v \frac{\varDelta p}{p} \,,$$

so that

$$\Delta F\,(\min) = H_v \cdot \frac{\Delta p}{p} \sin\,(\Delta p, H_v)\,. \tag{4.4}$$

As the direction is arbitrary this means

$$\Delta F\,(\min) = H_v \cdot \frac{\Delta p}{p} = \frac{H_v}{\lambda}\,. \tag{4.5}$$

Thus, if we have $\gamma_v > \gamma_o$, then the minimum of ΔF is determined by λ. Only if an astatic system is suspended in a homogeneous magnetic field and if the torsion of the suspension wire can be neglected, then λ is linearly related to the sensitivity by $\eta = \lambda/H$. In this case we can also write

$$\Delta F\,(\min) = \frac{H_v}{\eta H}\,. \tag{4.6}$$

From (4.3) it follows that

$$\gamma_v = \frac{H_v}{H}\,.$$

This is to be expected, as under these circumstances the system acts like a single magnet and so the deviations have to be independent of the astatism and sensitivity of the system.

From equation (4.5) we also see that if

$$\gamma_v = \frac{H_v}{H}$$

and $\gamma_v > \gamma_o$, it is of no use to increase the sensitivity in another way than by increasing λ. Compensating a part of the constant magnetic field H or applying an extra gradient to the field with the aid of an auxiliary magnet is of no use as the deviation due to H_v will increase at the same time. In the case $\gamma_v > \gamma_o$ it is better procedure to reduce the sensitivity until γ_v is of the order of γ_o, as by such a process the period can be reduced according to (2.1). This can easily be done by means of an auxiliary magnet. We will return to this point later.

SECTION V

APPLICATION TO THE THEORY

In the following we used data on some magnetic materials which are produced by N.V. Philips, Eindhoven, viz.:

Ticonal G	(T.G)
Ticonal G G	(T.GG)
Ticonal X	(T.X)
Ticonal XX	(T.XX)
Ferroxdure I	(F.I)
Ferroxdure II	(F.II)

The magnetization curves [1]) are shown in fig. 1; the slope of the straight lines indicates the values of H/B.

D is calculated by means of (2.16) and is drawn in fig. 2 as a function of β. Figure 3 shows the magnetization $J(\beta)$ against β. Figure 4 shows $f(\beta)$ calculated by means of formula (2.9); using the figures 3 and 4 it is now possible to determine the important characteristic $\Phi(\beta)$ of the magnet. This is shown in figures 5*a* and 5*b* for the case of longitudinal magnetization and transversal magnetization respectively. The figures 6*a* and 6*b* are nomograms from which the relationship between I_p/ρ, β, l, d can easily be derived. To that purpose equations (2.7a and 2.7b) have been brought into the form

(5.1a) $$I_{pl} = \frac{\pi}{16}\left(\frac{\beta}{4} + \frac{\beta^3}{3}\right) d^5$$ and

(5.1b) $$I_{ptr} = \frac{\pi}{16}\left(\frac{\beta}{2}\right) d^5 .$$

In the calculations we shall use here the values $\rho = 7.3$ (Ticonal) and $\rho = 4.8$ (Ferroxdure).

With the aid of these results it is possible to calculate the lower limit of

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[1]) The magnetization curves of these materials have been derived from a publication by H. J. Meerkamp van Embden (Philips Technisch Tijdschrift Vol. 19, p. 25, 1957).

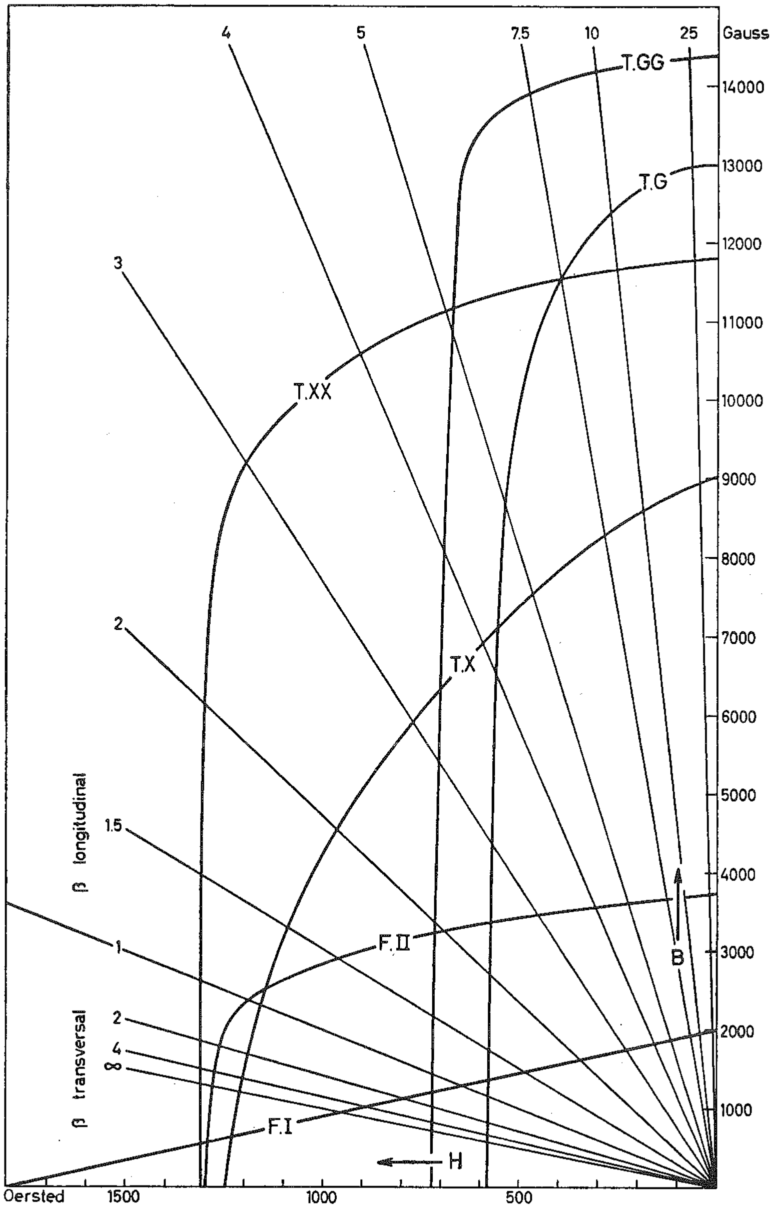


Figure 1. Magnetization curves for various magnetic materials; straight lines show the relation between B and H for some values of β.

the measuring range of an astatic system of magnets determined by the thermal noise

$$\Delta F\,(\text{min}) = \frac{2\pi}{\Phi(\beta)\,(\text{max})} \left\{ \frac{2^4\pi(kT)^2\gamma_0}{\tau^6\,(\text{max})} \right\}^{1/5}, \tag{3.10}$$

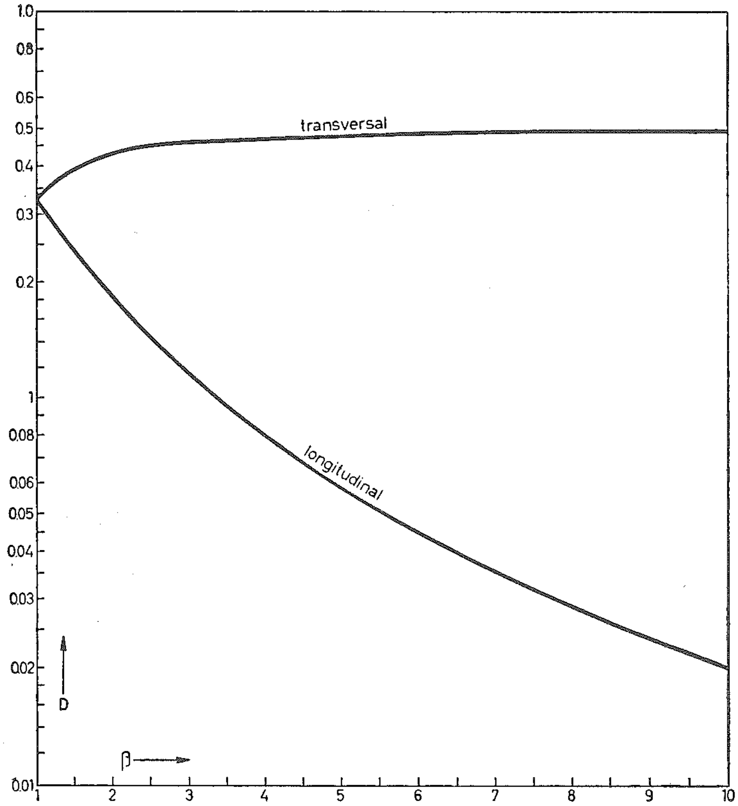


Figure 2. The demagnetization factor D as a function of β for ellipsoides in case of longitudinal and transversal magnetization.

k is Boltzmann's constant (1.38×10^{-16}),

T is the absolute temperature (300°),

$\Phi(\beta)$ is the characteristic of the magnetic material, its maximum value being about 450 c.g.s., e.m.u. This value may be attained with a magnet of Ticonal XX (magnetized longitudinally, $\beta = 3$) and of Ferroxdure II (magnetized transversally, $\beta = 4$),

τ (max) is practically limited to 30 seconds,

γ_o is the smallest angle of observation, being about 2.10^{-5} or 0.1 mm scale deviation at a scale distance of 2.5 meter.

