A STUDY OF THE PALAEOMAGNETISM OF ROCKS

FROM

YAMASKA AND BROME MOUNTAINS, QUEBEC

by

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INTRODUCTION

Reverse magnetic polarization of rocks "in situ" is a phenomenon which has been observed and reported by several workers since its discovery by Brunhes (1906) in baked clays and adjacent basalts of Miocene age in Central France. Earlier, Folgheraiter (1899) had noticed the reverse polarization of fragments of ancient pottery discovered in Central Italy and he had concluded from this observation that the earth's magnetic field was probably temporarily reversed from its present direction in this part of the world during Recent times. In Germany, Pockels (1901) and Toepler (1901) noticed that sometimes rocks "in situ" are reversely polarized by the action of lightning. Both Pockels and Toepler recognized however that lightning polarization of rocks is a very local phenomenon which never extends over areas larger than a few square meters*. In more recent years, reverse polarization of rocks "in situ" has been observed in many rock types of various ages and in different countries of the world. A list of such observations, as reported in the literature, is given in Table 1 below. Although admittedly incomplete, this list shows that reverse

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*Since lightning polarization is easily detected in the field and since it is of no palaeomagnetic interest, it is excluded from the present discussion. The other trivial case of reverse polarization of rocks "in situ" due to overturning of beds is also eliminated since determination of magnetic polarization always includes a correction for geological structure.

TABLE 1

REPORTED OCCURRENCES OF REVERSE POLARIZATION OF ROCKS IN SITU

Country	Rock Type	Age	Observer
Argentina	Basalt	Quaternary	Creer (1958)
Australia	Varved Clay	Carboniferous	Irving (1957a)
"	Basalt	Carboniferous	Irving & Green (1958)
"	Lava	Permian	Mercanton (1926)
"	Basalt	Tertiary	Irving & Green (1957)
Canada	Basalt	Keewanawan	DuBois (1957)
"	Anorthosite	?	Bourret (1949)
England	Sandstone	Precambrian	Irving (1957b)
"	Lava & Intrusives	Carboniferous	Clegg & al. (1957)
"	Red beds	Triassic	Clegg & al. (1954)
"	Limestone	Jurassic	Nairn (1957a)
"	Tholeite dyke	Tertiary	Bruckshaw & Robertson (1948a)
"	Lava	Tertiary	Bruckshaw & Vincenz (1954)
France	Sandstone	Permian	Nairn (1957b)
"	Dolerite	Permian	Roche (1957)
"	Andesite	Permian	Rutten (1957)
"	Sandstone	Triassic	Clegg & al. (1957)
"	Lava	Tertiary	Roche (1950, 1953)
Iceland	Basalt	Tertiary	Hospers (1953)
"	Lava & Seds.	Tertiary	Einarsson & Sigurgersson (1955)
"	Basalt	Tertiary	Brynjolfsson (1957)
"	Lava	Quaternary	Hospers (1953)

/...

TABLE 1 (Cont'd)

Country	Rock Type	Age	Observer
India	Lava	Cretaceous	Clegg & al. (1956)
Japan	Lava	Tertiary	Kato & Takagi (1955)
"	Tuff	Tertiary	Kawai (1951)
"	Lava	Quaternary	Nagata & al. (1957)
Norway	Andesite	Permian	Rutten & al. (1957)
Russia	Limestone	Tertiary	Kalashnikov & al. (1958)
South Africa	Dyke	Precambrian	Gough (1956)
" "	Basalt	Jurassic	Nairn (1957c)
U.S. (Mich.)	Dyke	Precambrian	Graham (1953)
" (N.Y.)	Igneous & Metamorphic	Precambrian	Balsley & Buddington (1958)
" (Okla.)	Granite	?	Hawes (1952)
" (Md.)	Sandstone	Silurian	Graham (1949)
" (Conn.)	Sandstone	Triassic	DuBois (1957)
" (Dak.)	Sandstone	Cretaceous	Runcorn (1956)
" (Ore.)	Lava	Miocene	Runcorn & Campbell (1956)
" (Ore.)	Basalt	Eocene	Cox (1957)
" (N.Mex.)	Basalt	Late Cenozoic	Muehlberger & Baldwin (1958)

polarization of rocks "in situ" is not an isolated phenomenon in nature and, for this reason, many theories have in the past been set forward to explain its existence. It is widely admitted today that the phenomenon is either the evidence of periodic reversals of the earth's magnetic dipole (as suggested in 1899 by Folgheraiter) or, in some special cases, the result of a "self-reversal mechanism" which is inherent in the mineral assemblage of certain rock types. As more polarization measurements are made, it seems that the hypothesis of dipole reversals is the most probable explanation in the majority of cases (Creer, 1958). This fact along with others is used in the foundation of the relatively new science known as palaeomagnetism.

One of the major problems in palaeomagnetism is the selection of rocks which are suitable for this type of study, i.e., rocks which may be considered as magnetically stable and of chemical and mineralogical compositions such that a mechanism of self-reversal cannot be evoked as the partial cause of their "anomalóus" polarization.

Graham (1949) designed a few tests to establish in the field the magnetic stability of sedimentary rocks with a minimum of doubt. However, the application of these tests to igneous and metamorphic rocks is seldom possible. In these cases laboratory tests such as those suggested by Thellier (1937), Thellier & Rimbert (1954), Rimbert (1955, 56, 57), Creer (1955), Grabovski & Petrova (1956), Doell (1956), are necessary.

Now that Graham's tests have been applied to thousands of sedimentary specimens (Runcorn, 1956) it can be stated that red beds of either fine-grained sandstone, siltstone or shale are generally the most magnetically stable sedimentary rocks. This is due to the almost exclusive presence of hematite as the ferromagnetic mineral in these rocks. Hematite is characterized by a high coercive force (much higher than that of magnetite) which is one of the main factors in determining the magnetic stability of a rock of a given grain size, (Grabovski & Petrova, 1956). It is noted, however, that other sedimentary rocks such as limestone, greywackes and impure sandstones have also been successfully used in palaeomagnetism.

Volcanic rocks have also been used extensively in such studies, as indicated in the above Table 1. Having magnetite or titaniferous magnetite as their main ferromagnetic constituents, these rocks generally have a stronger polarization than red beds. On the other hand, their magnetic stability is achieved by a sufficiently fine-grained dissemination which allows for a good coercivity (Gottschalk, 1941).

Relatively few attempts have been made to use intrusive rocks in palaeomagnetism. Polarization measurements of several oriented specimens of granite from Oklahoma were made by Hawes (1952). More recently, similar measurements on intrusive and metamorphic rocks from the Adirondacks were reported by Balsley & Buddington (1958). In both of these cases the directions of polarization were considerably scattered and the data were not considered suitable for a palaeomagnetic analysis. On the other hand, Armstrong (1957) was able to establish the age of certain basic intrusives in Ayrshire by comparing their direction of polarization with similar data obtained for rocks whose age had been determined on the basis of palaeontology. Again, Clegg et al (1957) used polarization measurements of intrusive rocks in England to determine the position of the earth's magnetic pole during Carboniferous time. It is interesting to note that in all of the four groups of measurements just referred to, at least some of the specimens were reversely polarized. Many more cases of reversely polarized intrusive rocks are reported in the geophysical literature and it is probable that most of these rocks have a stable component of remanent magnetization which was imposed on them by the Ambient earth's field at the time of their cooling.

Object of Thesis

The object of the present thesis is to study the possible geological significance of polarization measurements made on a suite of oriented specimens collected from the core of two of the Monteregian Hills in Southern Quebec. In particular, the magnetic stability of these rocks and the origin of their reverse polarization are considered. A comparison is made between the direction of polarization of these rocks and similar data reported in the literature for other rocks whose age has been determined on the basis of palaeontology. By means of this comparison an attempt is made to establish the approximate age of the Monteregian Hills in general.

Acknowledgements

The writer wishes to express his sincere gratitude to all of those who have helped him in the various phases of the present work. In particular, his thanks extend to Dr. L.W. Morley of the Geological Survey for his support and encouragement throughout the project, to Dr. V.A. Saull, McGill University, for his critical review of the manuscript and his valuable suggestions and to Mr. P.M. DuBois of the Geological Survey for his helpful suggestions. Mr. C.E. Anderson assisted the writer in some phases of the field and laboratory work and he is responsible for some of the drawings. This work was part of a research project carried out in the laboratories of the Geophysics Division of the Geological Survey of Canada.

CHAPTER I

NOTES ON THE GENERAL GEOLOGY OF YAMASKA AND BROME MOUNTAINS

Although it is not the specific object of this thesis to deal with the general geology of Yamaska and Brome mountains, it is pertinent to give a brief account of the main geological features insofar as they relate to the object of the thesis.

1- Yamaska Mountain

Yamaska mountain is situated about 30 miles east of Montreal, Quebec. At this point the present geomagnetic field would normally have a total intensity of 57,450 gammas, a declination of $16^{\circ}18'$W and an inclination of $74^{\circ}53'$. The mountain covers an area of $5\frac{1}{2}$ sq. miles, a little over 3 sq. miles of which is occupied by a core of basic intrusive rocks.

According to Young (1906) who first mapped in detail the geology of this mountain, the igneous core is the erosion remnant of a volcanic neck which punctures the Farnham (Cambro-Silurian) slates to the west and the Sillery (Upper Cambrian) slates to the East.

Considered from a petrologic point of view, the igneous core grades inward from an alkali syenite (akerite) near the rim, through a nepheline bearing gabbro (essexite), into a rock composed almost entirely of ferromagnesian minerals (yamaskite). These rocks are medium- to coarse-grained and generally have a granitic texture. *Akerite* forms only a small portion of the intrusive and is made up of plagioclase, alkali feldspars and microperthite for the most part. This rock also contains biotite, some pyroxene (diopside) and hornblende. Among the accessory minerals Young reports pyrite, apatite, zircon, titanite and "iron oxide". The latter is of particular interest in the present study owing to its ferromagnetic properties. *Essexite* forms the bulk of the igneous core and its composition and texture vary widely throughout the rock mass. In general plagioclase and potash feldspars account for about one third of this rock each and the rest is made up of hornblende, titaniferous augite and biotite, nepheline and some opaque minerals among which titaniferous magnetite is of main interest in the present study. *Yamaskite* occurs as isolated patches engulfed in the essexite. Titaniferous augite and hornblende form the bulk of Yamaskite and "much ilmenite and magnetite" are reported in it by Young (op. cit.).

According to Young the igneous core of Yamaska mountain is the product of a single intrusion. His conclusion is based upon the shape and dimensions of the body as well as on the fact that the contacts that he observed between the various igneous rock types are always gradational.

The time of intrusion of the igneous core is not accurately known. The youngest strata intruded are the Farnham slates which were last folded during the Taconic or possibly during the Acadian disturbances. Since the folding of these strata is not appreciably disturbed in the vicinity of the igneous core, Young concludes that the maximum age of the latter is Ordovician or possibly Middle Devonian. A minimum age has apparently not been estimated due to lack of conclusive evidence.

2- <u>Brome Mountain</u>

Brome mountain is located about 17 miles south east of Yamaska mountain. It covers an area of about 30 sq. miles 23 of which are underlain by a core of basic intrusive rocks.

Brome mountain was considered by Dresser (1906) as the erosion remnant of a lopolith. It has apparently not been disturbed since its original emplacement. Dresser believed however that two periods of intrusion contributed to the formation of the igneous core. A first intrusion of essexite was followed by the injection of nordmarkite between the former and the overlying sediments. In the present study, our attention was restricted to the essexite in the southern part of the igneous core. The essexite from Brome ressembles very much to that from Yamaska and contains equivalent amounts of ferromagnetic minerals.

Although he lacked conclusive evidence, Dresser (op. cit.) set the maximum age of the intrusions as Upper Ordovician and the minimum age as Permo-Carboniferous. The reason for setting the maximum age is the same as given above for Yamaska mountain. Evidence for establishing the minimum age is somewhat tenuous. Dresser noticed some degree of parallelism between certain structures in the igneous core and similar structures in the surrounding sediments. Assuming that the structures in the sediments could have been formed no later than the period of most recent folding east of the Logan's line, he concluded that they could not have taken place later than Permian time. Since the structures which he found in the igneous body were probably contemporaneous with the intrusion itself, he suggested that the intrusion did not take place later than Permian time.

