



GEOLOGICAL  
SURVEY  
OF  
CANADA

DEPARTMENT OF MINES  
AND TECHNICAL SURVEYS

This document was produced  
by scanning the original publication.

Ce document est le produit d'une  
numérisation par balayage  
de la publication originale.

**BULLETIN 69**

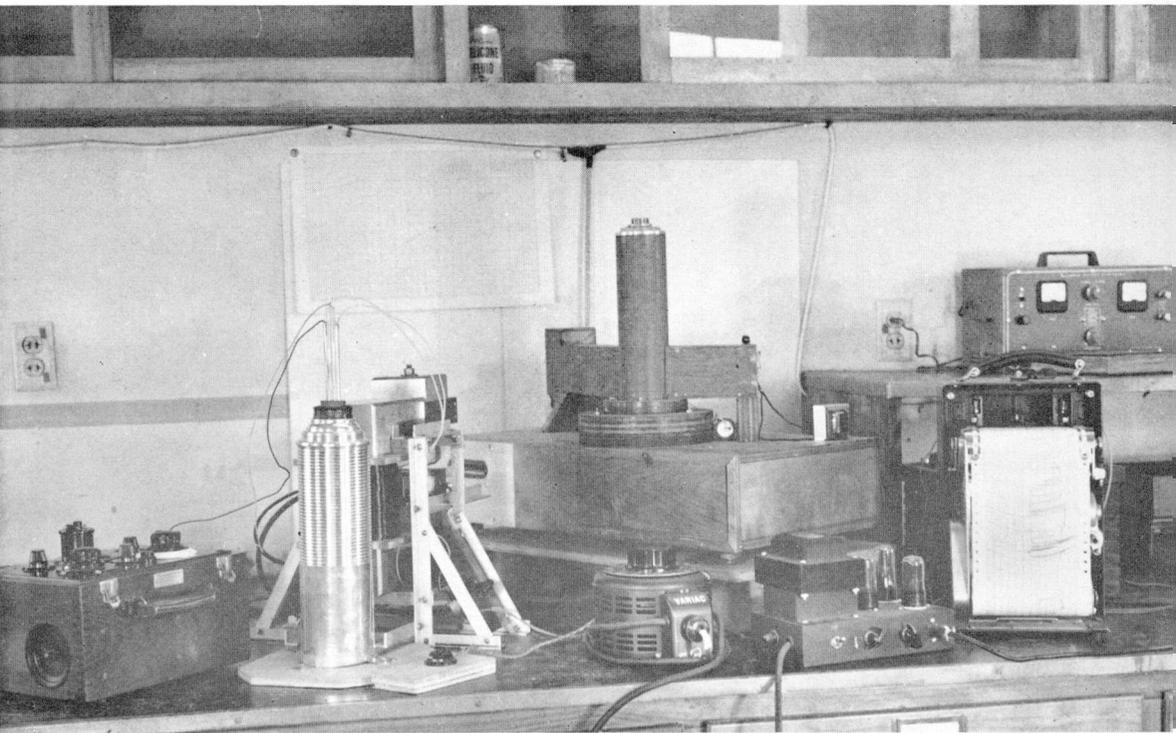
**DESIGN OF A  
CURIE POINT METER**

**A. Larochelle**

DESIGN OF A  
CURIE POINT METER

*3,000-1960-1818*

91594-2-1



110265

General view of Curie  
point meter



GEOLOGICAL SURVEY  
OF CANADA

*BULLETIN 69*

DESIGN OF A  
CURIE POINT METER

By  
A. Laroche

DEPARTMENT OF  
MINES AND TECHNICAL SURVEYS  
CANADA

ROGER DUHAMEL, F.R.S.C.  
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY  
OTTAWA, 1961

Price 50 cents

Cat. No. M42-69

## Preface

Magnetic properties are rarely used to identify minerals because they are generally difficult to detect or to determine accurately. Ferromagnetic minerals are, however, an exception. Not only can a family of ferromagnetic minerals be identified from its magnetic properties, but individual members of the family can be recognized. The Curie point is one of the most reliable magnetic properties for identifying such minerals.

The apparatus described in this bulletin was designed to permit the rapid, accurate measurement of the Curie point of the ferromagnetic minerals in rock specimens, and by this means to identify them.

J. M. HARRISON,

*Director, Geological Survey of Canada*

OTTAWA, April 28, 1960



## CONTENTS

	PAGE
Introduction .....	1
General description .....	1
The torsion balance .....	2
The recording system .....	6
The heating element .....	8
The electromagnet .....	9
Operation and calibration of the apparatus .....	12
Practical application .....	15
Bibliography .....	18
 Table I. Curie points of specimens of basic intrusive rocks .....	 16
 Plate I. General view of Curie point meter .....	 <i>Frontispiece</i>
 Figure 1. Schematic view of the Curie point meter .....	 2
2. Longitudinal section of torsion balance .....	3
3. Plan view of torsion balance .....	4
4. Circuit diagram of DC amplifier .....	7
5. Sectional drawing of heating element .....	8
6. Design of the electromagnet .....	11
7. Typical records obtained with the Curie point meter .....	14



## DESIGN OF A CURIE POINT METER

---

### *Abstract*

The Curie point of a substance is defined as the temperature at which that substance abruptly loses its *spontaneous magnetization* upon being heated. This property depends only upon the chemical composition of a ferromagnetic substance and it may thus be used to identify the members of ferromagnetic solid solution series found in rocks.

The instrument described is of the torsion-balance type, using a photoelectric recording mechanism. Details of the various components of the instrument and an outline of its calibration are discussed.

An attempt was made to confirm the idea that two distinct ferromagnetic minerals were present in a suite of igneous rocks. It was concluded that only one such mineral was present or if there were two, both had the same Curie point.

### *Résumé*

On définit le point de Curie d'une substance comme la température à laquelle celle-ci se voit soudainement départie de son *aimantation spontanée* au cours de son réchauffement. Cette propriété ne dépend que de la composition chimique d'une substance ferromagnétique et, en conséquence, elle peut servir d'indice dans l'identification des composantes des séries de solutions solides qu'on trouve au sein des roches.