Introducing these values in (3.10) we obtain $\Delta F = 2.6 \times 10^{-10}$ oersted as the lowest value which can be measured.

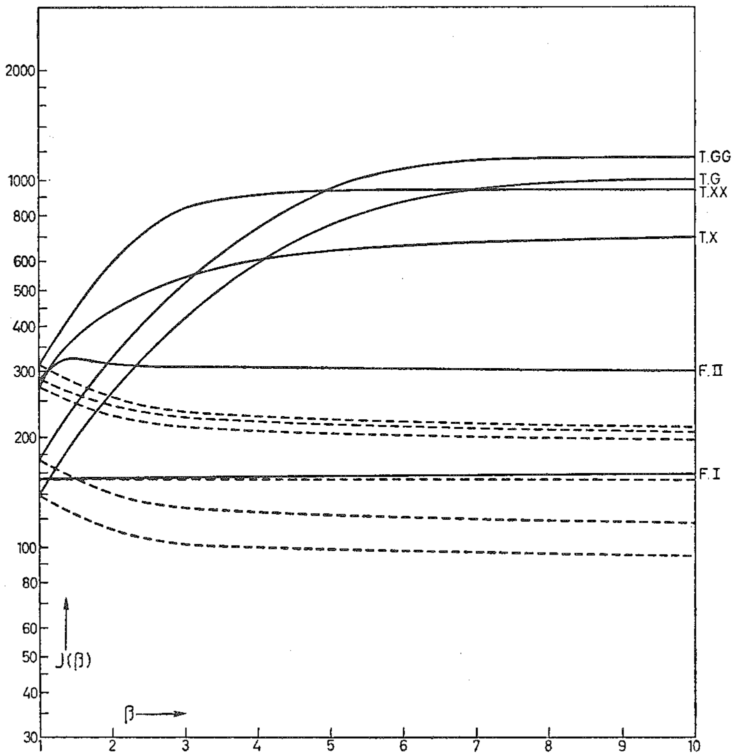


Figure 3. The magnetization J(β) for some magnetic materials. Full lines for longitudinal magnetization, dashed lines for transversal magnetization.

The constants of the system, which enable us to reach this minimum, are given by the equations (3.5) to (3.9). Substituting the above value of $F(\beta)$, γ, τ and $\delta = 2$, we find:

$$a = 10^{-4}$$
$$I = 2.2 \times 10^{-3}$$
$$I_p = 1.1 \times 10^{-3}$$
$$Q = 3.0 \times 10^{+3}$$
$$\eta = 7.7 \times 10^{+4}$$

The calculated values are all expressed in c.g.s. and e.m.u.

Using the nomograms of fig. 6*a* and 6*b*, the dimensions of the magnets become as follows:

for Ticonal XX, longitudinally magnetized, $\beta = 3$; $1 = 0.4$ cm, $d = 0.13$ cm;
for Ferroxdure II, transversally magnetized, $\beta = 4$; $1 = 0.8$ cm, $d = 0.2$ cm.

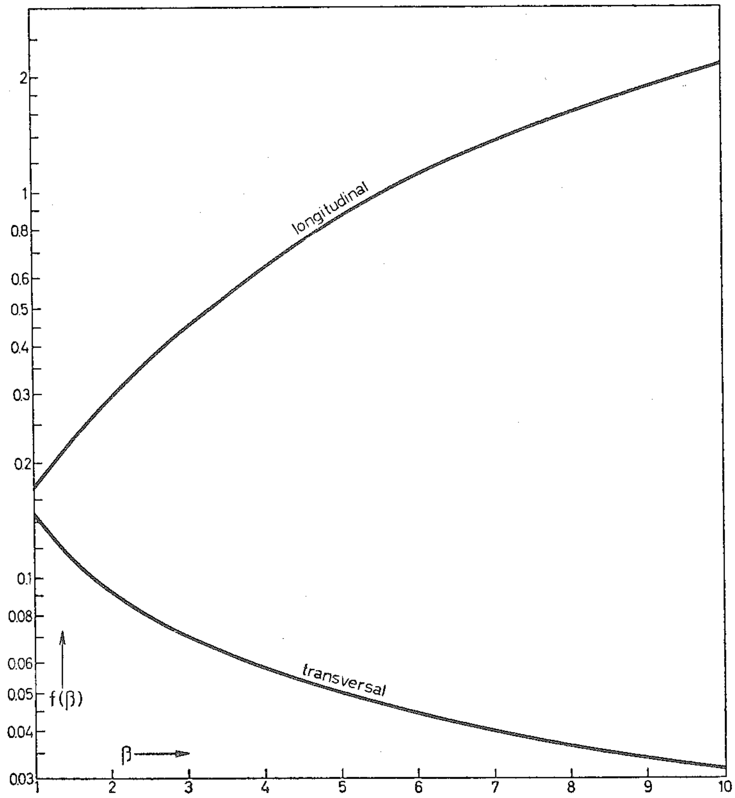


Figure 4. f(β) for longitudinal and transversal magnetization.

This system has the highest sensitivity which can be obtained at the maximum usable period of 30 sec, for which the deflections due to the Brownian motion are just below the limit of observation.

Until now only the disturbance caused by the Brownian movement has been considered in our calculations. In the presence of variations of the geomagnetic field $\Delta F_{\min} > H_v/\lambda$ according to (4.5). This means that H_v/λ has to be smaller

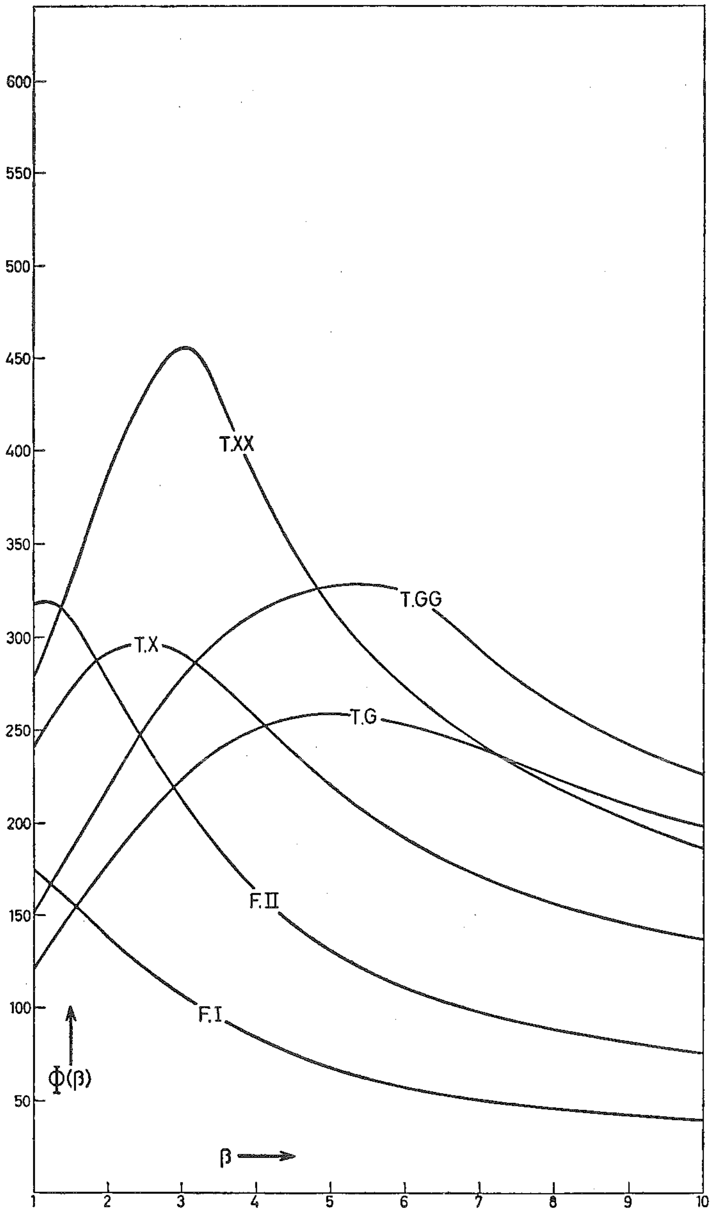


Figure 5*a*. $\varnothing(\beta)$ in case of longitudinal magnetization.