The present study is connected in particular with two aspects of the general geology of Yamaska and Brome mountains, namely the times of intrusion of the igneous cores and the composition of the ferromagnetic minerals referred to as "iron ore" by Young and Dresser. A comparison of the measured directions of magnetic polarization of these rocks with similar data obtained for other rocks of known age provides additional information concerning the probable age of these intrusives. Also, the Curie point determinations described in Chapter V add to our knowledge on the composition of the ferromagnetic minerals present in the rocks. A few polished sections of "magnetite" grains shown in Plate I also yield some information as to the intergrowth of ilmenite and magnetite in the same rocks.

CHAPTER II

PRELIMINARY MEASUREMENTS

A. Field Surveys

The first geophysical measurements ever published in connection with Yamaska and Brome mountains are reproduced in Figs. 1 and 2 below. They are the result of an airborne magnetometer survey flown by the Geological Survey of Canada in 1950.

A brief examination of Fig. 3 reveals a local magnetic relief of over 5,000 gammas near the core of Yamaska mountain and a magnetic depression of some 3,000 gammas below the regional magnetic background. These anomalies were also detected by the writer on the ground by means of an Askania type vertical magnetometer; on the ground, the observed magnetic relief reaches over 30,000 gammas with magnetic depressions of some 15,000 gammas. The magnetic and topographic depressions and peaks are not spatially interrelated, thus eliminating topography as the major cause of the magnetic anomalies. On the other hand, the anomalies spread horizontally over many hundreds of square feet, thus making lightning polarization the improbable cause of their occurrence, because it is known that lightning polarization rarely spreads out over more than a few square meters (Pockels, 1901; Toepler, 1901).

The fact that magnetic peaks and depressions are adjacent to one another could easily be explained by a variety of geometrical configurations. For example, one could visualize the whole intrusive as a complex arrangement of horse-shoe magnets pointing in different directions. It would be more difficult however to describe the geological mechanism responsible for such a model, especially if we recall that there is no evidence of tectonic movements within the intrusive since the time of its cooling. On the other hand, it is relatively easy to account for the coexistence of the positive and negative anomalies by assuming that the overall magnetization of the intrusive may be the resultant effect of several processes of magnetization which have been active in different directions, at different periods and more or less efficiently over different sections of the intrusive, depending upon the texture and composition of the rocks in each of these sections.

Similar remarks may be applied to the Brome mountain area with the difference that the magnetic fluctuations were less pronounced in the latter. Although the isogams of the aeromagnetic map never reach a value below the regional magnetic background, ground magnetic traverses showed the presence of a 12,000 gamma depression over an area roughly 2½ miles due East of Bull Pond.

The information disclosed by the above-mentioned surveys was strongly indicative of the presence of reversely polarized rocks on Yamaska and Brome mountains. The fact that there is no

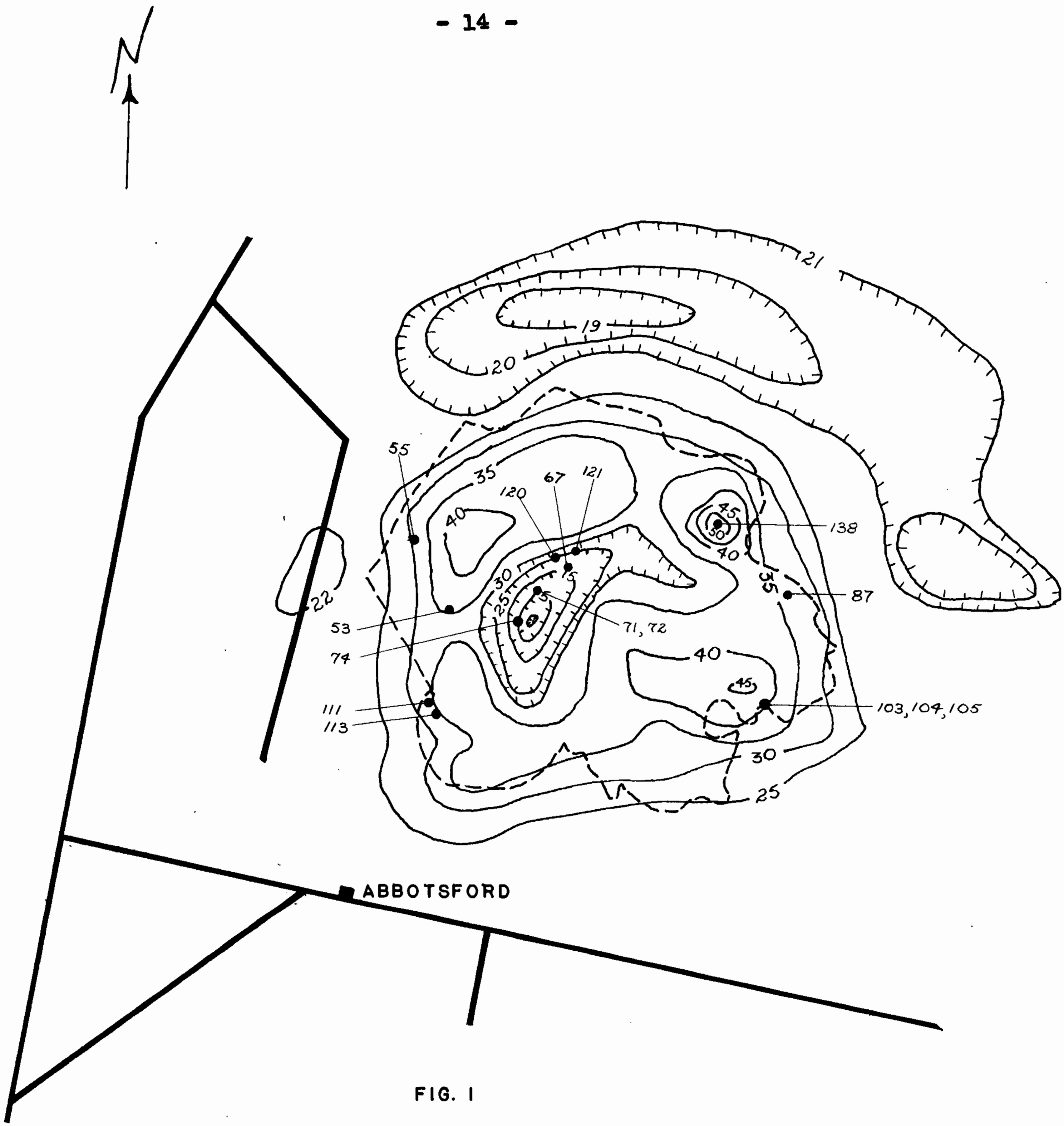


FIG. I

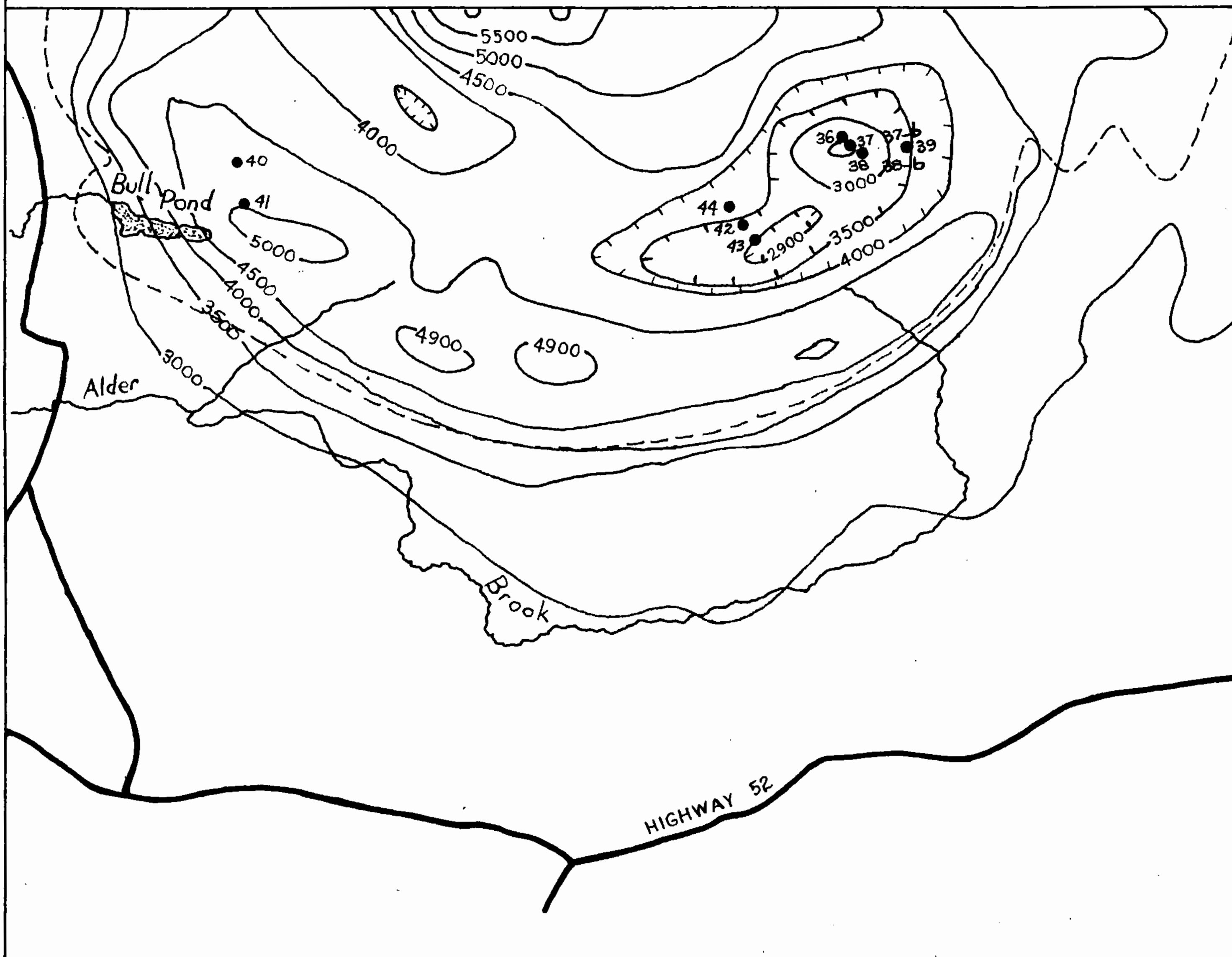
AEROMAGNETIC MAP OF YAMASKA MOUNTAIN

G.S.C. GEOPHYSICS PAPER NO. 171

--- IGNEOUS CONTACT	
TOTAL FIELD IN 100 GAMMAS	SCALE: 1 INCH = 2/3 MILE

AEROMAGNETIC MAP OF SOUTHERN PORTION OF BROME MOUNTAIN

G.S.C. GEOPHYSICS PAPER NO. 183



--- IGNEOUS CONTACT

SCALE: I INCH = 2/3 MI.

CONTOURS IN GAMMAS

FIG. 2

evidence that these rocks have been overturned in the past, suggested further the possibility of attempting palaeomagnetic studies in these areas.

B. Specimen Collection and Preparation

Oriented specimens are required for the purpose of studying the original direction of remanent magnetization of rocks. In the present study the following technique was used for specimen collection. A flat surface, for instance a joint plane, was sought on the outcrop and a horizontal arrow was drawn on that surface. The down-dip direction of the surface was also marked by a line perpendicular to the arrow. The azimuth of the arrow and the slope of the dip line were then measured with a Brunton compass and a clinometer respectively before the specimen was broken away from the outcrop. To eliminate errors from local effects, the compass reading was corrected by adding the angular difference between the apparent azimuth of the sun and its true azimuth as given in tables for the particular time at which the specimen was oriented. The geographic positions of the collected samples* are shown in Figs. 1 and 2.

In preparation for the actual measurements of their polarization, the specimens were first embedded in a base of plaster of Paris in such a way that their original attitude in the field was reproduced. A two-inch vertical core was then drilled from the specimen and the core was cut into two or

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*The specimens from Yamaska mountain were collected by Dr. R. Mitra of the G.S.C.

three one inch cubes, precaution being taken that the orientation reference lines were carried faithfully from the initial steps of the operation.