L'instrument décrit dans la présente étude est du type de la balance à torsion et il est muni d'un dispositif d'enregistrement photoélectrique. Les différents organes de l'instrument sont décrits en détail et la technique utilisée pour son étalonnage est donnée.

On a tenté de confirmer l'hypothèse de la présence de deux minéraux ferromagnétiques distincts au sein d'une série de roches ignées. On en a conclu qu'il n'y en avait qu'un seul ou que, s'il y en avait deux, ils avaient tous deux le même point de Curie.



## Introduction

The Curie point of a substance is defined as the temperature at which the substance upon being heated loses its ferromagnetic properties and begins to behave as a paramagnetic substance if placed in a magnetic field. It is therefore the temperature at which a ferromagnetic substance loses its *spontaneous magnetization* (Nagata, 1953, p. 8)<sup>1</sup>.

Similarly to the lattice constant of a crystalline substance, the Curie point is independent of external structures and it is governed only by the chemical composition of the substance for which it is characteristic. To this is due its potential usefulness in identifying the ferromagnetic members of a solid solution. It is particularly advantageous in identifying impure iron oxides found in many rocks because the determination of their Curie points does not require their previous separation from the paramagnetic matrix in which they are embedded.

Another application of Curie point determinations is the detection of the simultaneous presence in rocks of minerals of different Curie points. Such a coexistence has been proposed in the past (Néel, 1955) to account for the 'in situ' reverse magnetic polarization of certain rocks. An investigation of this type, which is briefly discussed at the end of this paper, led to the development of the instrument described below.

## General Description

Various types of instruments may be used to determine the Curie point of substances. The present instrument is of the torsion-balance type, which was originally suggested by Pierre Curie in 1894. Instruments of the same type were also built by Forrestier (1928) and Chevallier (1932). These instruments consist essentially of a torsion balance, a heating unit and thermocouple, an electromagnet, and a recording system. Before describing in detail each component of the present apparatus (*Frontispiece*), a general description will be given in order to explain the principle of its operation.

A T-shaped structure (*see* Fig. 1) is suspended at point 0 by a fine copper wire and balanced in the horizontal plane by the two counterweights, CW, and by the specimen, S, at their respective extremities of the T. The specimen, a 10-mm-long cylinder cut from the rock to be studied, is inserted in a sealed, air-free pyrex capsule. The capsule is fastened to one arm of the T by means of a platinum wire and it is free to penetrate into a small furnace, which in turn lies in the air gap of a specially designed electromagnet (DC energized).

When the specimen is at room temperature, it is attracted into the furnace by the influence of the electromagnet. A torsion is thus set in the suspension wire that allows for a restoring couple on the T, should the influence of the electromagnet on the specimen be cancelled. A narrow band of light 2 inches high originates from a source, L, passes through a 1-mm slit,  $\Sigma$ , and is reflected by the mirror, M, which is rigidly linked to the T structure. The light beam follows a path through the base of two triangular openings and it is then collimated and focussed on the screen of a phototube by means of two planoconvex cylindrical

---

<sup>1</sup>Names and dates in parentheses are those of references cited at the end of this report.

## Design of a Curie Point Meter

lenses. The output of the phototube is fed into a stable DC amplifier, the output of which drives an Esterline-Angus recorder. As the specimen is heated, its susceptibility increases only very slightly and no appreciable change is noticed in the position of the T. At the Curie point of the mineral, its spontaneous magnetization vanishes suddenly and the specimen ceases to be attracted by the electromagnet. The torsion stored in the suspension wire causes the T and the

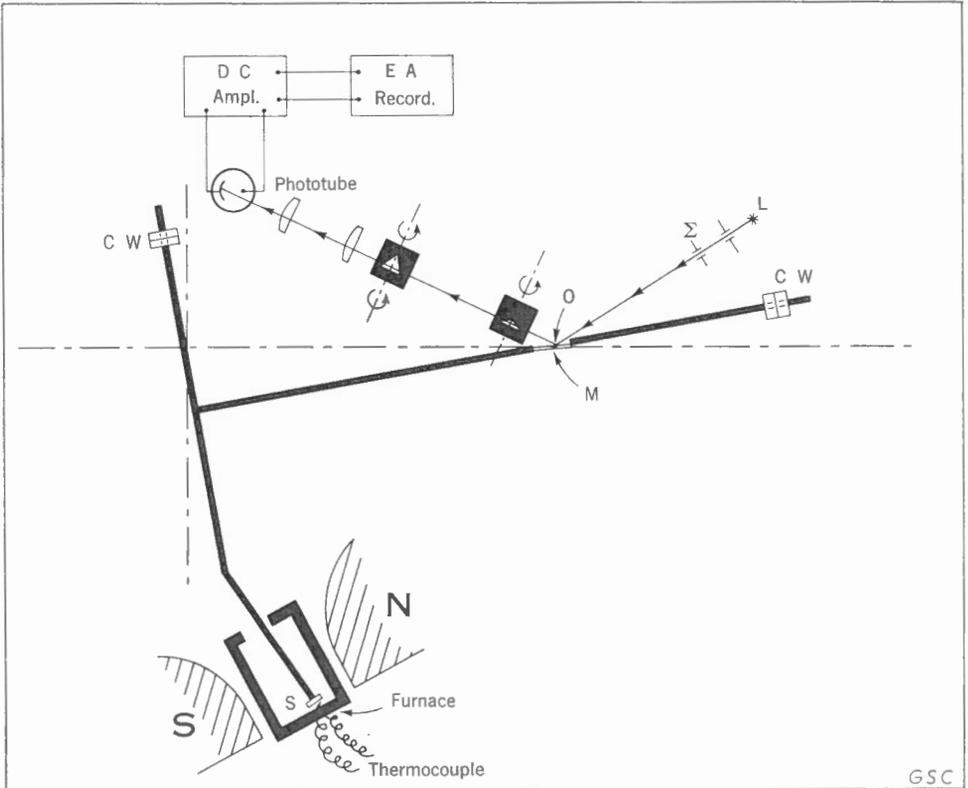


Figure 1. Schematic view of the Curie point meter.

attached mirror to rotate and, as a result, the light beam as it falls beyond the apex of the triangular openings, is reflected away from the phototube screen. When the specimen is later allowed to cool, the sequence of events is reversed. If the specimen has a single Curie point a simple curve is obtained (see Figs. 7A and B) but if the specimen has two Curie points, a step-like curve is observed (see Fig. 7C).