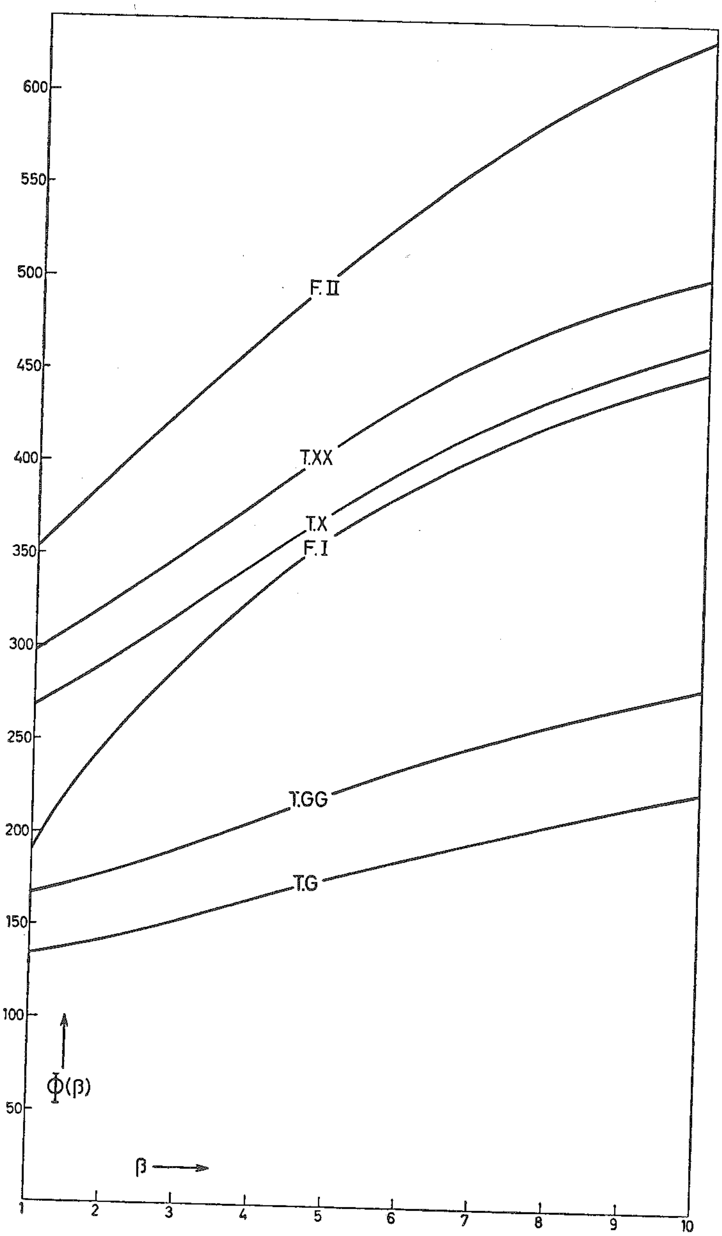


Figure 5*b*. $\varnothing(\beta)$ in case of transversal magnetization.

than 2.6 × 10^{-10}. Moreover, the deviation γ_v caused by the variable field has to be smaller than the minimum observable angle $\gamma_o = 2 \times 10^{-5}$. As $\gamma_v = H_v/H$ (eq. 4.3 and 4.6) it follows that $H_v/H_o \leqslant 2 \times 10^{-5}$; this means that in a place where $H = 0.2$, $H_v \leqslant 4 \times 10^{-6}$. Again as $H_v/\lambda \leqslant 2.6 \times 10^{-10}$ it follows that $\lambda > 1.5 \times 10^4$.

The condition for H_v is sometimes fulfilled on magnetically quiet days, but the condition that λ is 15000 or more is too stringent. Incidently, such a value

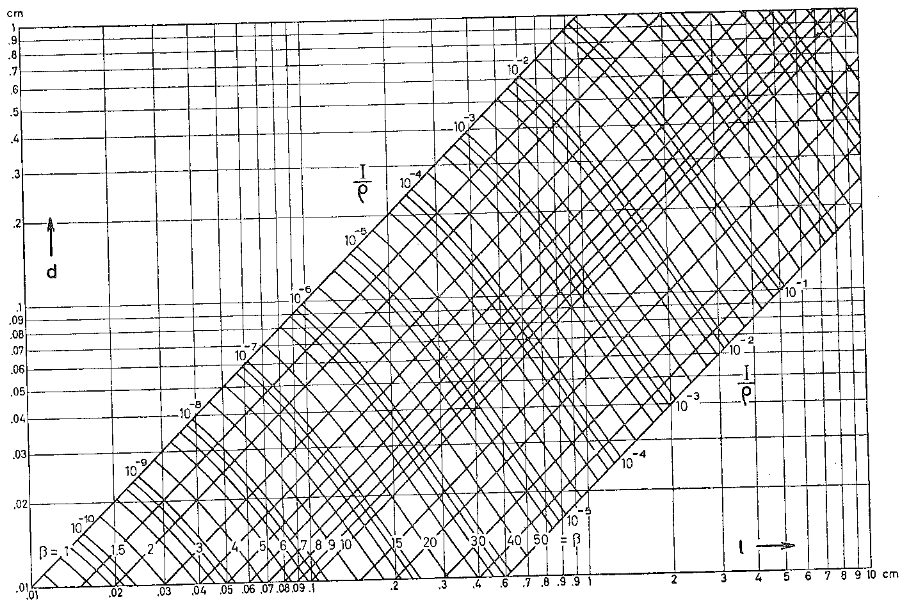


Figure 6*a*. Nomograms showing the relations between I/ρ, β, l and d in case of longitudinal magnetization.

may perhaps be reached for a short time, but in practice an astatic system will never keep such a high λ for a long time. This means that in practice it is not possible to approximate the minimum of ΔF determined by the thermal noise.

In actual circumstances λ is about 10^3 and $H_v = 10^{-5}$, so that the practical minimum will be $\Delta F = H_v/\lambda = 10^{-8}$ oersted. In this case $\gamma_v = H_v/H = 5 \times 10^{-5}$ which is of the order of γ_o, the smallest observable angle.

Apparently if $\gamma_v \geqq \gamma_o$ the minimum detectable field ΔF can only be decreased by increasing λ. The other methods for increasing the sensitivity, e.g. by compensating a part of the horizontal component of the constant field (1.9), or by applying a gradient by means of an auxiliary magnet (1.10) are in these circumstances ineffective, so that it is useless to increase the sensitivity beyond the value of $\eta = 5000$.

As the sensitivity is limited the factor of quality Q can now be increased by shortening the period, which can be done by choosing the shape and dimensions of the magnets. Again the Brownian movement cannot be ignored. In formula (3.8) we have determined a relation between τ and η taking this unrest

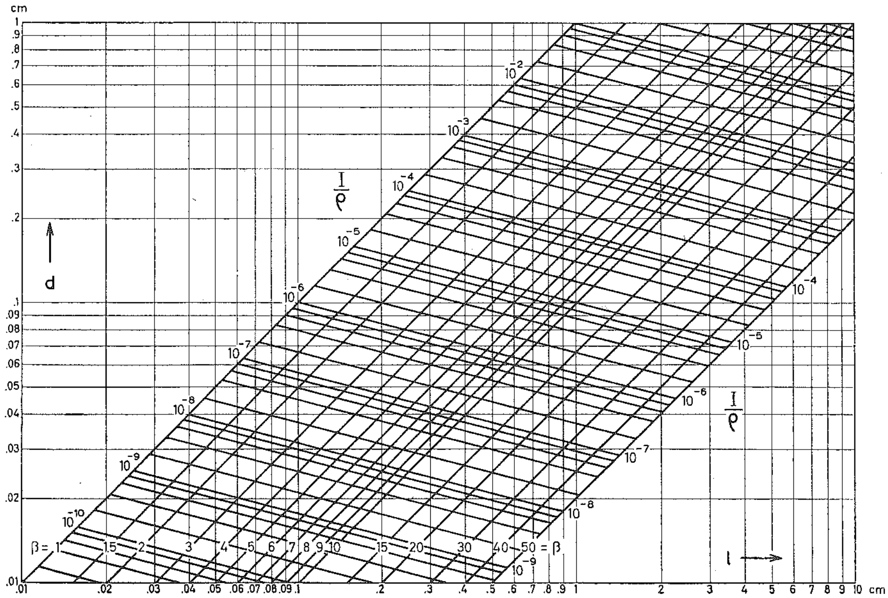


Figure 6*b*. Nomograms showing the relations between I/ρ, β, l and d in case of transversal magnetization.

into account. If we again require the deviation γ_b caused by the thermal noise to be smaller than the minimum observable angle γ_o, we find for the period

$$\tau \geqq \frac{2\pi\delta^{1/2}(kT)^{1/3}\eta^{5/6}}{\Phi^{5/6}(\beta)\gamma_o^{2/3}}. \tag{5.2}$$

Substituting the practical values $\Phi(\beta) = 450$, $\gamma_o = 2 \times 10^{-5}$, $kT = 4 \times 10^{-14}$, $\delta = 3\frac{1}{3}$, $\eta = 5000$, it follows from this formula that the Brownian movement will not be observable if the period is at least 4 seconds. The constants of this system can now be calculated. The moment of inertia of one magnet follows from (3.6): I_p is 1.2×10^{-5}. Using the nomograms of figures 6*a* and 6*b*, we see that for Ticonal xx, $\beta = 3$, $p = 7.3$, the length of a magnet must be $1 = 0.18$ cm and the diameter $d = 0.06$ cm. This system has the shortest period which can be obtained at the maximum usable sensitivity of 5000 and for which the Brownian movement is just not observable.