C. Measuring Instruments for Remanent Magnetization

The most widely used instruments for remanent polarization measurements are the astatic magnetometer and the rock generator or spinner type remanent magnetometer. The former is a very sensitive instrument but its operation is very slow and tedious. When the rocks to be measured are only weakly polarized, this instrument is the only one which can be used satisfactorily. A description of this apparatus and of its operation is given by Collinson & al. (1957). The rock generator, on the other hand, sacrifices some sensitivity and precision but its operation is much simpler and considerably faster. As we shall see later in this chapter, the rocks under study have a relatively strong magnetic polarization, and sensitivity was therefore considered as not to be a critical factor for the measuring instrument. On the other hand, it was desired to measure and remeasure a relatively large number of cubes. For these reasons preference was given to the rock generator in the choice of measuring instruments.

Rock generators have been fully described in the literature by Bruckshaw & Robertson (1948), Johnson & McNish (1938), Nagata & Rikitake (1943), Johnson, Murphy & Torreson (1948) and Hood (1956). Furthermore, the unit* used in the present study

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*This unit was designed and built by Mr. L.S. Collett & al. of the Geophysics Division of the G.S.C. in 1954.

is now superseded by much more refined instruments of the same type. For these reasons a detailed description of the instrument will be omitted here and only a description of the main features and operation of the device will be given with the help of the block diagram shown in Fig. 3 below.

When the motor is set in operation, two distinct voltages are generated across coils L_1 and L_2 by the reference magnet and the rock cube respectively. Coils L_2 and L_3 are two concentric flat coils which are wound in series opposition. Since L_3 is relatively far from the rotating rock cube, hardly any voltage is generated across it by the latter and the opposite is true for L_2. On the other hand any transient fluctuations in the magnetic field surrounding the instrument will affect both coils and the voltage thus generated will cancel automatically since the two coils are wound in series opposition. Amplifiers A and B are tuned to 30 c.p.s. to reject harmonics or any other type of disturbances. The output of these two amplifiers is fed into an electronic switch which permits the simultaneous tracing of the two generated voltages on the screen of a Cathode Ray Oscilloscope. The balancing of these two traces is done by revolving coil L_1 about the axis of the shaft and by varying the input of amplifier A by means of a graduated potentiometer. The first of these two adjustments cancels any phase shift between the two traces and the second eliminates differences in amplitude. When the two traces blend into one on the C.R.O. screen, the position of coil L_1 and the reading on the potentiometer are noted as a measure of the orientation and intensity

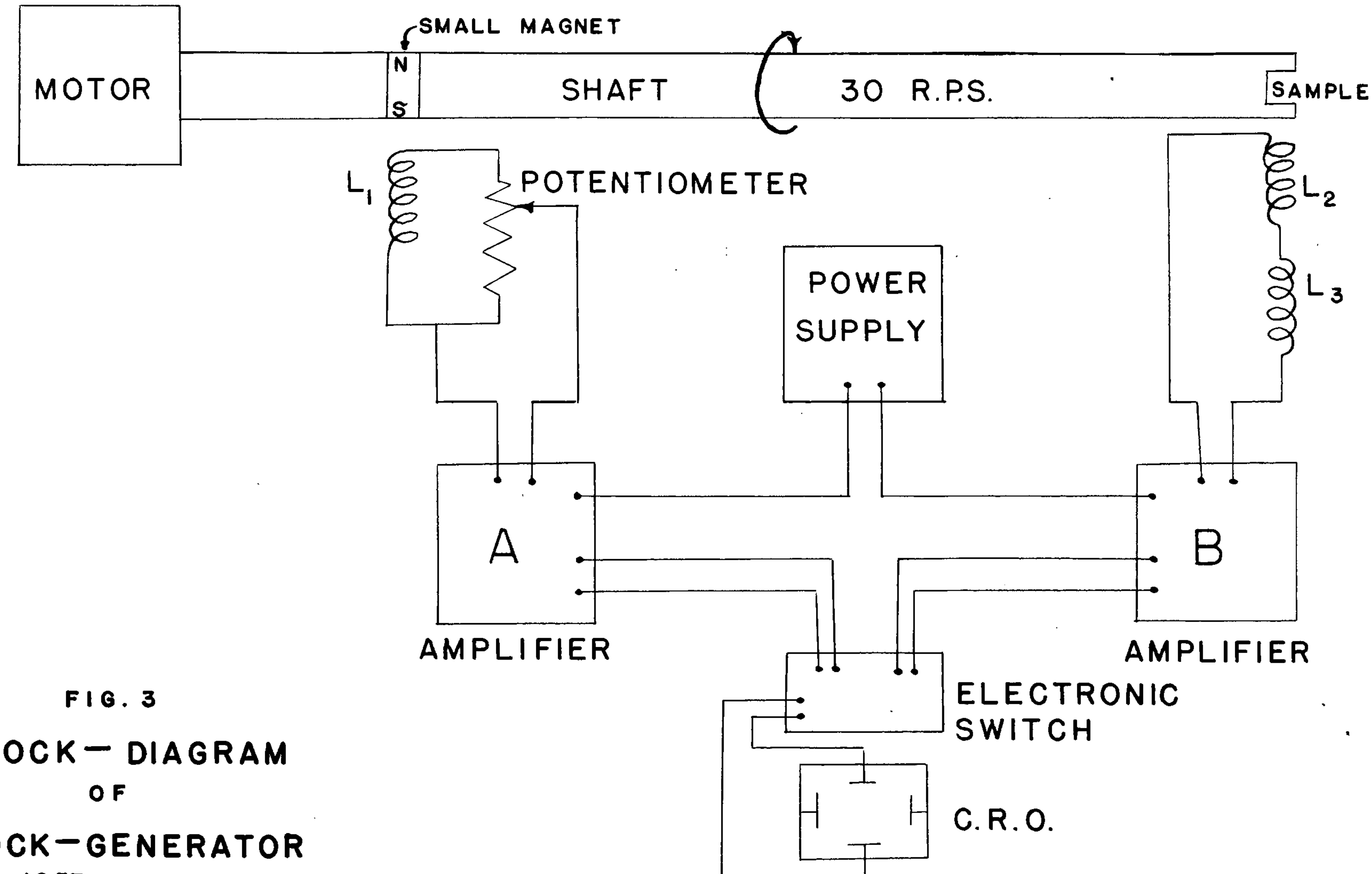

FIG. 3

BLOCK — DIAGRAM
OF
ROCK — GENERATOR

DEC. 1957 A.L.

of the component of magnetization in the plane perpendicular to the axis of rotation of the cube.

The limit of resolution of the instrument is of the order of 10^{-4} emu and angles can be measured with an accuracy of 5°. Time involved in the measurement of a cube averages to about 5 minutes.

D- Measurements and Calculations

Each cube was spun about three mutually perpendicular axes for the determination of its remanent polarization. The nomenclature used in the representation of the various magnetic components is indicated in Fig. 4-A below. The X axis of the cube corresponds with the "in situ" astronomic North of the specimen and its Z axis is along the Vertical and positive downward. Since the specimens were spun clockwise, angle α is the clockwise angle between the X axis and the magnetic component in the XY plane. The intensity of this component is referred to as I_{α}. Similarly, β and γ refer to the clockwise angles measured between the Y and Z axes and the components of magnetization in the YZ and XZ planes respectively. The three positions of spinning about the axes +Z, +X and +Y are indicated in Figs. 4-B, 4-C and 4-D respectively. Theoretically, only two of the three sets of values (θ, I_i) are necessary to determine both the orientation and intensity of the polarization vector of a cube. The three sets of values were recorded however for checking purposes.

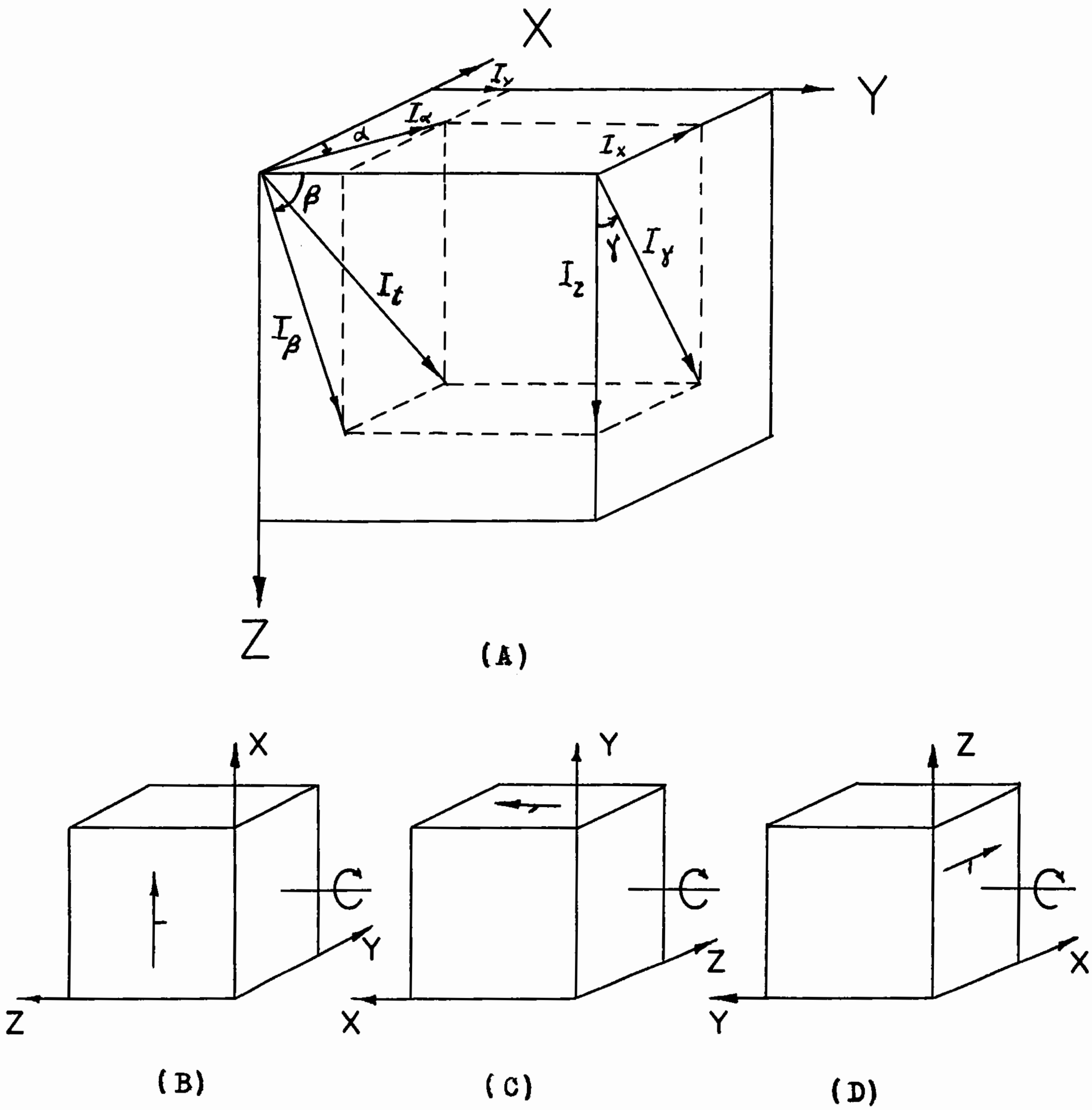

Fig. 4 - Nomenclature Diagram (A); Spinning positions to measure I_α and α (B), I_β and β (C), I_γ and γ (D).

From Fig. 4-A it is easy to derive the following relations:

$$(1)\quad \begin{cases} I_x = I_\alpha \cos\alpha = I_\gamma \sin\gamma \\ I_y = I_\beta \cos\beta = I_\alpha \sin\alpha \\ I_z = I_\gamma \cos\gamma = I_\beta \sin\beta \end{cases}$$

$$(2)\quad I_t^2 = I_x^2 + I_y^2 + I_z^2 = I_\alpha^2 \cos^2\alpha + I_\beta^2 \cos^2\beta + I_\gamma^2 \cos^2\gamma$$

$$(3)\quad I_t^2 = I_\alpha^2 + I_\gamma^2 \cos^2\gamma = I_\beta^2 + I_\alpha^2 \cos^2\alpha = I_\gamma^2 + I_\beta^2 \cos^2\beta$$

$$(4)\quad 3I_t^2 = I_\alpha^2 + I_\beta^2 + I_\gamma^2 + I_\alpha^2 \cos^2\alpha + I_\beta^2 \cos^2\beta + I_\gamma^2 \cos^2\gamma$$

$$(5)\quad 2I_t^2 = I_\alpha^2 + I_\beta^2 + I_\gamma^2$$

$$(6)\quad I_t = \sqrt{\frac{I_\alpha^2 + I_\beta^2 + I_\gamma^2}{2}}$$

Equation (6) was used in the calculation of the total intensity of polarization of the cubes.