## The Torsion Balance

Drawings showing a longitudinal section and a plan view of the torsion balance are given in Figures 2 and 3, respectively. The essential features of this component are the adjustable suspension Z, the suspension wire W, the beam and





cross-beam T structure to which the mirror M is rigidly linked, the damping mechanism D, the beam levelling counterweights E and F, and the specimen holder H. The support of this mobile system consists of a wooden container the base of which is set horizontally by means of the levelling screws U at each corner. Once the container is level the horizontality of the T structure is assured when it is not in contact with any of the reference bars  $K_1$ ,  $K_2$  and  $K_3$ , the gap being 0.5 mm at all three points when the T is horizontal. An ancillary system (not illustrated) warns the operator immediately if the plane of the moving system tilts by as little as 1 minute of arc in any direction.

The height of the T and its equilibrium position in the horizontal plane when the specimen is not subjected to any external force are both adjustable by means of the suspension screw Z. The suspension wire is passed through pinholes along the axes of two setscrews to each of which it is soldered at its extremities. The upper setscrew is locked to the support by means of another setscrew coaxial to it. The lower setscrew is locked against the aluminum tubing of the T and thus links the lower extremity of the wire rigidly to it. The free length of the wire is 12 inches and its diameter is 0.2019 mm (B & S gauge No. 32). Assuming a rotation of 4 degrees for the T about its points of suspension, i.e., a linear specimen displacement of 21.2 mm toward the furnace, the elastic couple stored by the twisted suspension wire may be calculated with the following formula:

$$\tau = \frac{\pi C \theta R^4}{2 L}$$

where  $\tau$  is the couple in dyne cms, R the radius of the wire in cms,  $\theta$  the angle of torsion in radians, L the length of the wire in cms, and C the torsion modulus of copper ( $4 \times 10^{11}$ ). In the present case,

$$\tau = \frac{\pi \times 10^{11} \times 4 \times (0.01)^4 \times 1}{57.5 \times 2 \times 12 \times 2.54} = 14.3 \text{ dyne cms}$$

The arm of the couple being 30.5 cm long, the minimum force impressed upon the specimen to cause the assumed rotation of the T is 14.3/30.5 or 0.475 dyne.

In order to obtain a qualitative appraisal of the sensitivity of the balance, a single crystal of magnetite weighing 10.34 mg<sup>1</sup> was set in the specimen holder and the electromagnet was energized with the minimum current necessary to cause a rotation of the T over the full range of 4 degrees and to give a full-scale deflection on the record. The restoring couple in the suspension wire was sufficient to return the T to its equilibrium position after the current was cut off and the return movement of the T was rapid enough to be visually perceptible. The relatively fast response of the instrument and its small magnetic moment resolving power allow very small quantities of material to be used for Curie point determinations.

<sup>1</sup>The average weight of the rock specimen to be analysed with the instrument is of the order of 300 mg.

The marked advantage of using small quantities of material is that the whole specimen rapidly acquires a uniform temperature upon being heated or cooled.

Special provisions had to be made so that the specimen holder and the adjacent end of the T would conduct a minimum of heat to the rest of the moving system. This difficulty was surmounted by terminating the brass rod of the cross beam by a pyrex rod into which was inserted a heavy platinum wire designed to hold the pyrex vial containing the rock specimen. The centre of gravity of the moving system, which would otherwise be above the median plane of the T due to the weight of the mirror and its support, is brought slightly below that plane by the weight of a solid brass cone which dips in a bath of high viscosity silicone oil. This provides the T with extra stability in the horizontal plane, should there be mechanical vibrations in the room where the instrument is being used. It also supplies a damping mechanism preventing overshooting of the moving beam beyond its range of 4 degrees, when the attraction on the specimen is suddenly applied or released.

### The Recording System

The instrument's recording system depends on the linearity of response of a phototube to the quantity of light allowed to reach the latter's screen. If the intensity of the light source is kept constant, the quantity of light reaching the screen of the phototube is governed only by the position of the light beam along the height of the triangular openings. In turn, the position of the beam is determined by the position of the mirror, which is also that of the T.

The light source consists of three No. 222 flashlight bulbs connected in series to the secondary of a 115/6.6 volt transformer. The primary of the transformer is connected to the output of a constant voltage SOLA transformer, thus eliminating the effect of line voltage fluctuations on the light source intensity. Sudden changes in the line voltage could otherwise be mistaken on the record as indications of shifts in the position of the T, and consequently as discrete variations in the magnetic properties of the rock specimen under study.

The narrow light beam from slits is reflected by the flat mirror M, which is made of a thin plate of glass in order to prevent secondary reflections. The collimating and focussing lenses are identical cylindrical planoconvex lenses whose focal distance is 154 mm. The lenses are so positioned that their focal axes are on the median lines of both the mirror and the phototube screen. The shapes of the triangular openings, which are cut in copper sheets, are shown in Figure 3. The inside walls of the light conduits are coated with dull black paint from the light source to the phototube.

The phototube of the recording system is the vacuum type No. 917. Behind it is mounted an electrostatic shield of *aluminum foil*. An output resistor of 22 megohms was found adequate to allow a linear response from the phototube and to yield a sufficient input for the DC amplifier.

The DC amplifier (Fig. 4) was adapted to the present needs from a circuit published by Rively (1948). It is characterized by good stability resulting from

a high degree of degeneration. A qualitative appraisal of this stability was obtained by varying the line AC voltage over a range of 25 volts about its normal value of 115 volts. The corresponding voltage variation at the input of the recorder was less than 10 millivolts.