In our former calculations we have supposed that the torque working on the system was due to the horizontal component of the earth's magnetic field only. This means that the torsion of the suspending wire can be neglected. The Brownian movement becomes observable when the torque

$$a = \frac{kT}{\gamma_0^2}$$

(see 3.4). Substituting the numerical values we find $a = 10^{-4}$. Hence the torsion coefficient σ of the wire must satisfy $\sigma \ll 10^{-4}$. This condition can easily be fulfilled.

SECTION VI

THE USE OF THE ASTATIC MAGNETOMETER IN PALEOMAGNETIC RESEARCH

Let us suppose that a rock sample is placed in the medium plane of the system. This medium plane is the horizontal plane through the centre of the system. The sample is placed in such a way that the vertical plane through the centre of the sample and the axis of the system is perpendicular to the direction of the magnetization of the magnets. In measuring rocks we assume that a

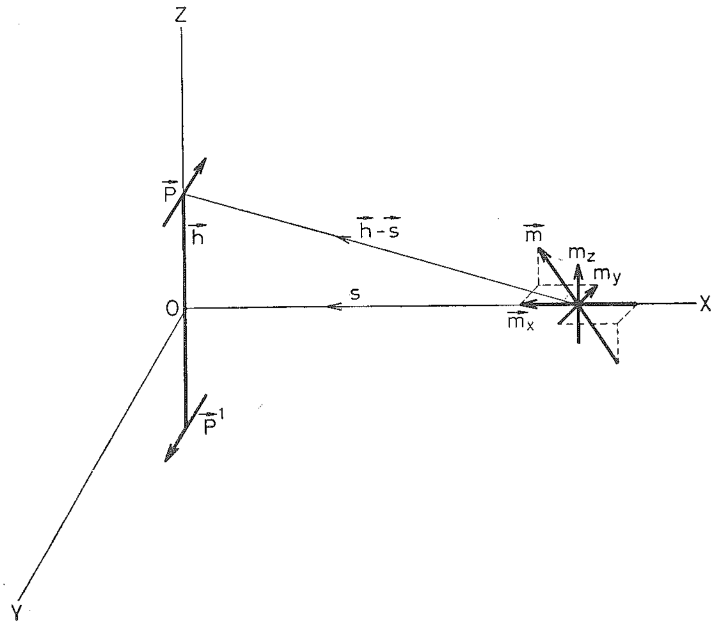


Figure 7. The astatic system and the magnetic moment of the sample placed in orthogonal coordinates.

sample is uniformly magnetized so that it acts as a dipole when placed at a large distance from the magnetometer. We will show that the horizontal component of a dipole in the medium plane does not affect the system. Thus the deviation of the system when a dipole is placed in the medium plane is caused only by the vertical component of the dipole.

In deducing our equations we choose our coordinate system as follows: the z-axis is laid along the suspending wire, the y-axis is parallel to the direction of magnetization of the magnets, and the xy-plane is the medium plane. The moments of the magnets are **p** and **p**′; the distance between the magnets is $2h$. A dipole **m** of arbitrary direction is placed on the x-axis at distance s from the origin.

The field G' caused by **m** at the centre of the magnet **p** is

$$(6.1)\qquad \mathbf{G}' = \frac{3}{|\,\mathbf{h}-\mathbf{s}\,|^5}\{(\mathbf{h}-\mathbf{s})\,\mathbf{m}\}(\mathbf{h}-\mathbf{s}) - \frac{\mathbf{m}}{|\,\mathbf{h}-\mathbf{s}\,|^3},$$

or

$$(6.2)\qquad \mathbf{G}' = \frac{3\,(hm_z - sm_x)(\mathbf{h}-\mathbf{s})}{|\,\mathbf{h}-\mathbf{s}\,|^5} - \frac{\mathbf{m}}{|\,\mathbf{h}-\mathbf{s}\,|^3}.$$

The horizontal component of this field is

$$(6.3)\qquad \mathbf{F} = \frac{3\,(hm_z - sm_x)(-\,\mathbf{s})}{|\,\mathbf{h}-\mathbf{s}\,|^5} - \frac{\mathbf{m}_x + \mathbf{m}_y}{|\,\mathbf{h}-\mathbf{s}\,|^3}.$$

In the same way we find for the horizontal component of the field at the centre of **p**′

$$(6.4)\qquad \mathbf{F} = \frac{3(-\,hm_z - sm_x)(-\,\mathbf{s})}{|\,\mathbf{h}-\mathbf{s}\,|^5} - \frac{\mathbf{m}_x + \mathbf{m}_y}{|\,\mathbf{h}-\mathbf{s}\,|^3}.$$

The difference between these horizontal components due to the sample is

$$(6.5)\qquad \Delta\mathbf{F} = \mathbf{F} - \mathbf{F}' = -\,\frac{6hm_z}{(h^2+s^2)^{5/2}}\,\mathbf{s}\,.$$

From this equation we see that ΔF is caused only by the vertical component m_z and that $\mathbf{\Delta F}$ is perpendicular to the direction of the moments of the magnets.

A maximum of ΔF occurs, when h is constant and s variable, for

$$s = \frac{h}{2}\,;$$

when s is constant and h is variable for

$$h = \frac{s}{2}.$$

The maximum of ΔF in these cases is respectively

$$\Delta F = \frac{96}{125} \sqrt{5} \frac{m_z}{h^3}, \tag{6.6}$$

and

$$\Delta F = \frac{96}{125} \sqrt{5} \frac{m_z}{s^3}. \tag{6.7}$$

There is still one point for discussion. In deducing equation (1.7) from (1.6) we used the relation

$$\frac{\Delta p}{p} \ll \frac{\Delta F}{F}.$$

It is not certain whether this condition is always fulfilled. In general we have

$$k = p \cdot \Delta F + | \mathbf{\Delta p} \times \mathbf{F} |. \tag{6.8}$$

We can imagine $\mathbf{F}$ to be composed by the fields $\mathbf{F}^x$, $\mathbf{F}^y$, $\mathbf{F}^z$; in which $\mathbf{F}^x$, $\mathbf{F}^y$ and $\mathbf{F}^z$ are the horizontal components of the fields caused by m_x, m_y and m_z respectively, and we have

$$\mathbf{\Delta p} \times \mathbf{F} = \mathbf{\Delta p} \times \mathbf{F}^x + \mathbf{\Delta p} \times \mathbf{F}^y + \mathbf{\Delta p} \times \mathbf{F}^z \tag{6.9}$$

As we shall see in section 8 we can, in our calculations, eliminate the influence of the deviations caused by the "disturbing" torques $\mathbf{\Delta p} \times \mathbf{F}^x$ and $\mathbf{\Delta p} \times \mathbf{F}^y$, by means of a combination of measurements. So we have only to pay attention to $| \mathbf{\Delta p} \times \mathbf{F}^z |$. It is obvious from the equation (6.4) that

$$\mathbf{F}^z = \frac{+ 3\, h m_z}{(h^2 + s^2)^{5/2}} \mathbf{s}, \tag{6.10}$$

so that using (6.5) and neglecting the terms caused by $\mathbf{m}_x$ and $\mathbf{m}_y$ we have

$$k = p \cdot \Delta F + |\, \mathbf{\Delta p} \times \mathbf{F}^z \,| < \left(p - \frac{\Delta p}{2}\right) \frac{6hsm_z}{(h^2 + s^2)^{5/2}},$$

but since

$$\frac{\Delta p}{p} \ll 1\,,$$

it follows that approximately $k = p \cdot \Delta F$.