If D and I refer to the "in situ" declination and inclination (positive downward) of the magnetic vector respectively, then:

$$(7)\quad \tan D = I_y / I_x$$

$$(8)\quad \cos I = I_\alpha / I_t = \sqrt{(I_x^2 + I_y^2)} \,/\, I_t$$

Theoretically angles D and α should be identical but it is found in practice that this is seldom the case due both to inhomogeneity in the ferromagnetic mineral distribution in the rock, and to the possible error of 5^{0} involved in the measurements. The determinations of D and I were actually done graphically in the present study. The steps involved in this operation are described in detail in Appendix I at the end of this thesis.

E- Results

The raw data as obtained from the measurements are tabulated in Appendix I. A summary of the graphically determined declinations and inclinations and of the calculated intensities appears in Tables 2 and 3 below. The parameters given in these tables are the arithmetic means of determinations on two or three different cubes of a given sample. The north-seeking poles of the magnetization vectors are plotted on stereographic projections in Figs. 5 and 6.

F- Discussion of Results and Conclusions

(i) Specimens from Yamaska mountain.

An examination of Table 2 and Fig. 5 reveals that there is little consistency in the orientation of the magnetization vectors of the rocks from Yamaska mountain. Exception being made for specimens Nos. 104 and 111, it is noticeable however that all other specimens have a North-South component plunging between 50^{0} and 70^{0} either upward or downward. The fact that many of the specimens collected in zones of positive anomalies (see Fig. 1) are reversely polarized is also of interest. Reversely and normally polarized rocks are represented by specimens of both strong and weak polarizations.

TABLE 2

SUMMARY OF POLARIZATION MEASUREMENTS
FOR SPECIMENS COLLECTED ON YAMASKA MOUNTAIN

Sample No.	Number of Cubes	Decli- nation	Incli- nation	Intensity emu/cu. in X10^{-5}	Polarity
53-A*	2	085°	-14°	756	up
55-A	2	258	-35	1,895	up
67-Y	3	144	-43	40,400	up
71-E	2	219	-56	33,900	up
72-E	2	208	-67	72,400	up
74-E	2	111	-46	26,900	up
87-Y	3	036	+51	4,373	down
103-Y	3	242	+40	59,766	down
104-Y	2	018	-16	56,500	up
105-Y	3	174	-69	2,340	up
111-E	3	319	+38	4,586	down
113-E	3	265	+15	22,600	down
120-E	3	228	-63	29,200	up
121-Y	3	230	-57	25,166	up
138-E	2	073°	+46°	1,660	down

*Specimens labelled A are Akerite, those labelled Y are Yamaskite and those labelled E are Essexite.

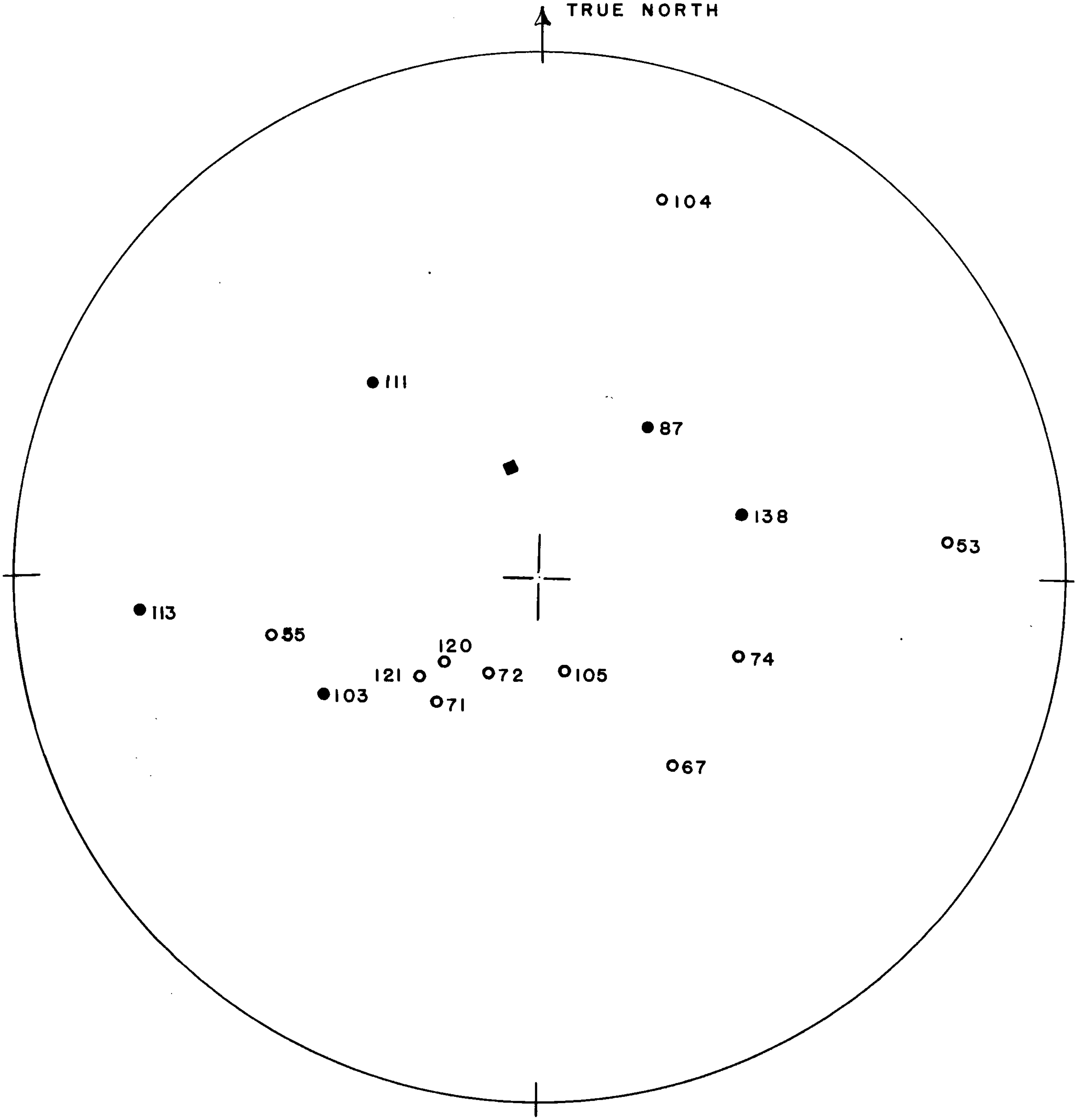

Fig. 5 Stereographic Projection of Magnetization Vectors for 15 samples from Yamaska Mountain, before Magnetic Washing.

● : pointing down   o : pointing up

■ : direction of present earth's field

TABLE 3

SUMMARY OF POLARIZATION MEASUREMENTS
FOR SPECIMENS COLLECTED ON BROME MOUNTAIN

Sample No.	Number of Cubes	Decli-nation	Incli-nation	Intensity emu/cu. in $X10^{-5}$	Polarity
36	2	145°	+05°	3,880	down
37	2	160	-24	14,675	up
37-B	2	123	-15	14,300	up
38	2	142	-22	8,485	up
38-B	2	115	-24	10,645	up
39	2	134	-16	35,050	up
40	2	001	+38	37,650	down
41	2	014	+42	2,720	down
42	2	043	-19	97,800	up
43	3	147	-28	51,030	up
44	3	142°	-28°	9,080	up

These facts suggest the possibility that more than one agent contributed in the polarization of the specimens collected from Yamaska mountain. Furthermore it is possible that some of these agents were equally active in the polarization of all the specimens whereas others were efficient only on some specimens and to different degrees. If the effect of the latter group could be eliminated, the polarization directions would then be more consistent from one specimen to another. This aspect of the problem is considered in the following chapter.

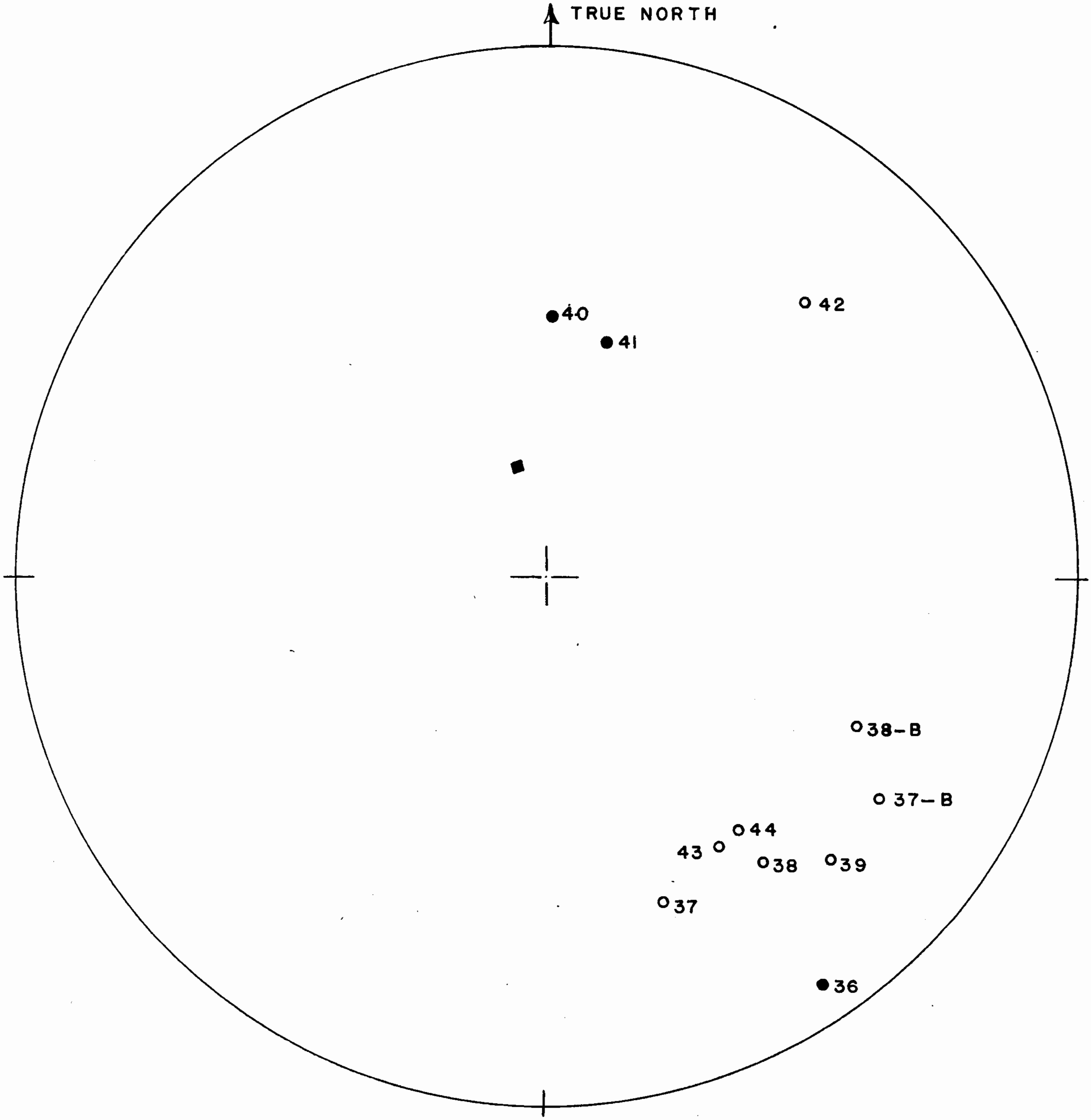

Fig. 6 Stereographic Projection of Magnetization Vectors for 11 samples from Brome Mountain, before Magnetic Washing.

● : pointing down   o : pointing up

■ : direction of present earth's field

(ii) Specimens from Brome mountain.

Table 3 and Fig. 6 indicate a much more consistent distribution in the magnetization vectors obtained for the rocks from Brome mountain. Two reasons may explain this fact, namely that the rocks were sampled in a more restricted area and from the same rock type. Specimens Nos. 40 and 41 were collected from the flank of a positive anomaly and they are polarized almost in the direction of the present earth's field. The suggestion that these rocks were once uniformly polarized in one direction is even stronger than in the Yamaska case.