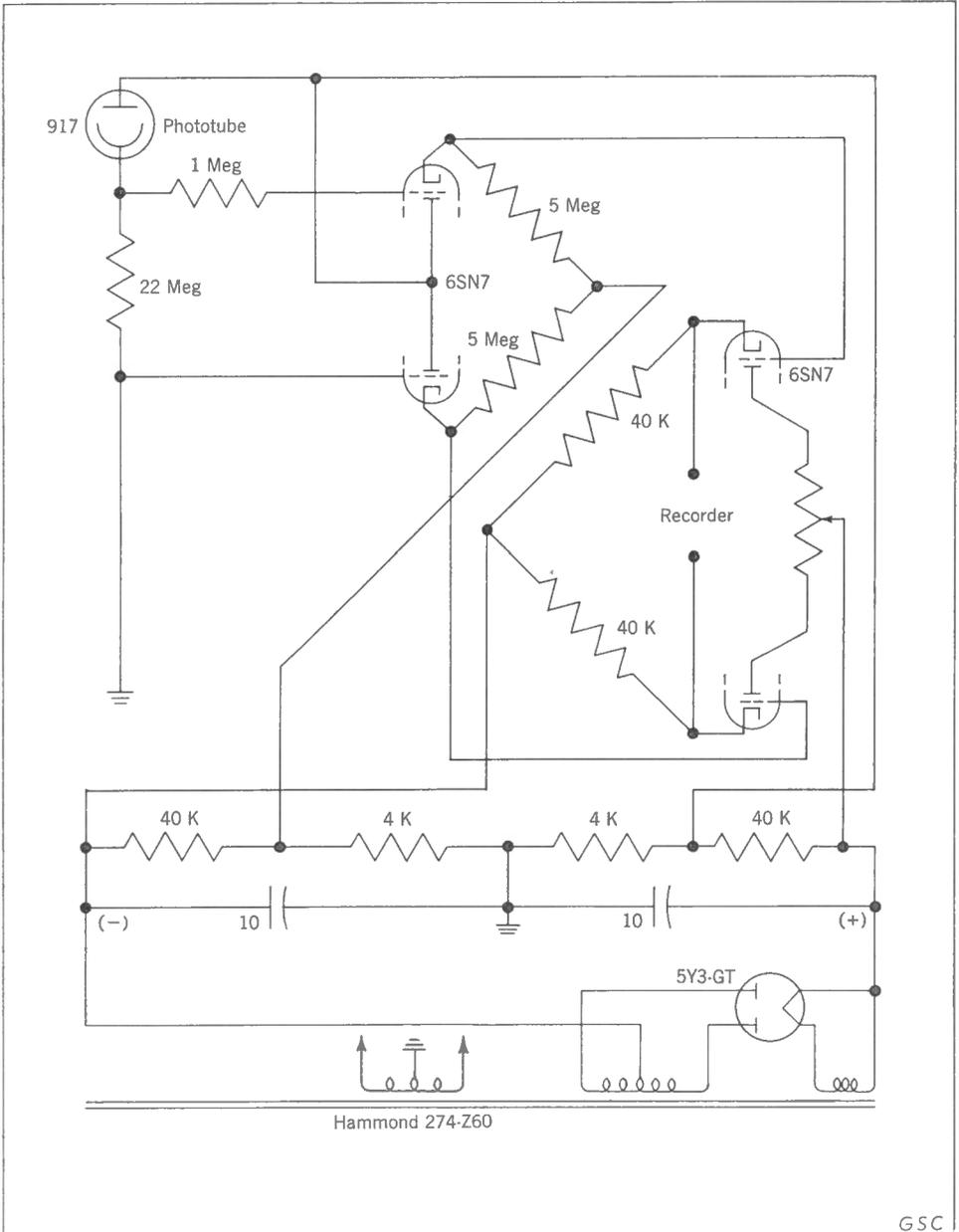


Figure 4. Circuit diagram of DC amplifier.

## The Heating Element

Several requirements had to be met in the design of the heating element. As it fits in the air gap of the electromagnet, it must be relatively compact but still large enough to allow movement of the specimen along its axis and to reach relatively high temperatures. External radiation of heat must be kept to a minimum in order to allow a relatively high rate of heating and to prevent changes in