SECTION VII

THE MAGNETOMETER OF THE "KONINKLIJK NEDERLANDS METEOROLOGISCH INSTITUUT"

The magnetometer of the K.N.M.I. is shown in figures 8–12. Box and tube are made of perspex; the dimensions of the box are $5 \times 10 \times 10$ cm^3, the length of the tube is 70 cm. The magnetic system is suspended above a copper plate, by means of which the damping can be adjusted to aperiodicity. The suspension wire is made of terlenka of 0.75 denier, which means that the diameter is about 5μ; the torsion-coefficient is 3.10^{-6} c.g.s.

The magnets are cylinders of Ticonal G (length 0.5 cm, diameter 0.1 cm). They are connected by a thin axis of glass (length 5 cm, diameter 0.5 cm); on this axis a mirror is fixed (diameter 0.5 cm, thickness 0.02 cm).

The constants of this system are in c.g.s. and e.m.u.:

the distance between the magnets	$2h = 5.0$
the length of a magnet	$l = 0.5$
the diameter of a magnet	$d = 0.1$
moment of inertia of one magnet	$I_p = 6.5 \times 10^{-4}$
inertia ratio ($I/I_p = \delta$)	$\delta = 2.8$
magnetic moment of one magnet	$p = 3.3$
the quality factor	$Q = 1.8 \times 10^3$
the astatism factor	$\lambda = 1.0 \times 10^3$
the sensitivity	$\eta = 5.5 \times 10^3$
the period of the system	$\tau = 13$
minimum observable deviation angle	$\gamma_o = 2 \times 10^{-5}$
torsion-coefficient of the suspension wire	$\sigma = 3 \times 10^{-6}$

We see that this system works at the maximum usable sensitivity of about 5000. However, the shortest period of 4 seconds, calculated for a system with $\eta = 5000$ for which the deflections by the Brownian movement are not observable, has not been reached. It must be possible to construct a system with a period shorter than 13 seconds by using better magnetic material, e.g. Ticonal xx, and by diminishing the dimensions of the magnets until the limit of $\delta = 3\frac{1}{3}$ has been reached.

According to (1.7) the minimum observable field for this magnetometer is $\Delta F = \gamma_0/\eta = 2 \times 10^{-5}/5 \times 10^{-3} = 4 \times 10^{-9}$. The minimum measurable magnetic moment depends on the distance from the magnetic system. As we shall

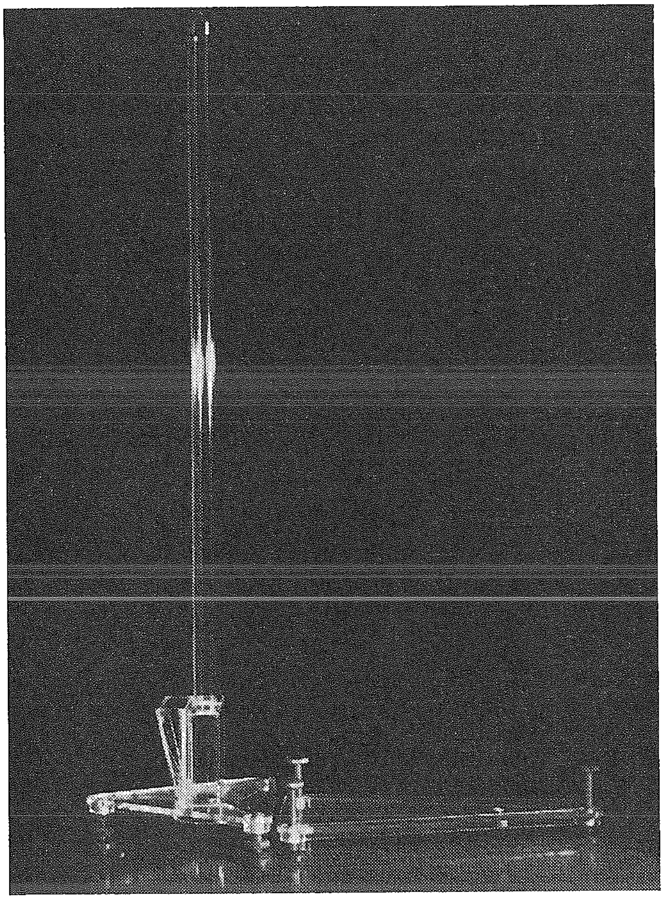


Figure 8. The astatic magnetometer.

see later rock samples are used which have volumes either of 8 cm^3 or of about 200 cm^3. The samples of 8 cm^3 cannot be placed nearer than 3 cm from the system, whereas the samples of 200 cm^3 cannot be nearer than 10 cm. Using equation (6.5) it follows that in these cases the minimum value for m_z is 5×10^{-8} or 3×10^{-7} gauss cm^3 respectively, which means that the minimum detectable magnetization per cm^3 is 7×10^{-9} or 2×10^{-9} respectively.

The procedure of making a system astatic consists of the following manipulations. Firstly, to direct the magnets exactly opposite each other, secondly one has to make the magnets of equal moment. The correct opposite direction

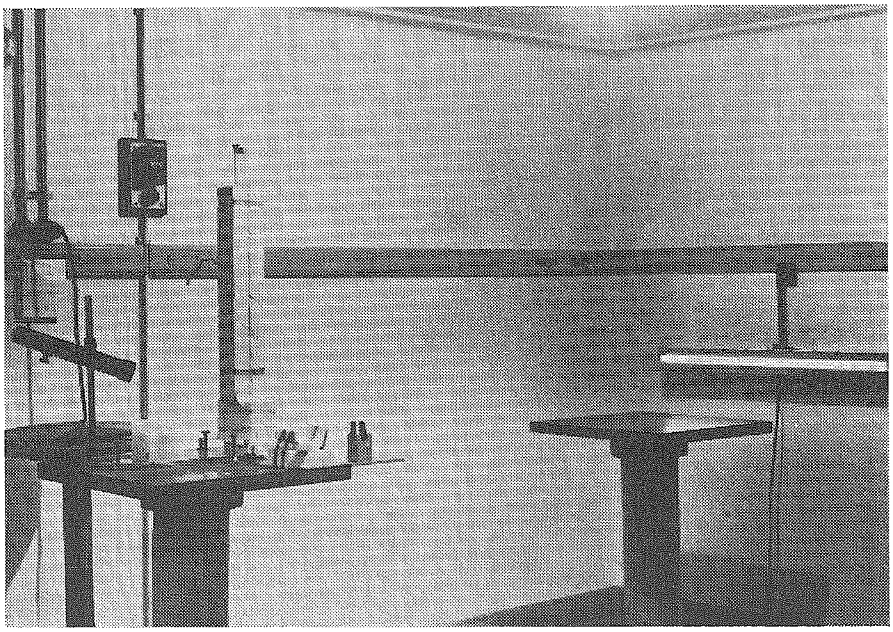


Figure. 9. The astatic magnetometer with telescope and reading scale.

can be obtained by adjusting the magnets so that they point north-south in free suspension. The equalizing is done by partial demagnetization of the stronger magnet with alternating fields until the magnets are almost equal. In demagnetizing a variable transformer is used to regulate the alternating currents through a coil and the alternating fields in the coil are increased and decreased which is repeated with increasing peak value. This demagnetization is continued until the system turns from the north-south plane and sets itself in an east-west direction. In this case the difference in magnetic moment is orthogonal to the direction of the magnets. Hence a redirection of the magnets till they point north-south again is necessary. After this operation a demagnetization is repeated, until the required factor of astatism is obtained.

After each manipulation the period of the system is checked as the factor of astatism can be determined from this period. When τ_0 is the period of a system with both magnets in the same direction and when τ is the period of the system with opposite by directed magnets, then obviously

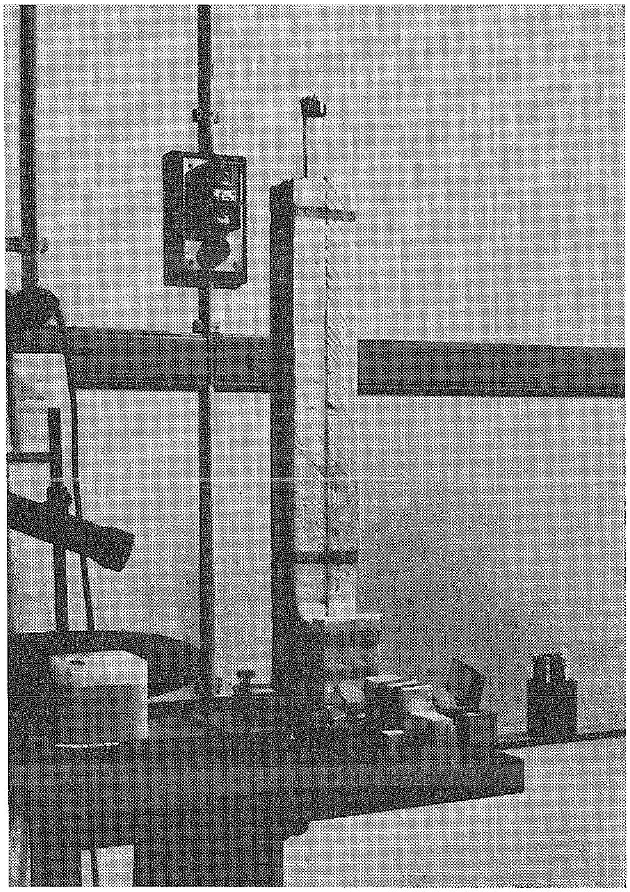


Figure 10. Left: cube of paraffine wax containing a rock sample. In front of the magnetometer and at the right: auxiliary magnets in isolating material for regulating sensitivity and direction of the astatic system.