The suitability of the rocks from both Yamaska and Brome mountains for palaeomagnetic studies depends upon their magnetic stability and on the possibility of removing the components of magnetization which were possibly imposed on them after their cooling to ordinary surface temperatures. These matters will be treated next.

CHAPTER III

STABILITY OF THE REMANENT MAGNETIZATION

A. Separation of the Magnetic Components

If an igneous rock is susceptible of being permanently polarized magnetically, it may reach that state by at least three different processes. These have been described by the terms "thermomagnetization", "anhysteritic" magnetization* and "isothermal" or "viscous" magnetization. Two or three of these processes can occur successively in the same rock mass and the resultant magnetization corresponds to the vectorial sum of the two or three components involved. We shall review briefly the meaning of these three types of magnetization in connection with the present problem.

It is a well known fact that if a rock is heated above a critical temperature (known as the Curie point of the ferromagnetic minerals present in the rock), it loses all of its remanent magnetization. If the same rock is then cooled from that temperature in a constant magnetic field, it acquires a component of magnetic polarization directed along the ambient field. This process is known as thermomagnetization.

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*Referred to as "ideal" magnetization in Russian literature.

Anhysteritic magnetization is impressed on a rock specimen when the latter is subjected to a rapidly fluctuating magnetic field to which is superposed a constant field, e.g. the earth's field. This set of conditions is roughly reproduced when a rock mass is struck by lightning. As mentioned earlier, Pockels (1901) and Toepler (1901) observed field examples of rock magnetic polarization resulting from lightning and they both recognized that this phenomenon is localized and can rarely be traced for more than a few meters around a point. The effect of the electrostatic discharge taking place during lightning is the only known natural mechanism of anhysteritic magnetization of rocks. For this reason anhysteritic magnetization and lightning polarization are generally considered as the same in palaeomagnetism.

A rock becomes isothermally magnetized if it is subjected to a constant field at ordinary surface temperatures for a certain period of time. The intensity of this component of magnetization depends upon several factors of which the main ones are the intensity of the acting field, the interval of time elapsed between the application and the removal of the field and the size, distribution, and composition of the ferromagnetic minerals in the rock.

Isothermal magnetization may be applied over a whole rock body, but for the reasons given in the previous paragraph, its intensity may not necessarily be uniform over the whole region of the body. Furthermore, diurnal and secular variations in the declination and inclination of the earth's field would create so many components in a given rock mass over a period of millions of years that the vectorial sum of these components could not refer to any particular stage in the history of the rock. This component of magnetization is therefore not desirable in rocks which are to be examined from the standpoint of palaeomagnetism.

As pointed out earlier, anhysteritic magnetization is a localized phenomenon. Moreover, the direction of magnetic polarization resulting from this process is governed partly by the declination and inclination of the ambient constant field but mainly by the path of the electric currents circulating through the rock after the electrostatic discharge. Pockels (op. cit.) observed that the magnetization directions radiated from a central point at the sites where he studied the phenomenon. For these reasons anhysteritic magnetization cannot be used reliably in establishing the orientation of the earth's field at the time of its imposition in the rock. Lightning polarization is thus considered as an undesirable component of magnetization in rocks which are to be used for palaeomagnetism.

The last component to be considered is thermomagnetization. Its importance in palaeomagnetism lies in the fact that it registers the direction of the geomagnetic field for the limited period of time it took an igneous rock to cool from the Curie point of its ferromagnetic minerals to ordinary temperatures at the surface of the earth. It may be inferred that this interval of time is in fact considerably shorter yet, since according to the results of Grabovski, Petrova and Isakova (1956), 90% of the thermomagnetic component is installed in the rock during the time it takes its ferromagnetic minerals to cool from their Curie point to a temperature about 50°C. below it.

The possible coexistence of several components of magnetization in the same rock sample brings with it the problem of isolating these components if the rock is to be used for palaeomagnetic studies. This will be possible if the different components respond differently to certain treatments.

It has been shown experimentally by Nagata & Kasahara (1953), Thellier & Rimbert (1954) and Rimbert (1955, 56, 57) that if a slowly decreasing alternating magnetic field is imposed on a rock specimen which is otherwise lying in a magnetic-field-free space, amplitudes of less than 200 oersteds for the alter-nating field are sufficient to destroy completely the isothermal magnetization in the specimen. A similar treatment applied to rocks whose magnetization is exclusively of the thermomagnetic type has a considerably weaker effect in reducing the intensity of magnetization unless the peak values of the alternating field reach several hundreds of oersteds. Anhysteritic magnetization resists to the same treatment considerably more than isothermal magnetization but it is "softer" than thermomagnetization. Therefore, if it can be ascertained by other means that no anhysteritic component is present in a given rock sample, it will be possible to isolate the desirable thermomagnetic component present in it by the use of the above-described technique. If, furthermore, after repetition of the operation with increasing amplitudes of the alternating field over successive runs, the sample reaches a state where its magnetization remains constant, it may be concluded that its thermoremnant component is stable. The foregoing technique will be referred to as "magnetic washing" in the following. It has been used recently on intrusive rocks by Armstrong (1957), and on volcanic rocks by Brynjolfsson (1957).

Another laboratory technique used in studying the magnetic stability of rocks consists in leaving the sample oriented with its magnetization vector opposed to the earth's field, and in measuring its polarization at intervals of days or weeks. This method was suggested first by Thellier (1937). Clegg & al. (1954) used a variation of this technique by replacing the earth's field by a field of the order of 5 to 10 oersteds.

A third way of determining the magnetic stability of rocks in the laboratory consists in heating the sample to 100°C., and in keeping it at this temperature for one hour or so in a magnetic-field-free space which is sometimes referred to as a "magnetic vacuum". It has been suggested by Néel (1955) that under these conditions, isothermal magnetization is very unstable and is effectively destroyed. On the other hand, thermomagnetization remains unaltered when exposed to the same treatment.

If, after repetition of the above treatment, the sample's magnetization remains unchanged, the specimen may be considered as stable and freed from an isothermal component. This technique has been used recently by Doell (1956) on sediments, by Cox (1957) on basalts, by Roche (1953) on lavas.

The first of the three techniques just described was used in the present study. With the dual purpose of verifying the applicability of this procedure to the rocks under study and of testing the suitability of the equipment built for this purpose, a series of simple experiments were carried out by the writer. Before describing this equipment, mention will be made of these experiments.

Experiment No. 1: Complete magnetic washing

An oriented cube of essexite from Yamaska mountain was heated to 700°C. and kept at this temperature for a period of one hour. It was then permitted to cool to room temperature in a magnetic vacuum. About 96% of the original magnetization was destroyed by this operation. The 4% of the original magnetization left in the sample is most likely an isothermal component introduced in it during the interval of time between the cooling operation and the measurement of the polarization. The changes in the actual magnetic parameters of the cube are as follows:

	Declination	Inclination	Intensity emu/cu. in. $\times 10^{-5}$
Before heating:	126°	-41°	26,885
After heating :	244°	-04°	1,110

Experiment No. 2: Thermomagnetization

An oriented cube of essexite from Yamaska mountain was heated to 700°C. and kept at this temperature for a period of one hour. After orienting the cube so that its X axis pointed North approximately and its Z axis pointed downward, the rock was allowed to cool to room temperature in the earth's field. The result of this operation was that, although the original intensity of magnetization was not changed appreciably in magnitude, its polarity was reversed by nearly 180° in space. The changes in the actual parameters of the cube are as follows:

	Declination	Inclination	Intensity emu/cu. in. $X10^{-5}$
Before heating:	230°	-52°	42,560
After heating :	357°	88°	47,662

It is noted that the inclination of the thermomagnetization obtained after cooling is slightly different from the actual inclination of the earth's field in Ottawa (about 75°). This may be explained partly by a possible error of 5° in the measurements and partly by the fact that the cube was cooled while resting on surface which was not perfectly level.

Experiment No. 3: Isothermal Magnetization and Magnetic Washing

An oriented cube of essexite from Yamaska mountain was submitted to a constant field of 115 oersteds for a period of 5 minutes. As a result of this its original intensity of magnetization was increased 23.6 times. The specimen was then submitted to the treatment of magnetic washing. After the cube had reached its original state of magnetization, little change was observed in its magnetic parameters upon applying the treatment of magnetic washing with demagnetizing fields of relatively large amplitudes (390 oersteds). This experiment demonstrates the relatively higher resistance of thermomagnetization to magnetic washing as compared with isothermal magnetization. The variations in the intensity of magnetization is plotted in Fig. 7 and the most significant among the observed magnetic parameters obtained after each run are as follows:

	Declination	Inclination	Intensity emu/cu. in. X10^{-5}
Before Magnetization:	225°	-83°	12,150
After Magnetization : (115 Oersteds, D.C.)	302°	-85°	276,000
After the 4th run : (150 Oersteds, A.C.)	130°	-82°	11,300
After the 8th run : (390 Oersteds, A.C.)	138°	-83°	5,870

It is noticed that the declination before magnetization and after the 8th run are very different. However the angles of inclination are relatively large in both cases and it turns out that the angle between the two vectors considered is less than 10°.

<u>Experiment No. 4</u>: Thermomagnetization Stability

The cube of Experiment No. 2 was submitted to the treatment of magnetic washing as described later in Part C of this

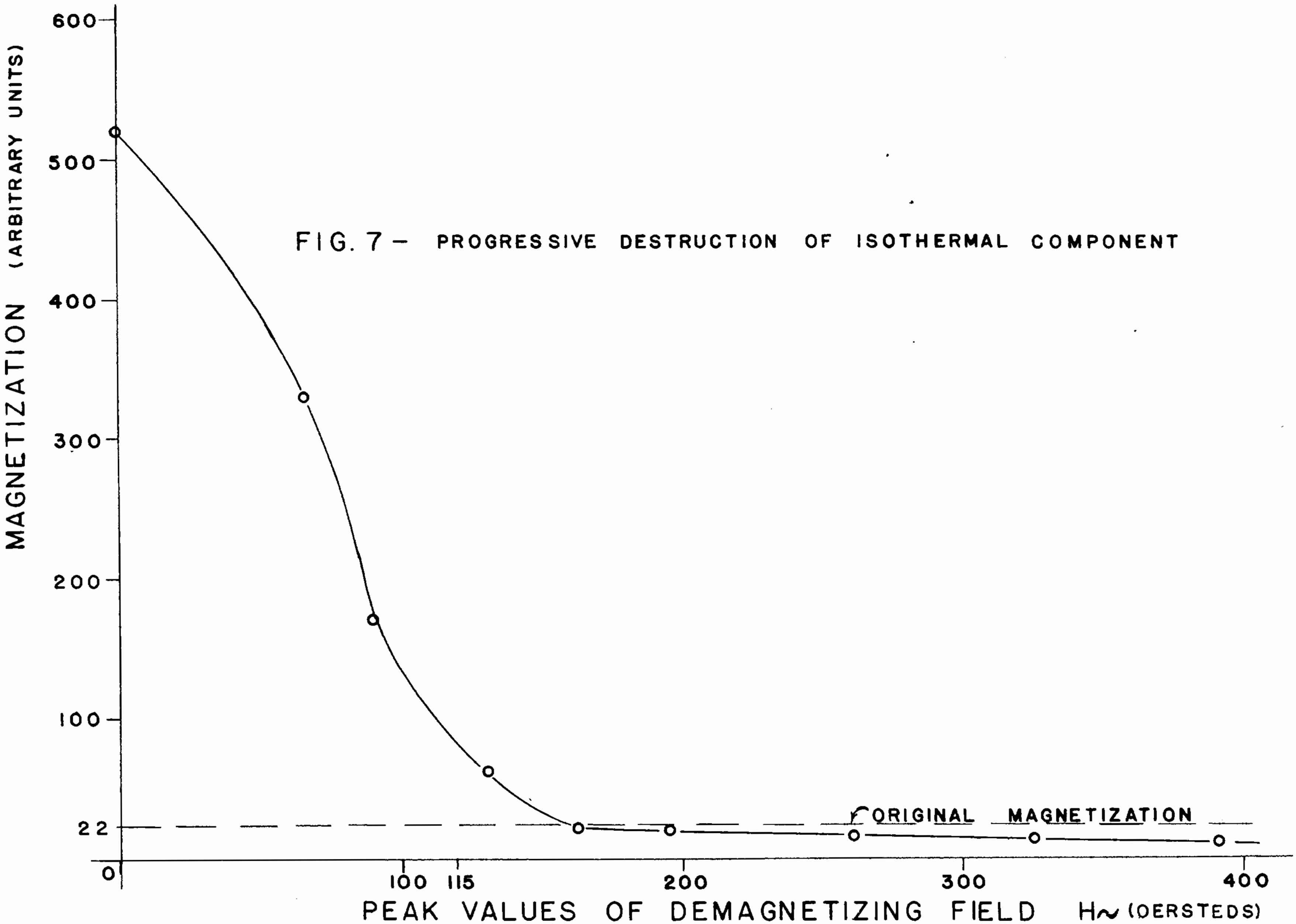

FIG. 7 – PROGRESSIVE DESTRUCTION OF ISOTHERMAL COMPONENT

chapter. An amplitude of 262 oersteds was given to the alternating demagnetizing field. The initial and final magnetic parameters are as follows:

	Declination	Inclination	Intensity emu/cu. in. $X10^{-5}$
After Experiment No.2:	357°	-88°	47,662
After Magnetic Washing: (262 Oersteds, A.C.)	304°	-80°	22,994

It is noticed from these results that even after the application of a 262 oersted demagnetizing field almost 50% of the thermomagnetization is still present in the rock specimen. The fact that the declination changed by 53° during the treatment is hardly significant for the same reason given in the previous experiment.