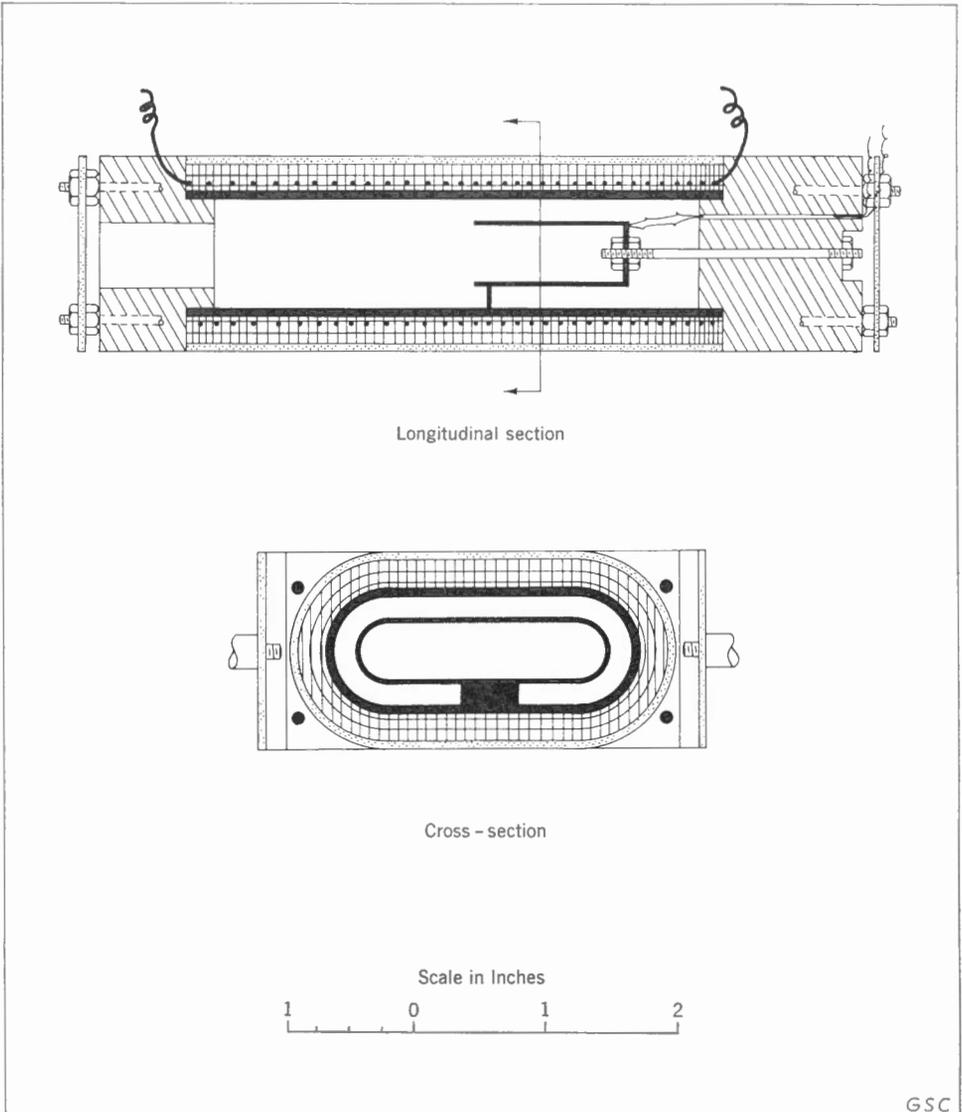


Figure 5. Sectional drawings of heating element.

the magnetic properties of the material comprising the pole pieces. The heating element must also be non-magnetic so that its presence in the vicinity of the electromagnet does not interfere with the expected configuration of the magnetic field in the air gap. Uniform temperature inside the furnace is prerequisite if the whole specimen is to change temperature simultaneously. Another reason for uniformity of temperature inside the element is that the temperature of the specimen is, within a constant, proportional to the temperature of the furnace lining to which is joined the hot junction of the thermocouple.

The geometrical and dimensional requirements of the heating element were fulfilled by choosing the size and shape shown in Figure 5. In order to promote uniformity of temperature inside the element, it is lined with a sheet of silver 1 mm thick and a 'bell' of the same material is added to the region immediately surrounding the specimen during the normal operation. A chromel almel thermocouple is soldered to the bottom part of the 'bell'. The output terminals of the thermocouple are connected to the copper leads of a Cambridge potentiometer through two columns of mercury which are kept at 0°C in a thermoflask filled with melting ice.

The DC magnetic field distortion caused by the furnace is kept to a minimum by constructing the furnace of low magnetic susceptibility materials (e.g., copper, aluminum, soapstone, brass, and silver) and by using alternating current in the winding. The winding is made of 33 turns of No. 20 B & S gauge Nichrome wire which carries a maximum of two amperes when the temperature of the specimen reaches 600°C. The winding is isolated from the silver lining by a layer of asbestos paper and is embedded in a matrix of porcelain (SAUREISEN) cement. The element is then covered by three layers of insulating asbestos paper and by an aluminum girdle that serves to reflect the radiant heat.

### The Electromagnet

The design of the electromagnet was based on the following theoretical considerations.

If a volume element  $dv$  of material whose magnetic susceptibility is  $k$  is placed in a magnetic field of intensity  $H$ , it will acquire a magnetic moment  $\overline{M}$  which is given by the relation:

$$(1) \quad \overline{M} = \left[ \frac{k \overline{H}}{(1 + Nk)} \right] dv$$

where  $N$  is known as the demagnetizing factor of the volume element  $dv$  and is dependent upon its shape.

If, on the other hand, a magnetic dipole of moment  $\overline{M}$  is set in a magnetic field  $\overline{H}$ , it acquires a potential energy  $W$  whose value is given by the relation:

$$(2) \quad W = M H \cos \theta = \overline{M} \cdot \overline{H}$$

### Design of a Curie Point Meter

where  $\theta$  is the angle between the magnetic dipole and the field. From (1) and (2) we may derive the expression for the potential energy of a magnetic particle of volume  $dv$  in a magnetic field, namely:

$$(3) \quad W = \left[ \frac{k\bar{H}}{(1 + Nk)} \right] dv \cdot \bar{H} = \frac{kH^2 dv}{(1 + Nk)}$$

The force acting upon the particle in any direction  $s$  is then:

$$(4) \quad F_s = - \frac{\partial W}{\partial s} = \left[ - \frac{2k dv}{(1 + Nk)} \right] \left[ H_x \frac{\partial H_x}{\partial s} + H_y \frac{\partial H_y}{\partial s} + H_z \frac{\partial H_z}{\partial s} \right]$$

and, in particular, if:

$$(5) \quad H_x = H_z = 0 \quad \text{and} \quad H_y = H,$$

then:

$$(6) \quad F_x = \left[ \frac{-2k}{(1 + Nk)} \right] \left[ H_y \frac{\partial H_y}{\partial x} \right] dv$$

By an appropriate design of the pole pieces of the electromagnet the product

$$H_y \left( \frac{\partial H_y}{\partial x} \right)$$

can be made a constant over an interval of at least 20 mm along the  $x$  axis and the condition expressed by (5) may be achieved at the same time. The force attracting the volume element  $dv$  would then be:

$$(7) \quad F_x = K \left[ \frac{k}{(1 + Nk)} \right]$$

where  $K$  is a constant equal to  $-2 H_y dv \left( \frac{\partial H_y}{\partial x} \right)$ .

It is known from experience (Nagata, 1953, p. 44) that  $k$  is a function of the temperature  $T$  of the specimen, i.e.,  $k=f(T)$ . It follows that  $F_x$  is also a function of  $T$ ,  $\Phi(T)$ . Now if  $f(T)$  can be differentiated over the interval  $0 < T < \theta_c$  ( $\theta_c$  being the temperature of the Curie point), it is possible to evaluate  $\partial F_x / \partial T$  for any temperature of that interval. Thus:

$$(8) \quad \left( \frac{\partial F_x}{\partial T} \right) = K \left[ \frac{1}{(1 + Nk)^2} \right] \frac{\partial k}{\partial T}$$

According to experimental data (Nagata, 1953), when a ferromagnetic mineral is heated from room temperature to a temperature above its Curie point  $\theta_c$ , its magnetic susceptibility  $k$  increases very slowly up to its Curie point and at that temperature decreases abruptly. Mathematically, this may be expressed as:

$$(9) \quad \left( \frac{\partial k}{\partial T} \right)_{T < \theta_c} \geq 0 ; \left( \frac{\partial k}{\partial T} \right)_{T = \theta_c} \gg 0 \quad \text{and} \quad \left( \frac{\partial k}{\partial T} \right)_{T > \theta_c} = 0$$