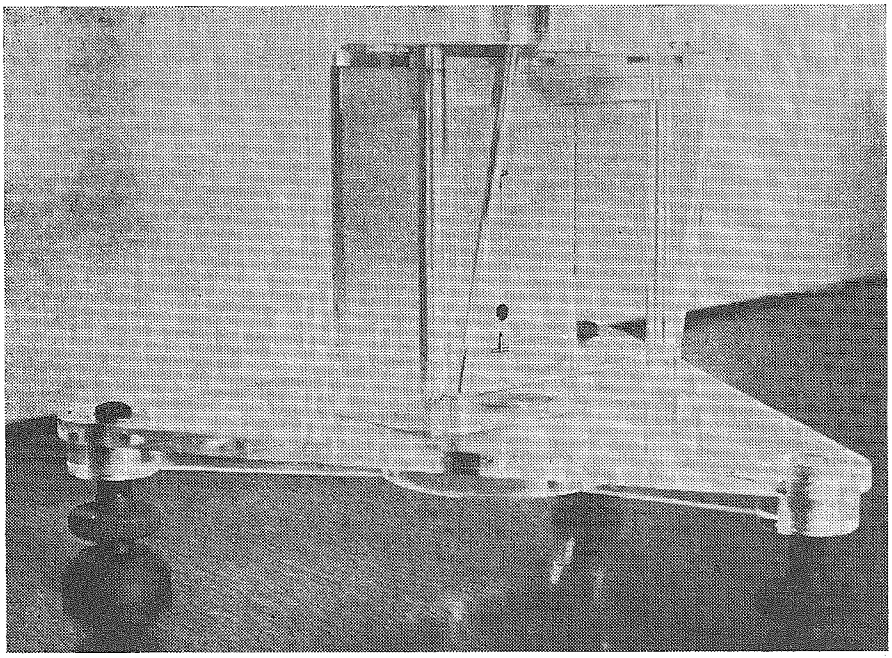


Figure 11. Lower part of the magnetometer (isolating cover removed).

$$(7.1)\qquad \tau^2/\tau_0^2 = 2p/\Delta p\,, \qquad \text{or} \qquad \lambda = \frac{p}{\Delta p} = \tfrac{1}{2}\,\frac{\tau^2}{\tau_0^2}\,.$$

The method explained above can only be applied in a homogeneous magnetic field. If the field is not homogeneous, then these adjustments can also produce a high period, but in that case this does not mean that a high factor of astatism has been reached.

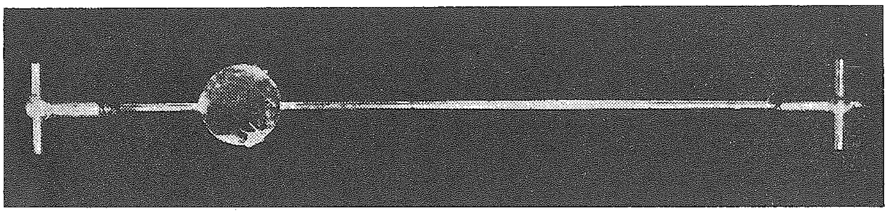


Figure 12. The magnetic system.

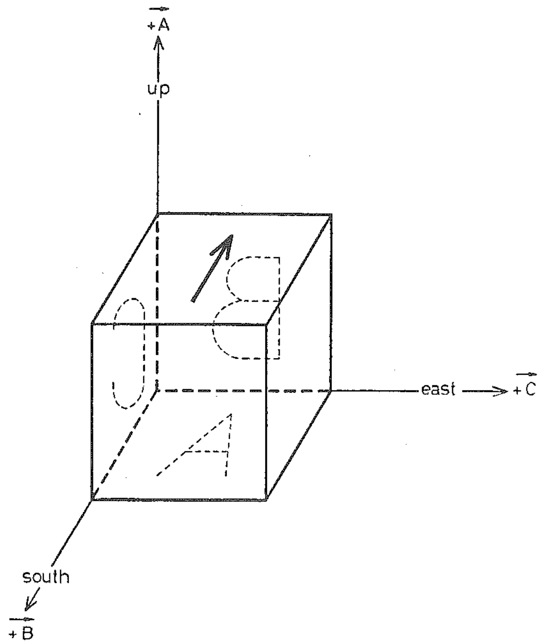
When setting up the instrument in a laboratory, where the magnetic field shows a gradient, one has to use a secondary magnet, vertically placed in the medium plane, to compensate for the existing gradient. This compensation is obtained when the period is the same as in the homogeneous field, in which the system was astatized. At the same time the direction of the system can be changed to any wanted direction by means of this auxiliary magnet.

The instruments are situated in a room with constant temperature. Moreover the magnetometers are provided with a mantle of thermo-isolating material to prevent any fluctuations of the temperature. A high humidity in the room is favourable to prevent electrostatic charges on the instrument, which may cause many difficulties.

SECTION VIII

THE METHOD OF MEASURING ROCKS

In order to facilitate the measurements it is convenient to have the samples in the form of cubes. This can be attained either by sawing or by imbedding them in paraffine wax or in plaster of Paris. In using plaster of Paris it may be



that a weak remanent magnetization appears which is due to ferromagnetic impurities. Therefore this plaster of Paris cannot be used for rocks with weak magnetization. When paraffine wax is used one has to take into account that it is diamagnetic.

The cubes have to be orientated so that one plane represents the upper horizontal plane of the field-position of the sample and that one edge of that same plane is parallel to the north direction. An arrow on that plane indicates the north direction. To define three orthogonal axes, according to which the magnetization has to be measured, the bottom plane is indicated with an A, the north plane with a B, and the west plane with a C. The respective components of magnetization A, B and C are considered positive, when they are directed respectively upward, to the south and to the east. See fig. 13.

For measuring the cubes they are placed on a plateau near the magnetometer, so that the centre of the cube is in the medium plane of the magnetic system and in the plane orthogonal to the direction of the magnets. The distance between sample and meter is adjusted in relation to the magnetization of the sample.

The magnetization consists of two components: viz. one caused by the remanent magnetization and one component due to the permeability of the rocks. We can separate the induced magnetism from the remanent magnetism by the following combination of readings:

1)	zero position	r_1
2)	after placing the cube	u_1
3)	after rotating the cube over 180° round a horizontal axis	u_2
4)	after rotating 180° round the vertical axis	u_3
5)	after rotating 180° round the same horizontal axis as under 3	u_4
6)	zero position after removing the cube	r_2
7)	after replacing the cube rotated 90° round the vertical axis	u_5
8)	after rotating the cube over 180° round the horizontal axis	u_6
9)	after rotating 180° round the vertical axis	u_7
10)	after rotating 180° round the horizontal axis	u_8
11)	zero position after removing	r_3

The observed deviations u_1 etc. are composed of the following quantities:

r = zero position of the instrument,

R = deviation caused by the vertical component of the remanent magnetization of the sample,

G = deviation due to the magnetic moment induced in the sample by the vertical component of the magnetic field,

k^x and k^y = deviations caused by the torques $|\mathbf{\Delta p} \times \mathbf{F}^x|$ and $|\mathbf{\Delta p} \times \mathbf{F}^y|$ respectively,

d = drift of the system between two successive readings (supposed to be linear in time).

The following equations give the relation between various quantities:

$$\begin{aligned}
u_1 &= r_1 + R + G + k^x + k^y + d \\
u_2 &= r_1 - R + G - k^x + k^y + 2d \\
u_3 &= r_1 - R + G - k^x - k^y + 3d \\
u_4 &= r_1 + R + G + k^x - k^y + 4d \\
r_2 &= r_1 + 5d \\
u_5 &= r_2 + R + G + k^x + k^y + d \\
u_6 &= r_2 - R + G - k^x + k^y + 2d \\
u_7 &= r_3 - R + G - k^x - k^y + 3d \\
u_8 &= r_4 + R + G + k^x - k^y + 4d \\
r_3 &= r_2 + 5d
\end{aligned}$$

From this we deduce for the vertical component in the position considered

(8.1) $$8R = (u_1 + u_4) - (u_2 + u_3) + (u_5 + u_8) - (u_6 + u_7)\,,$$

(8.2) $$8G = (u_1 + u_2 + u_3 + u_4 + u_5 + u_6 + u_7 + u_8) - 2(r_1 + 2r_2 + r_3)\,.$$

To obtain the value of magnetization it is necessary to multiply by the calibrating factor. This factor is determined by placing a coil in the medium plane in the same position in which the rock samples have been measured. The magnetic moment of the coil is

(8.3) $$M = \frac{niO}{10} \text{ gauss cm}^3,$$

n = number of turns,

O = surface of the coil,

i = current in ampères.