B. Construction of the Magnetic Washing Apparatus

Two precautions are necessary in the application of the treatment of rocks by magnetic washing using alternating magnetic fields. First, the specimen must be set in a magnetic-field-free space in order to prevent the formation of an anhysteritic component upon being exposed to the alternating field. Second, a mechanism must be provided so that the amplitude of the alternating field decreases gradually without any sudden jumps, no matter how small the latter may be.

In the present apparatus, the magnetic free space is

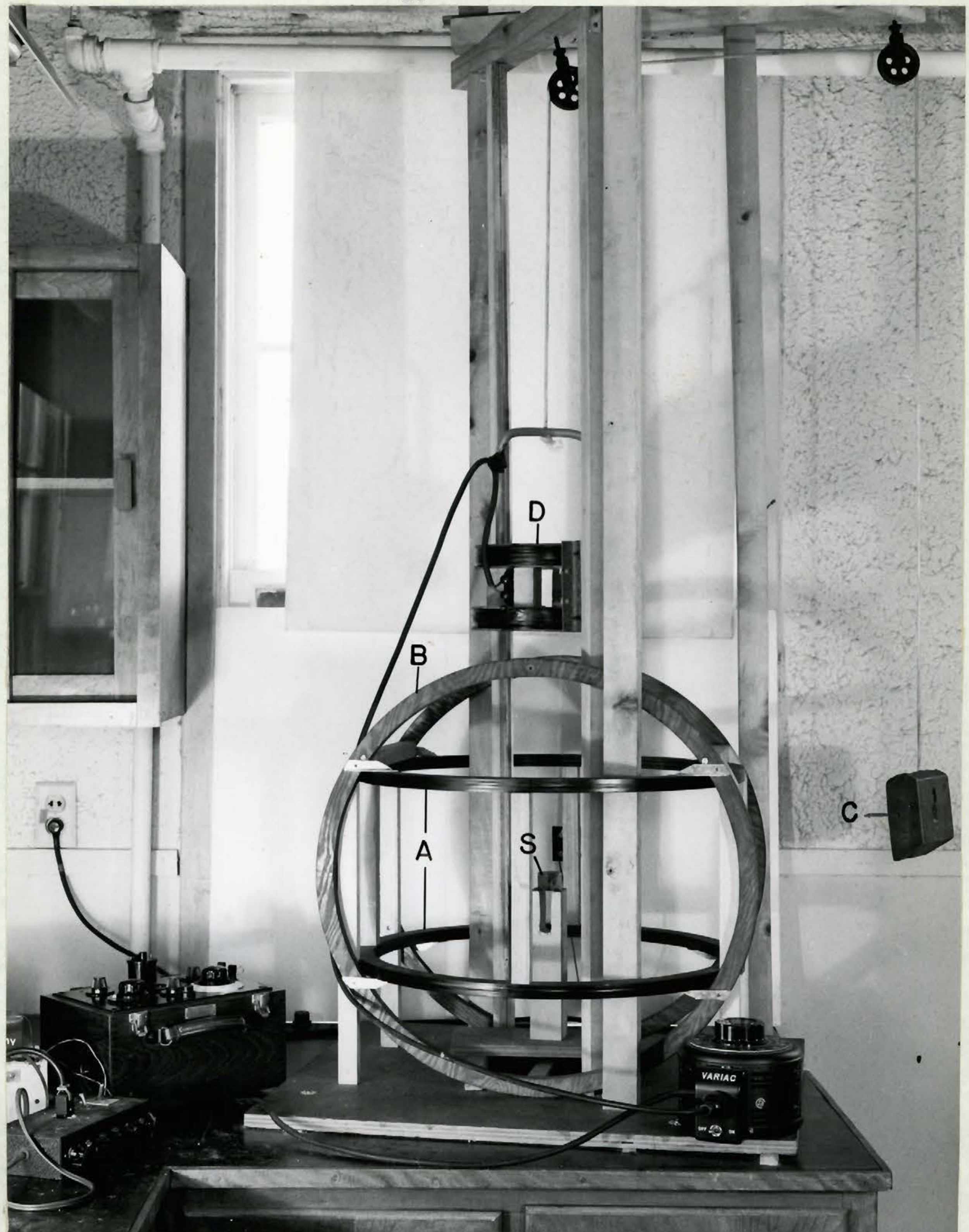

FIG. 8: MAGNETIC WASHING APPARATUS

A- Vertical Field Coil C- Counterweight
B- Horizontal Field Coil D- Demagnetizing Coil

obtained by means of two mutually perpendicular Helmoltz coils whose axes correspond with the Vertical and the direction of magnetic North respectively. The actual physical dimensions of the coils are given in Fig. 9. Enamel coated copper wire No. 32 B & S gauge was used in the windings and precaution was taken to use only aluminum and non-magnetic brass where metal was required for mechanical strength. The electrical specifications of the coils are as follows:

Coil A	Number of turns	Resistance Ohms	Coil Constant gammas/ma	Average Current milliamps.
Coil A (Vert.)	312	350	1,005	59.2
Coil B (Horiz.)	340	450	1,005	18.1

The two coils are connected in parallel to six 45-volt dry batteries linked together in parallel. The current in each coil is controlled by three variable resistors in series with each coil and it is measured by means of a Cambridge Potentiometer which is connected across precision resistors of 2 and 10 ohms respectively in series with each coil.

The assurance of zero intensity magnetic field inside the non magnetic space was verified by means of a transistorized fluxgate magnetometer unit which was designed and built by the Magnetic Division of the Dominion Observatory. The builders of this instrument claim its suitability to detect as little as 10 gammas. It was possible to balance the current in the coils of the null-field device so that no deflection was indicated

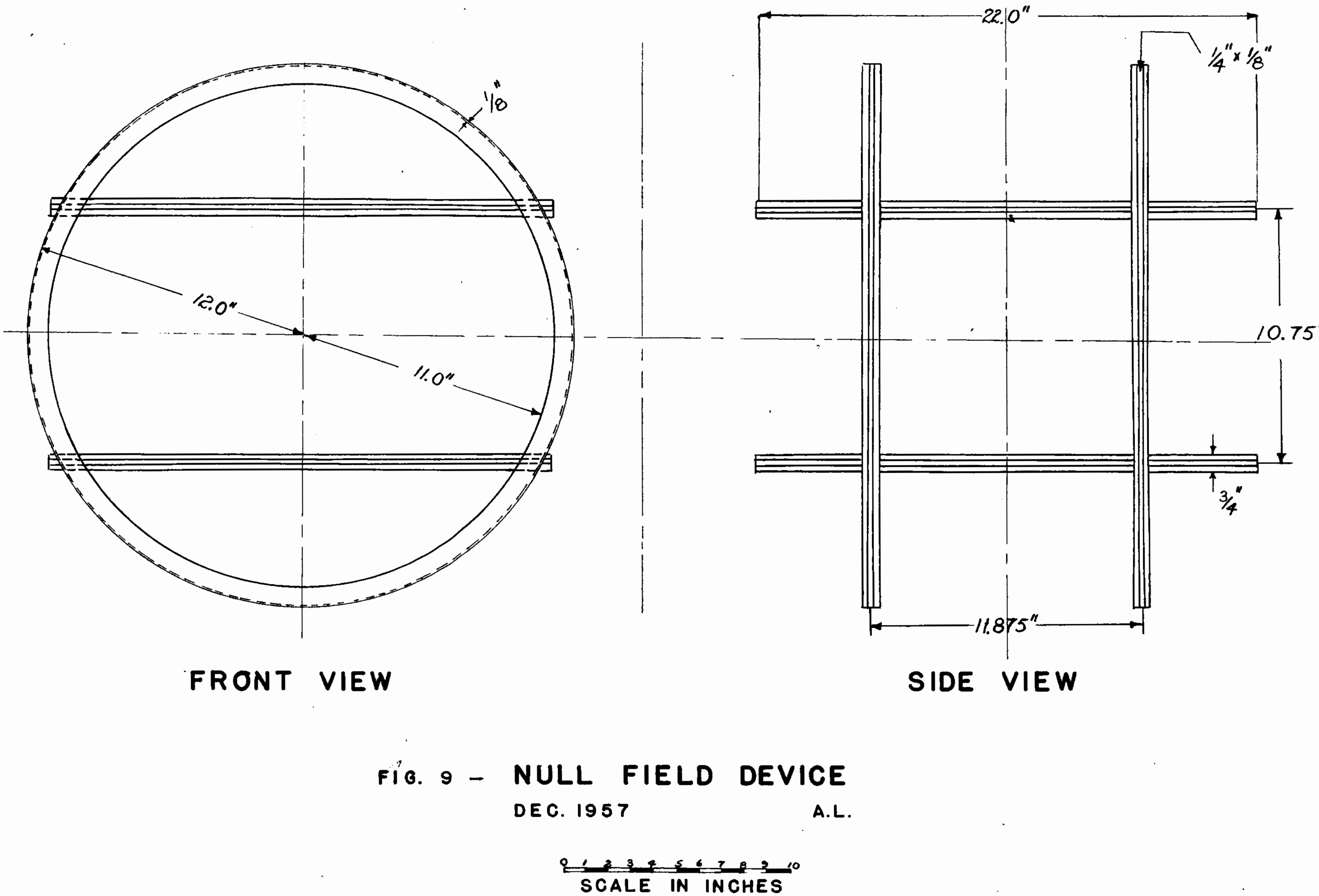

FIG. 9 – NULL FIELD DEVICE

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on the magnetometer dial. On the other hand, a considerable deflection was indicated by the magnetometer needle if the current varied by as little as 0.01 ma. It thus seems that the magnetic vacuum was easily established to less than 50 gammas, which is less than one part per thousand of the earth's field.

The alternating demagnetizing field was produced by another Helmoltz coil of smaller dimensions, across which a 60 cps voltage source was connected. The dimensions and electrical specifications of this coil are given in Fig. 10 below. The maximum RMS current through this coil was 10 amperes.