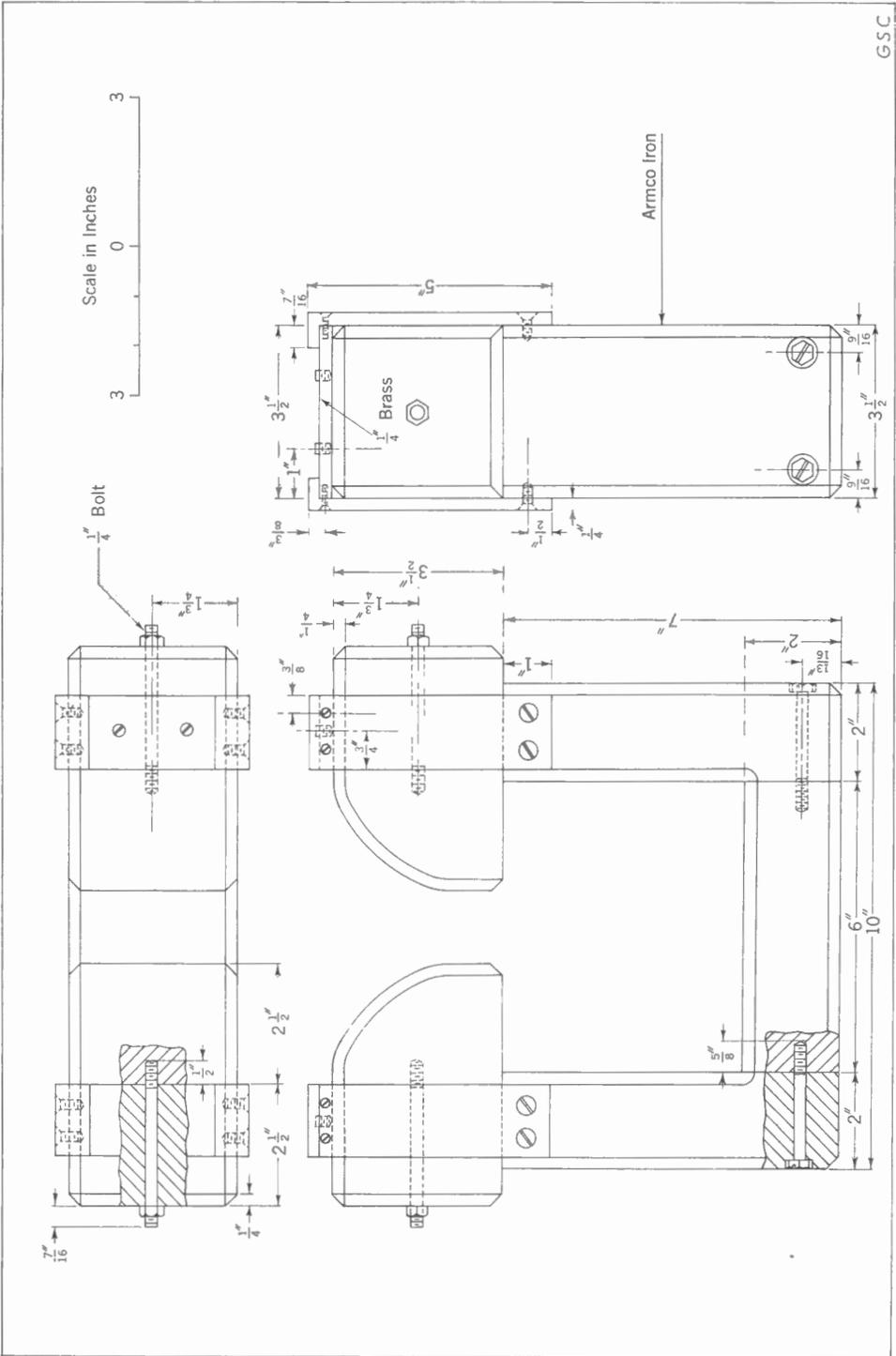


Figure 6. Design of the electromagnet.

Introducing (9) into (8) yields:

$$(10a) \quad \left( \frac{\partial F_x}{\partial T} \right)_{T < \theta_c} \doteq 0$$

$$(10b) \quad \left( \frac{\partial F_x}{\partial T} \right)_{T = \theta_c} = K \left( \frac{\partial k}{\partial T} \right) \text{ using } k \rightarrow 0 \text{ as } T \rightarrow \theta_c$$

where  $\left| \left( \frac{\partial k}{\partial T} \right) \right|_{T = \theta_c} \gg 0$ .

Equations (10a) and (10b) show that the force impressed upon the specimen at any temperature below the Curie point may generally be considered constant and that it varies abruptly at the Curie point. Furthermore, from equation (7),  $F_x = 0$  at the Curie point, as  $k$  vanishes at that temperature.

The fact that ferromagnetic minerals may sometimes be polarized permanently in a direction that is not that of the  $y$  axis is negligible, as the polarization induced into the specimen by a field of the order of 500 Oersteds is considerably larger than the remanent polarization of the specimen.

The above theory shows that it is possible to determine very accurately the Curie point of ferromagnetic minerals if the conditions

$$H_x = H_z = 0 \text{ and } H_y \left( \frac{\partial H_y}{\partial x} \right) = \text{Constant},$$

are fulfilled by the magnetic field. These conditions are very closely met if the pole pieces of the electromagnet have the form illustrated in Figure 6. This pole piece design was used before by Foëx and Forrer (1926) and by Pacault (1946) and it was originally suggested by Weiss.

Armco Iron was selected for the material forming the core and pole pieces on account of the high permeability and low retentivity of this material. The air gap between the pole pieces is adjustable by means of non-magnetic brass clamps which cause no distortion in the magnetic field in the gap.