If the deviation of the magnetometer caused by the coil is ω, the calibrating factor q is

(8.4) $$q = \frac{nO}{10}\,\frac{i}{\omega}\,.$$

The declination D, the inclination I and the total intensity T can be calculated from the measured components of the magnetization A, B and C by means of the relations:

$$\text{tg}\, D = -\frac{C}{B}, \tag{8.5}$$

$$\text{tg}\, I = -\frac{A}{C}\sin D, \tag{8.6}$$

$$T = -\frac{A}{\sin I}. \tag{8.7}$$

In order to obtain the value of the magnetization per cm^3, one has to divide T by the volume of the rock sample.

The theory of measuring rock samples by the method described above has been developed for a dipole. This representation of the magnetic moment of the sample by a dipole appears to be quite sufficient in practice. The irregularities in shape and the non-homogeneity of the magnetization do not influence the results in any important way, as the effects are cancelled by the above procedure.

PART II

THE RESEARCH ON THE PROPERTIES OF THE REMANENT MAGNETISM OF ROCKS

In paleomagnetic research we often find a great dispersion in the measured directions of magnetization in rocks from the same place and the same age, even when the rocks are sampled from one layer. In the stereographic projection these directions often show a shift versus the present field direction. In such cases it is evident that an additional and viscous remanent magnetism has been induced by the present field. Usually we wish to determine the direction of the fossil field, that is the magnetic field at the time of diagenesis, metamorphosis or sedimentation of the rocks. Thus, in measuring field directions with the aid of remanent magnetism in rocks we have to investigate as to how far the direction of magnetization in the samples has been affected by post-depositional fields. Therefore an investigation of stability is necessary. Various methods of stability tests are already well known from publications by Graham (1949), Nagata (1953 and 1954), Irving and Runcorn (1957), Brynjolfsson (1957), and Creer (1958 and 1959).

One of the methods is the method of testing magnetizations by investigating their behaviour during the application of alternating fields. By means of this method we have the advantage that, after testing some samples of a collection, we have not only indications on the stability of the magnetization, but moreover we obtain indications on how to clean the samples of that collection from non-fossil magnetizations, by partial demagnetization by alternating fields.

The magnetic cleaning method of rocks is based on the supposition that when a measured direction of magnetization in a rock shifts from the fossil field direction towards the present field direction, the total magnetization originates from at least two fractional magnetizations. It is supposed that these belong to magnetic fractions which have not only different magnetic properties, but also have their own directions. Thus it is possible that the magnetization of one fraction is directed according to the fossil field and that another fraction shows the direction of the present field. These different magnetic fractions can be present when various magnetic minerals exist in the rocks. It also may be

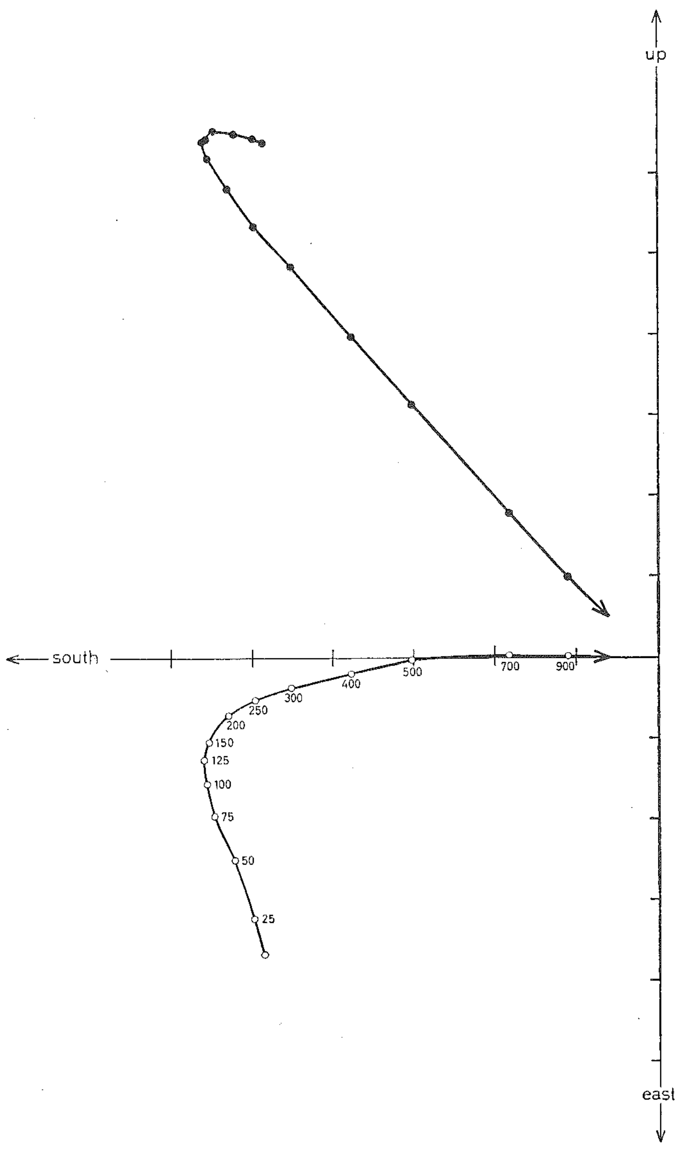


Figure 14. Demagnetization curve for a sample of dolerite from the Estérel (S. France). Open circles: projection on the meridional plane, black dots: projection on the horizontal plane. The values of the alternating fields used for progressive demagnetization are indicated.

that one mineral is present in grains of different sizes, and that the stability depends on the size of the ferromagnetic grains.

In such cases we can use the magnetic properties to demagnetize totally one or more fractions, which do not have the fossil field direction, while retaining the "stable" magnetization in a measurable quantity.

These suppositions were confirmed by the progressive demagnetization tests (As and Zijderveld, 1959). In these tests the rocks are exposed to repeated demagnetization with increasing intensity. After each demagnetization step the intensity and the direction of the rock magnetism is measured. When fractions exist with different directions, they will not react in the same way and at the same time. One of the fractions will react first and when the magnetization is represented by a vector, we observe in a progressive demagnetization the vectorial subtraction, by which the total magnetization vector changes its direction. If we observe only a shrinking vector without rotation it is certain that only one direction of magnetization is present.

As the magnetizations with higher coercive force remain, it may be expected that these are directed according to the fossil field direction.

From many tests already executed it appeared that in almost every collection of rock samples some specimens occur to be more or less influenced by the present field. In a special study of this subject J. D. A. Zijderveld [1]) has investigated the behaviour of rock magnetism under alternating fields.

In the study it is shown that there is a great variability in the behaviour of rock magnetism. The values of the magnetic field necessary for cleaning vary from 100 up to 1000 oersted and more.

In the figures 14, 15 and 16 some graphs of Zijderveld are shown demonstrating the progressive demagnetization tests. In using the orthogonal projection the vertex of the magnetization vector is projected both on the meridional plane and on the horizontal plane.

Fig. 14 shows that the vectorial subtraction is almost in a constant direction when demagnetizing from 0 to 75 oersted. This is the direction of the present geomagnetic field at the place of sampling. The vector decreases without rotation during demagnetization by a field of more than 700 oersted, which means that the sample has been totally cleaned. Thus the direction of this vector very probably represents the fossil field direction.

Fig. 15 shows a change which has more or less the direction of the present

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[1]) This study will be published in the form of a doctoral thesis.

field when the rock is demagnetized up to 100 oersted. After a treatment by 200 oersted the greater part of the disturbing magnetizations is removed. Total cleaning is reached by a treatment with 700 oersted.

In fig. 16 a treatment by 700 oersted was necessary for cleaning. In this case the fossil field direction may be found by vectorial subtraction between the values of 700 and 1000 oersted as the vector does not shrink exactly to the origin.