The problem of varying slowly and regularly the alternating field amplitude around the specimen could not be solved by simply inserting a rheostat in series with the demagnetizing coil. One of the reasons for this is that the current used in some cases is fairly high (10 amps.). More important and probably less obvious is the fact that, because of its inherent design, an ordinary rheostat permits voltage changes in discrete jumps only. This might create an anhysteritic component in the specimen being treated. Similar drawbacks are brought in by the use of a variable transformer. The method commonly used consists either in removing the sample from the demagnetizing coil or vice versa. Hood (1958) made use of the first method recently. The second of these methods was used in the present project since, in the writer's opinion, there is less chance in this way that the alternating field affects the sample when it is out of the magnetic vacuum. The Variac shown in Fig. 8 was used only to set

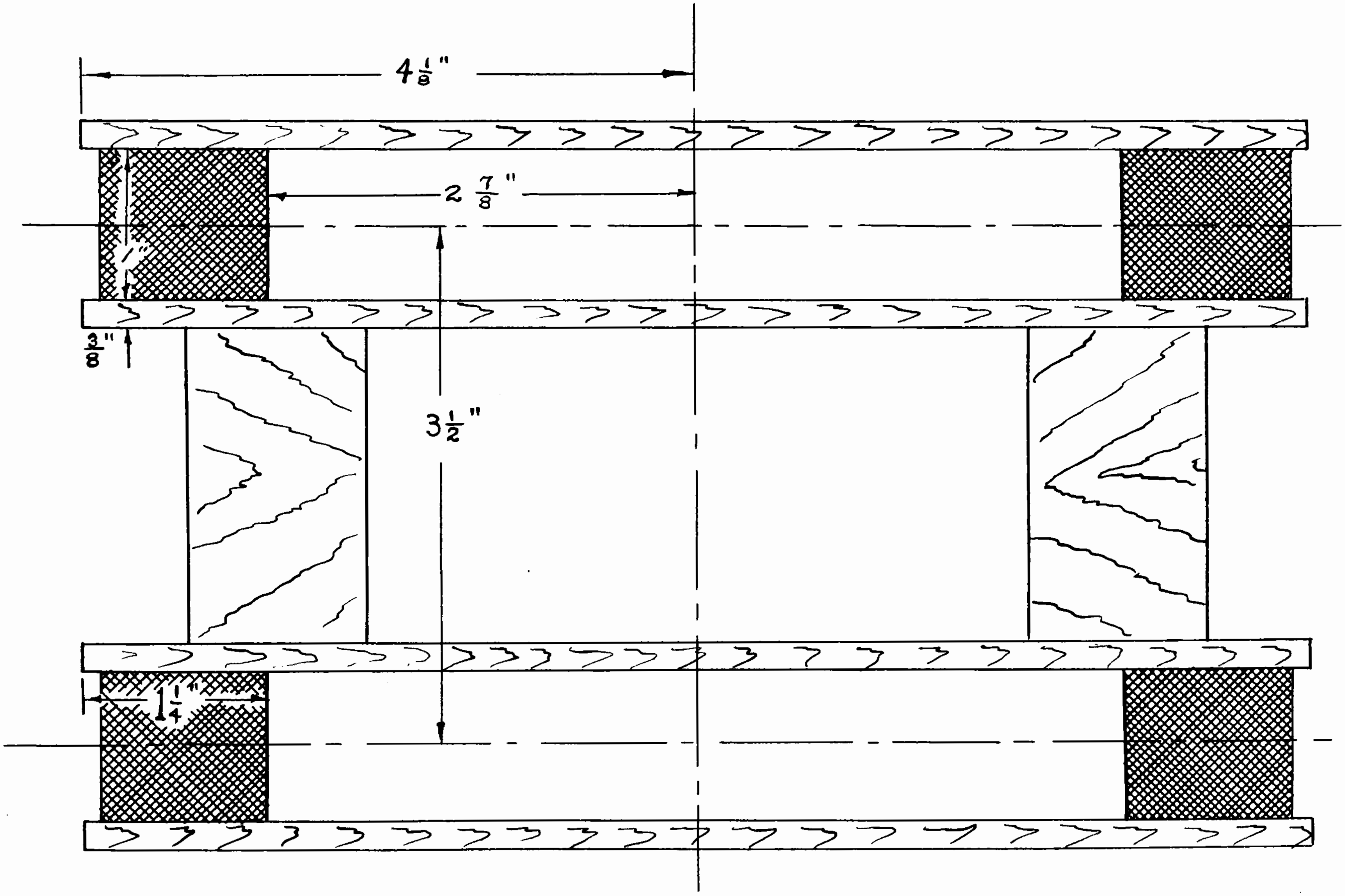

FIG. 10: DEMAGNETIZING COIL DESIGN

R = 2.3 Ω, L = 24.5 MHS, COIL CONSTANT = 23.05 OE./AMP.
450 TURNS — NO. 13 B&S GAUGE

the amplitude of the demagnetizing field before the actual operation of magnetic washing, i.e. when the coil was still away from the specimen.

When the demagnetizing coil D is lowered so as to surround Specimen S (see Fig. 8), the two systems of coils (D and A-B) are electromagnetically coupled. As a result of this coupling, an A.C. current is induced in each of the Helmoltz coils if the demagnetizing coil is connected to an A.C. voltage source. By connecting a vacuum-tube voltmeter successively to the terminals of coils A and B, it was verified that the D.C. component of the total voltage across them is not modified by the introduction of the demagnetizing coil, even if the latter is energized to yield an alternating field of 350 oersteds. It is concluded from this test that the cancellation of the earth's field by the null-field device in the region surrounding the specimen S is not affected by the introduction of a demagnetizing field in this region.

In order to obtain an estimate of the alternating field produced by the A.C. current induced in the Helmoltz coils, an alternating field of 250 oersteds was set along the axis of the demagnetizing coil and the latter was lowered in the region of the specimen S. A vacuum-tube voltmeter was connected successively to the terminals of coils B and A and the maximum A.C. voltages induced across them was noted as the demagnetizing coil was lowered. Maximum voltages of 0.25 and 25 volts were observed across coils B and A respectively. Assuming that the reactance of these coils is negligible* at 60 c.p.s., the approximate

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*If the reactance of coils A and B is taken into consideration, the induced A.C. field is even less.

horizontal and vertical alternating field components were calculated to 500 and 72,000 gammas respectively. Because the fields yielded by coils A and D are out of phase by 180° the amplitude of their resultant is equal to the algebraic sum of their respective amplitude. It is noticed, however, that the alternating field produced by coil A (72,000 gammas or 0.72 oersteds) is very small compared to the field of 250 oersteds produced by coil D.

C. Magnetic Washing and Results

For the actual washing operation, the current necessary in each of the Helmoltz coils for total cancellation of the earth's field is first determined with the help of the fluxgate magnetometer. The current in these coils is kept constant by frequent checks during the operation. The cube is then introduced at the center of the magnetic vacuum with, for instance, its X axis along the vertical. For a first run, the demagnetizing field amplitude is set at 50 oersteds by means of the Variac. The demagnetizing field source is then brought very slowly toward the sample by lifting the counterweight (see Fig. 8) until the specimen is completely surrounded by the coil. Successive runs were made with demagnetizing field amplitudes of 100, 150 and 200 oersteds. Most of the change took place in the magnetization of the rock during the first two runs.

A summary of the results obtained in measuring the polarization of the magnetically washed samples is given in Tables 4 and 5 and stereographic plots of the magnetization vectors appear in Figs. 11 and 12. These are averages obtained for two or three cubes of each sample measured. The method used in computing and determining the various magnetic parameters was the same as that described in Chapter II. The measured quantities are listed for each cube in Table A-I of Appendix I.

TABLE 4

SUMMARY OF POLARIZATION MEASUREMENTS
FOR "WASHED" SPECIMENS COLLECTED ON YAMASKA MOUNTAIN

Specimen No.	Number of Cubes	Before Magnetic Washing			After Magnetic Washing		
		Declination	Inclination	Intensity emu/cu.in X10^{-5}	Declination	Inclination	Intensity emu/cu.in X10^{-5}
53	2	085°	-14°	756	169°	-59°	1,336
55	2	258	-35	1,895	170	-61	190
67	3	144	-43	40,400	162	-67	56,733
71	2	219	-56	33,900	171	-61	15,600
72	2	208	-67	72,400	160	-53	18,550
74	2	111	-46	26,900	128	-70	20,600
87	3	036	+51	4,373	025	-65	1,555
103	3	242	+40	59,766	225	-18	2,593
104	2	018	-16	56,500	341	-57	1,924
105	3	174	-69	2,340	148	-66	1,973
111	3	319	+38	4,586	022	-70	2,303
113	3	265	+15	22,600	315	-60	3,156
120	3	228	-63	29,200	204	-66	40,950
121	3	230	-57	25,166	198	-71	27,533
138	2	073°	+46°	1,660	304°	-65°	1,435

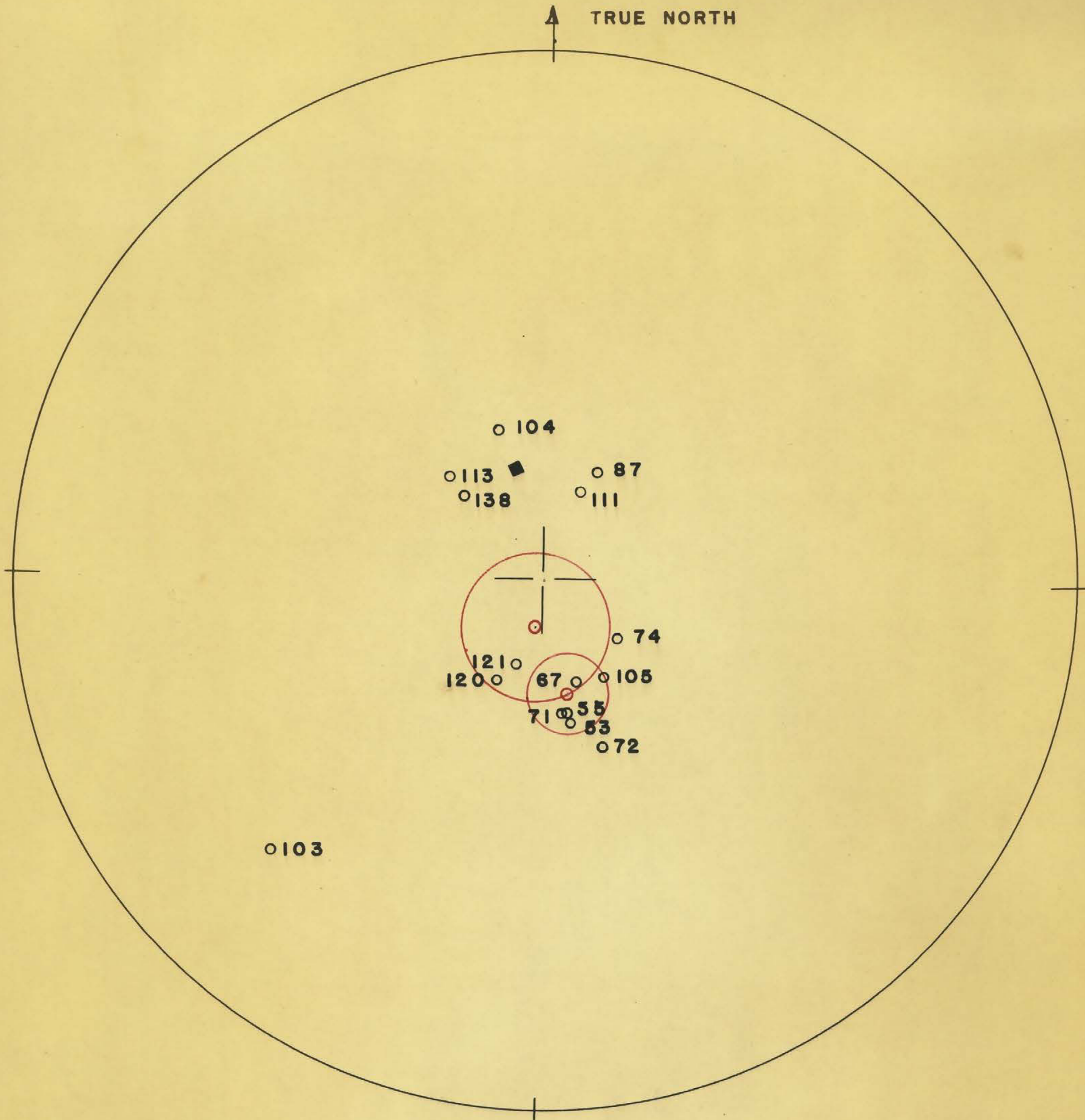

Fig. 11 : Stereographic Projection of Magnetization Vectors for 15 samples from Yamaska Mountain, after Magnetic Washing.

● : Pointing down   o : Pointing up

■ : Direction of Present Earth's Field.