The coil of the electromagnet (not shown in Figure 6) was wound with No. 22 B & S gauge enamel-coated wire and it contains approximately 2,300 turns. Its DC resistance is 39 ohms. The electromagnet is energized by one or two 12-volt car batteries. The current in the coil may be coarsely adjusted to the required magnitude by changing the voltage across the coil terminals in steps of 2 volts from the intermediate terminals of the batteries. Finer current adjustments may be made by means of a rheostat in series with the coil. An average current of 0.25 ampere was necessary to attract the rock specimens into the furnace.

### Operation and Calibration of the Apparatus

After the specimen has been fastened to the specimen holder, the  $T$  is balanced into the horizontal plane and the electromagnet is energized with sufficient current to attract the specimen to its position of maximum displacement. The heating element is then turned on and placed around the specimen until the

latter almost touches the bottom of the 'bell'. The magnetic field is then temporarily released to verify that the system is freely suspended.

The magnetic field is then adjusted to the minimum value necessary to keep the specimen in its position of maximum displacement. This precaution is necessary because if two minerals of different Curie points are present in the specimen and if the magnetic field is too high, the transition through the lower Curie point may pass unnoticed as the force acting on the higher Curie point mineral alone may be sufficient to keep the specimen in its position of maximum displacement.

The preferred rate of temperature change is about 5°C per minute. It is maintained by means of a variable voltage transformer, the output of which is gradually increased. It is important to keep this rate relatively low in order that the instrument be given time to resolve two or more Curie points if necessary. Temperature readings are made every four or five minutes unless sudden changes are indicated on the record, in which case they are made every minute, or more often if necessary. The time of each temperature reading is indicated on the record by means of a fiducial mark opposite which is indicated the potentiometer reading or the corresponding temperature in °C.

When the highest Curie point of the specimen has been reached, the temperature is slowly reduced and recorded at regular short intervals until the lowest Curie point is indicated on the record. The cycle may be repeated as often as desired without any fear of masking previous records such as would be so with plate photographic recording.

The first step in calibrating the instrument consisted in comparing the thermocouple voltage with another temperature-measuring device. This was done up to 500°C with a mercury thermometer and the calibration curve thus obtained was a straight line which was extrapolated for the range 500°C to 700°C. The thermometer was introduced into the region of the heating element occupied by the specimen during the normal operation and, when the mercury column in the thermometer had stabilized, simultaneous readings of the thermometer and potentiometer were made. Five points equally spaced between 20°C and 500°C were thus obtained during the process of heating the element and a like number of determinations were made during its cooling. The possible error involved in determining the temperature of the specimen from the potentiometer reading and from this calibration is of the order of 2°C.

The reliability of the instrument was further tested with minerals of known Curie points. A few octahedral crystals of a magnetic, black mineral were extracted from a hand specimen of chlorite schist. An X-ray powder pattern confirmed that this mineral is pure magnetite.<sup>1</sup> As heat was applied to the specimen, its position remained unchanged until its temperature reached 583°C. At this temperature the force exerted on it by the electromagnet vanished abruptly, as indicated on a reproduction of the record in Figure 7A. As long as the temperature remained above 580°C, the specimen was not attracted to the electromagnet but it was

---

<sup>1</sup> This pattern was obtained by Mrs. J. Climo of the Geological Survey of Canada. The lattice constant of the mineral was computed to  $8.35\text{\AA} \pm 0.002$ .



abruptly returned to the position of maximum displacement at a temperature slightly below 580°C. The temperature lag obtained in the cooling curve relative to the heating curve is explained by the inertia of the moving system and, as the difference between the true and apparent Curie points have different signs in the cooling and heating curves respectively, the arithmetical mean (581.5) of the two was taken as the true Curie point of the substance.

The highest Curie point for magnetite quoted by Chevallier, Mathieu and Vincent (1954) is 583°C. On the other hand, Akimoto (1957) gives 578°C for the Curie point of the same mineral. It is possible that the minerals investigated in those two determinations were slightly different. The value obtained in the present determination is nevertheless very close to the Curie point of magnetite as reported by these authors.

As a second test, the Curie point of a specimen of pyrrhotite was determined. As indicated in Figure 7B, this specimen lost its magnetization at about 335°C; on the cooling curve, it completely recovered its magnetic character at 310°C. The heating and cooling cycles were repeated several times with this specimen and similar results were obtained. Here again, it is possible to explain part of the temperature lag as due to the inertia of the moving system, but it also seems that a reversible chemical or phase change may have occurred in the mineral above its Curie point.

Nagata (1953, p. 33) stated that the Curie point of pyrrhotite varies between 300 and 325°C, depending upon the composition of the mineral. Haraldsen (1937) established independently the temperature range of 250 to 330 degrees for the same solid solution series of minerals. As the composition of the mineral used by the author is not exactly known and as some uncertainty as to the Curie point of pyrrhotite exists, the author's experiment cannot be used as a test of the accuracy of the apparatus.

A third test was designed to observe the type of curve to be expected from a sample containing two minerals of different Curie points. The two minerals mentioned above were mixed in about equal proportions and enclosed in an evacuated pyrex vial. The record obtained from this specimen is reproduced in Figure 7C. Two distinct breaks are indicated on the record and these breaks took place in the neighbourhood of 338 and 583 degrees, respectively, on the heating part of the record. As noticed in Figure 7C, temperature lags were again a feature of the cooling part of the curve.

These experiments show that the present apparatus may be used to determine the Curie point of minerals with an accuracy of  $\pm 2^\circ\text{C}$  and, more important for the study for which it was primarily designed, it can be used to detect the presence of more than one ferromagnetic mineral in a rock.

## Practical Application

A phase of a recent study by the writer (1959) on the remanent magnetism of a series of intrusive rocks consisted of verifying the possible coexistence of two ferromagnetic minerals in the rocks. Such coexistence seemed necessary to

explain the in situ reverse magnetic polarization of certain rocks by one of the self-reversal mechanisms postulated by Néel (1955). Microscopic examination of some of the iron-titanium oxides in these rocks had revealed intergrowths of a member of the ilmenite-hematite series with a member of the ulvöspinel-magnetite series, but it was not possible to determine by optical means whether the two minerals were ferromagnetic and whether they had different Curie points. Neither did it appear practical to attempt to identify more accurately these two minerals by chemical analysis because of the uncertainties inherent in such analysis and the difficulties to be expected in obtaining pure samples.