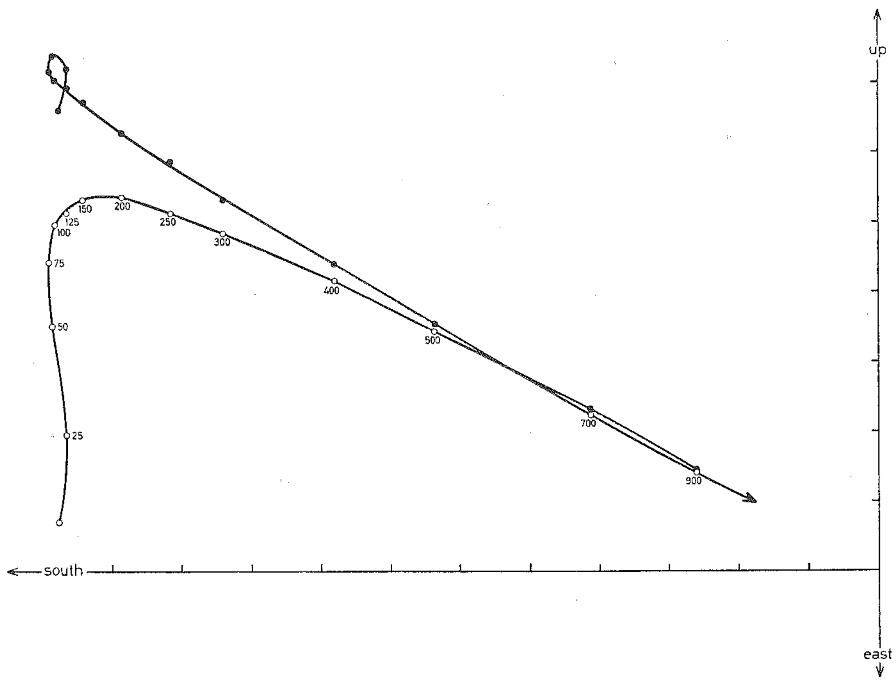

Figure 15. Demagnetization curve for a sample of dolerite from the Estérel (S. France).

Another method of magnetic cleaning makes use of high temperatures, or a combination of alternating fields and heating. This may easily be done when the rocks are cast in plaster of Paris, as this acts as an isolating cover.

In order to avoid magnetization induced by the present field during the operation, the demagnetization has to take place in a zero field. For this purpose a set of Helmholtz coils, radius 65 cm, is used. The field in the centre of the Helmholtz coils is adjusted to zero, which is checked by means of an oerstedmeter of Förster. The demagnetization coil is placed in the centre of

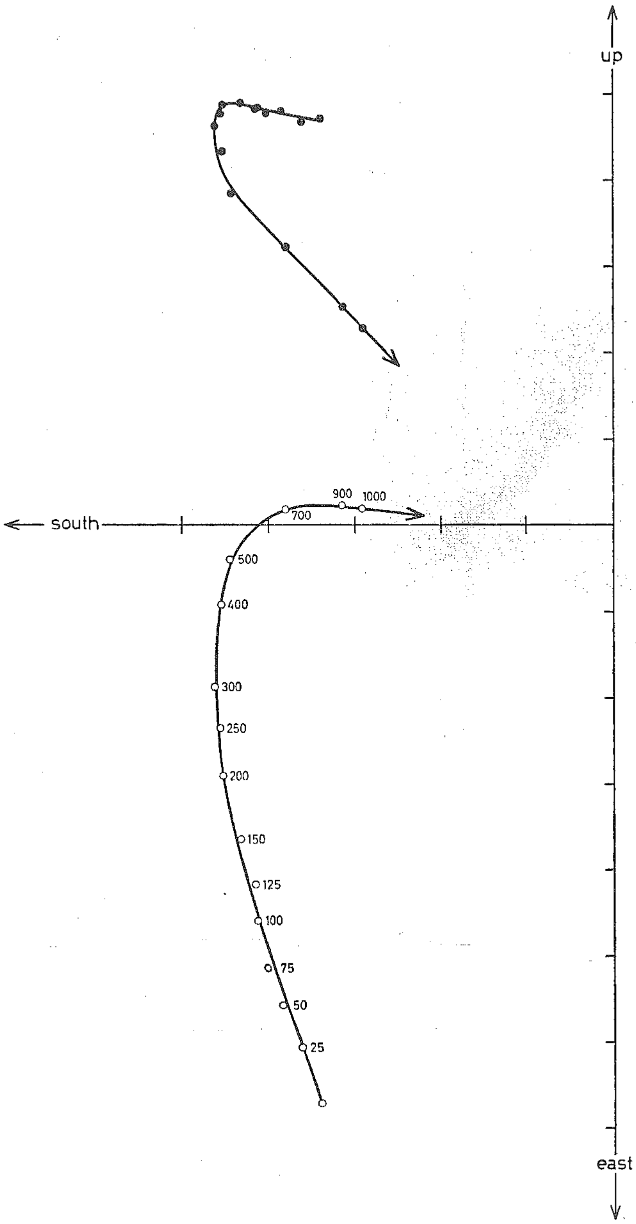

Figure 16. Demagnetization curve for a sample of dolerite from the Estérel (S. France).

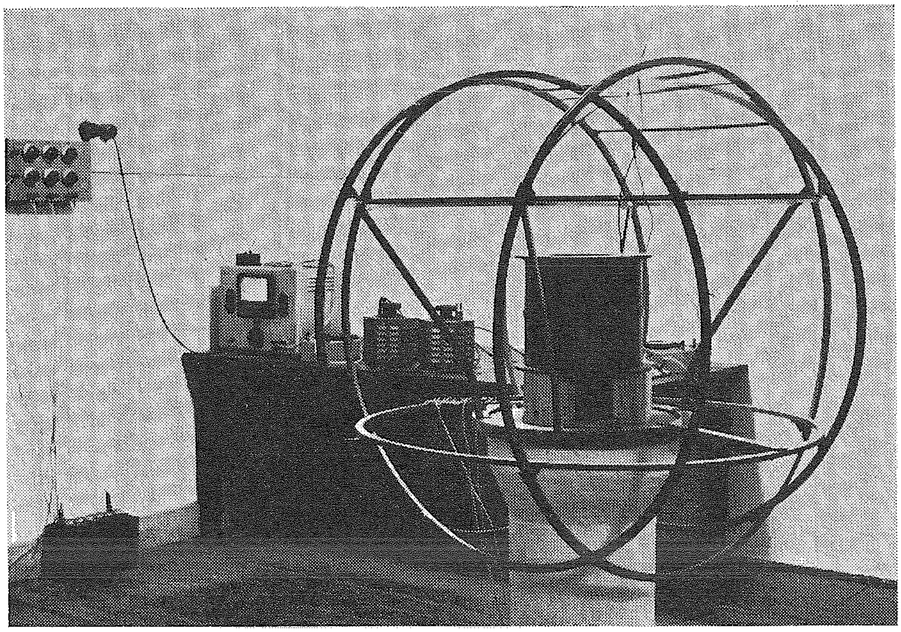

Figure 17. The apparatus for cleaning the rock samples by means of alternating fields.

the Helmholtz coils; the internal diameter is 20 cm and the length is 30 cm. It contains 2550 windings in 23 layers; the copper wire has a diameter of 1.8 mm. A field of 1000 oersted can be produced.

The 50 c/sec alternating current used has to be free from even harmonics, as

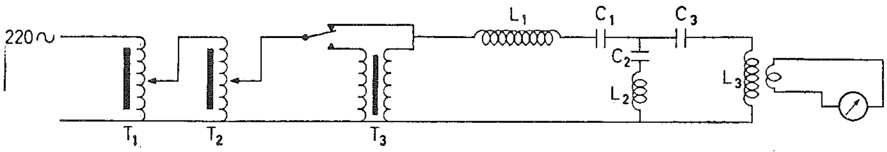

Figure 18. Demagnetization circuit. T_1, T_2 and T_3 are transformers, L_3 is the demagnetization coil, the other elements are used for filtering.

L_1: inductance 0.601 H; resistance 13.7 Ω
L_2: inductance 0.225 H; resistance 5.33 Ω
L_3: inductance 2.090 H; resistance 19.9 Ω
C_1: capacitivity 17.4 μF
C_2: capacitivity 10.7 μF
C_3: capacitivity 4.27 μF.

these harmonics cause an asymmetric distortion of the current, resulting in alternating fields which have different peak values in opposite directions. This causes a magnetization in the direction of the highest peak value.

To avoid these disturbances the even harmonics, and especially the first one, have to be filtered out. This has been done by applying a 50 c/sec pass filter and a shunt to by-pass the 100 c/sec.

A scheme of the demagnetization circuit is given in fig. 18. L_3 is the demagnetization coil, which is tuned with a set of condensors (C_3) to 50 c/sec, as in coil L_1, with condensor C_1. Coil L_2 with condensor C_2 is tuned to 100 c/sec. Two variable transformers and one fixed transformer are used to regulate the current intensity in the circuit.

The intensity of the alternating field is determined from the output of a secondary winding of the demagnetization coil.

The demagnetization is effected by placing the sample in three perpendicular positions. It is obvious that the process of cleaning is effective when the measured direction of magnetization does not change by a second demagnetization of the same intensity with another sequence of the three different positions.

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