A more direct approach in investigating the ferromagnetic character of the minerals was to attempt to detect two Curie points in the rock specimens, and at the same time to attempt to obtain at least an approximate value for  $x$  and  $y$  in the series  $x(\text{FeO} \cdot \text{TiO}_2) \cdot (1 - x)\text{Fe}_2\text{O}_3$  and  $y(2\text{FeO} \cdot \text{TiO}_2) \cdot (1 - y)\text{Fe}_3\text{O}_4$ , which represent the two intergrown minerals. The determinations of  $x$  and  $y$  depend on relationships that are known to exist (Pouillard, 1950; Akimoto, 1954; Chevallier, Bolfa, and Mathieu, 1955) between the chemical composition, the lattice constant, and the Curie point of each member of the series.

The Curie points of twenty-one rock specimens were then determined and the resulting data appear in Table I.

**Table I**  
*Curie Points of Specimens of Basic Intrusive Rocks<sup>1</sup>*

Specimen No.	Location	Curie Points C°	Specimen No.	Location	Curie Points C°
37	Brome Mtn.	492 & 530	71	Yamaska Mtn.	462 to 535
37-b	"	565	72	"	542
38	"	580	74	"	535
38-b	"	295 & 475	87	"	568
40	"	570	105	"	553
42	"	580	111	"	568
43	"	565	113	"	576
44	"	567	120	"	538
53	Yamaska Mtn.	582	121	"	552
55	"	581	138	"	462 & 565
67	"	538	—	—	—

<sup>1</sup> Specimens collected on Mount Yamaska and Mount Brome, two intrusive bodies belonging to the Monteregian Hills series in southeastern Quebec.

As shown in Table I, the presence of a ferromagnetic mineral with a Curie point above 582°C was not detected in any of the specimens analysed. This confirms the fact that no pure hematite was observed as polished sections. The second observation is that, in most cases, only one Curie point was detected and

in them it ranged between 538° and 582°C. This fact may be interpreted either as an indication that only one of the two intergrown minerals is ferromagnetic or that they both have the same Curie point. In either event, their reverse polarization could not be accounted for by the self-reversal mechanism previously mentioned. Thirdly, three of the twenty-one specimens were found to have a double Curie point and the reverse polarization of these specimens was tentatively accounted for by Néel's third self-reversal mechanism (op. cit.). Finally, specimen No. 71 presents a particular case among the specimens studied. The continuous drop in magnetization from 462° to 535°C and the sharp drop at 535°C were interpreted as the result of incomplete exsolution of ilmenite from the member of the ulvöspinel-magnetite series whose Curie point is 462°C. As ilmenite is removed from the series the Curie point increases. The exsolution having taken place at different degrees in distinct grains of the rock, the most highly exsolved grains had a Curie point of 535 degrees, approaching that of pure magnetite.

The fact that three different Curie point distributions were obtained from a suite of oriented specimens that were all reversely polarized is strongly suggestive that the Curie points of these rocks have no bearing on the reverse polarization. Furthermore, sedimentary rocks adjacent to the previously mentioned intrusive rocks were also found to be reversely polarized, despite the fact that the two are completely different in texture and mineral composition. The conclusion of this study was then that the reversal of magnetic polarization observed in the igneous rocks was more probably due to a past reversal of the earth's field rather than to the existence of a self-reversal mechanism in the rocks.

## Bibliography

- Akimoto, S.  
1954: Thermomagnetic Study of Ferromagnetic Minerals Contained in Igneous Rock; *J. Geomagnetism and Geoelectricity*, vol. 6, No. 1 (Mar. 1954), pp. 1-15.  
1957: Magnetic Properties of Ferromagnetic Oxide Minerals as a Basis of Rock Magnetism; *Adv. in Physics*, vol. 6, No. 23, p. 288.
- Chevallier, R., and Pierre, J.  
1932: Propriétés thermomagnétiques de roches volcaniques; *Ann. de Phys.*, ser. 10, vol. 18, p. 383.
- Chevallier, R., Bolfa, J., and Mathieu, S.  
1955: Titanomagnétites et ilménites ferromagnétiques; *Bull. Soc. Franc., Minér. Crist.*, vol. 78, No. 7, p. 307.
- Chevallier, R., Mathieu, S., and Vincent, E. A.  
1954: Iron-titanium Oxide Minerals in Layered Gabbros of the Skaergaard Intrusion, East Greenland, Part II—Magnetic Properties; *Geochim. et Cosmochim. Acta*, vol. 6, p. 27.
- Curie, P.  
1895: Propriétés magnétiques des corps; *Ann. de Chimie et de Physique*, 7 ser., vol. 5, p. 289.
- Föex, G., and Forrer, R.  
1926: Sur un appareil sensible pour la mesure précise des coefficients d'aimantation a diverses températures; *J. Phys. et Radium*, vol. 7, 6 ser., No. 6, p. 180.
- Forrestier, H.  
1928: Unpublished thesis; Univ. Paris.
- Haraldsen, H.  
1937: Eine thermomagnetische Untersuchung der Umwandlungen im Troilit-Pyrrothin-Gebiet des Eisen-Schwefel-Systems; *Leit. f. anorg. allg. chem.*, vol. 231, p. 78.
- Larochelle, A.  
1959: A Study of the Palaeomagnetism of Rocks from Yamaska and Brome Mountains, Que.; McGill Univ., Unpub. thesis.
- Nagata, T.  
1953: Rock Magnetism; Tokyo, Maruzen Co. Ltd.
- Néel, L.  
1955: Some Theoretical Aspects of Rock Magnetism; *Adv. in Physics*, vol. 4, No. 14, p. 191.
- Pacault, A.  
1946: Recherches magnétostatiques; *Ann. de Chimie*, 12 ser., vol. 1, p. 527.
- Pouillard, E.  
1950: Sur le comportement de l'alumine et de l'oxyde de titane vis-à-vis des oxydes de fer; *Ann. de Chimie*, 12 ser., vol. 5, p. 190.
- Rively, C. M.  
1948: Phototube Amplifier for Measuring Ultra-violet Radiations; *Electronics*, vol. 21, pp. 130, 162.