TABLE 5

SUMMARY OF POLARIZATION MEASUREMENTS
FOR "WASHED" SPECIMENS COLLECTED ON BROME MOUNTAIN

Specimen No.	Number of Cubes	Before Magnetic Washing			After Magnetic Washing		
		Declination	Inclination	Intensity emu/cu.in $X10^{-5}$	Declination	Inclination	Intensity emu/cu.in $X10^{-5}$
36	2	145°	+05°	3,880	122°	-40°	2,670
37	2	160	-24	14,675	119	-51	6,550
37-b	2	123	-15	14,300	118	-42	7,215
38	2	142	-22	8,485	113	-45	4,045
38-b	2	115	-24	10,645	098	-45	4,480
39	2	134	-16	35,050	109	-41	5,155
40	2	001	+38	37,650	136	-63	683
41	2	014	+42	2,720	111	-60	885
42	2	043	-19	97,800	139	-38	7,075
43	3	147	-28	51,030	136	-35	13,923
44	3	142°	-28°	9,080	087°	-40°	2,360

D. <u>Discussion of Results</u>

(i) Specimens from Yamaska mountain:

An examination of Fig. 11 reveals that all the washed specimens from Yamaska mountain have an upward pointing magnetic polarization. For the sake of discussion, these polarizations may be classified into two groups, namely those which cluster about a point South of the Zenith (Nos. 53, 55, 67, 71, 72, 74, 105, 120 and 121) and those which fall away from the same point

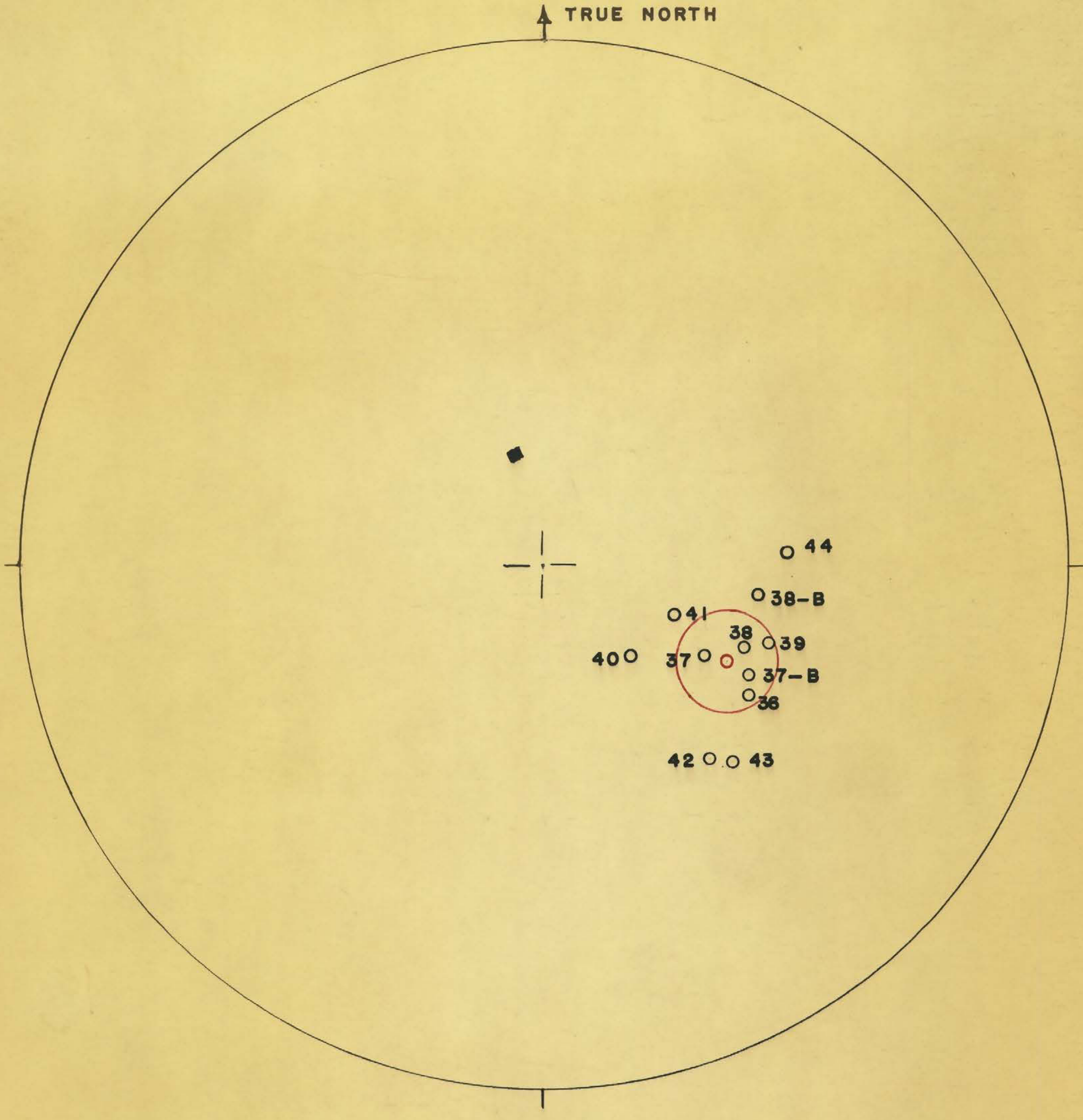

Fig 12 Stereographic Projection of Magnetization Vectors for 11 samples from Brome Mountain, after Magnetic Washing.

● : Pointing down o : Pointing up

■ : Direction of Present Earth's Field

(Nos. 87, 103, 104, 111, 115 and 138). It is interesting to note that if exception is made of specimen No. 104, all the specimens of the second group were polarized downward and those of the first group were polarized upward before the magnetic washing.

It is shown in Table 4 that, as a rule, the intensities of magnetization decreased appreciably by the magnetic washing. However, increases in intensity are noticed for a few specimens of the first group but for none of the second group. These facts may be explained if it is considered probable that, prior to the magnetic washing, an isothermal downward component was acting against a more stable component which remained more or less unaltered after the magnetic washing.

The fact that from a chaotic distribution of polarization directions a certain degree of order was achieved by magnetic washing is interesting in itself. Still more interesting is the fact that the stable component of magnetization of the rocks is directed almost opposite to the direction of the present earth's field in the majority of cases.

The use of a demagnetizing field of about 400 oersteds was attempted in order to improve the clustering of the specimens of the second group with those of the first group. This last treatment proved useless however because from a comparison of the polarization directions of all the cubes of a specimen submitted to this treatment, it was found that the declinations and inclinations were distributed at random. The magnetization of the sample thus treated was measured repeatedly over a period of a few days, and it was found to vary each time according to the attitude given to the cubes in the ambient earth's field between the measurements.

At this point the hypothesis may be formulated that, among the specimens from Yamaska mountain, some are apt to acquire a strong but "soft" component of isothermal magnetization. The polarization of these rocks is complex and it may have a significance only if the unstable isothermal component is removed from them. On the other hand, the specimens whose direction of polarization was practically not modified by magnetic washing were probably not modified by the isothermal magnetization to any great extent.

(ii) Specimens from Brome mountain:

Just as the original polarizations of the Brome mountain specimens were much more consistent than those from Yamaska mountain, so are the polarization directions of the washed samples. In all cases the intensities of magnetization were reduced by magnetic washing. The results listed in Table 5 and illustrated in Fig. 12 show that the stable component of magnetization is far from pointing in the direction of the present earth's field. Although specimens Nos. 40, 41, 42 and 44 are probably less stable than the others in the group, it is nevertheless considered that their stability is sufficient to give the magnetization of these specimen a possible palaeomagnetic significance.

E. Statistical Analysis of Results

Given a group of unit vectors with different orientations in space, it is possible to find mathematically the orientation of their mean which corresponds to that of their vectorial sum. If each of the magnetization vectors referred to above are given a unit length in order to give each of them equivalent statistical importance, their mean orientation may thus be established. The problem of determining mathematically the probability that this orientation is significant within a given cone of confidence was very elegantly solved by Fisher (1953). The latter showed that, if θ is the half-angle of the cone of confidence, then:

$$(1) \quad (1-\cos\theta) = \left(\frac{(N-R)}{R}\right)\left[\left(\frac{1}{(1-P)^{1/(N-1)}}\right) - 1\right]$$

where N is the number of samples involved, R the magnitude of their vectorial sum, and P the probability that the orientation of their vectorial sum lies within the cone of confidence of half-angle θ. It is common practice to use P= 95% in palaeomagnetic calculations.

The values of θ, R, D and I were calculated separately first for the whole of the 15 specimens collected from Yamaska mountain and second for the 9 specimens of the first group mentioned above. The same quantities were also computed for the specimens from Brome mountain. In all cases a P of 95% was used for the calculation of θ. The results of these calculations are as follows:

Group of Specimens	N	R	D	I	θ
Yamaska (1)	15	13.05	190°	-79°	15.5°
Yamaska (2)	9	8.85	167°	-65°	07.0°
Brome	11	10.68	117°	-46.5°	08.3°

The values of D, I and θ for the two Yamaska groupings are represented in red in Fig. 11. The large dotted line circle represents the cone of confidence of half-angle 15.5° and the open dot at its center indicates the position of the mean for all the samples collected from Yamaska mountain. The smaller full-line circle represents the cone of confidence whose half-angle is 7° for the restricted group of 9 specimens from Yamaska mountain. Similarly, the D, I and θ calculated for the Brome specimens are represented by the red dot and circle in Fig. 12.

In order to measure the scattering within a set of unit vectors, Fisher (op. cit.) derived the equation:

$$(2) \quad K = (N-1)/(N-R)$$

where K is an index of the scattering and R and N have the same meanings as in the above equation (1). When K is very large, the scattering is very small and vice versa. In particular, it is easy to see that if all the vectors are parallel the value of K is infinite since then N = R. On the other hand, K may be smaller than unity if R is sufficiently small. The application of the above formula (2) to the present data yields scattering indices of 6.7, 53.4 and 31.2 for the Yamaska (1), Yamaska (2) and Brome groupings respectively.

F. Conclusions

(1) The directions of polarization of more than half of the specimens from Yamaska mountain and those of nearly all the specimens from Brome mountain were only slightly modified by the treatment of magnetic washing. It is concluded that the main component of magnetization of these specimens is stable, and that it is either the result of thermomagnetization or of anhysteritic magnetization. On the other hand, the scattering indices of these two groups of specimens are high, and this fact leaves little doubt that anhysteritic magnetization by lightning is an important component of their polarization.

(2) If the data obtained for all the specimens from Yamaska mountain are considered significant, the scattering index K is considerably decreased, but it is still too large for a random distribution such as would be expected from anhysteritic magnetization by lightning.

(3) Whether or not we consider significant the data obtained from all the specimens from Yamaska or only the data obtained from those of group one mentioned in section D of this Chapter, the mean polarization of each grouping is oriented almost opposite to the direction of the present earth's field. The same remark applies to the specimens collected on Brome mountain.

(4) Since anhysteritic magnetization does not appear as the probable process by which these rocks were polarized, it is concluded that their stable component of magnetization is the result of thermomagnetization.

(5) As pointed out earlier, a rock may be reversely polarized "in situ" either because the earth's field had a direction opposite to its present one at the time of its cooling or because a self-reversal mechanism once operated in it. Such a mechanism would be inherent in the mineralogical assemblage in the rock.

(6) We have no proof that the earth's field was reversed at the time of cooling of the Yamaska and Brome rocks because we do not know at what time since Ordovician this cooling took place. On the other hand, it was observed during Experiment No. 2 (p.35), that a specimen of essexite from Yamaska mountain which was originally reversely polarized "in situ" acquired a normal polarization upon cooling in the earth's field from 700°C to room temperature. The same experiment was repeated with other specimens from Yamaska and Brome mountains with the same result. It is concluded that either a self-reversal mechanism never existed in the rocks considered or that it is not present in them any longer due to chemical alterations in the rock. It is also possible that the mechanism which may have had to operate for millions of years to achieve the present state of reverse polarization could not yield the same result during the short interval of time it took the rocks to cool from 700°C to room temperature. It may be that the pressure under which rocks acquire their polarization plays an important part in the orientation of this polarization. If such is the case, the results of the above-mentioned experiment are far from being conclusive because the heating and cooling of the rocks took place under atmospheric pressure.

(7) If we consider that the results of Experiment No. 2 fail to show whether or not a self-reversal mechanism ever existed in these rocks, we must investigate further this possibility. As a first step towards this goal, a review of the self-reversal mechanisms suggested in the literature is necessary. This forms the subject of the following Chapter.

CHAPTER IV

THE HYPOTHESIS OF MAGNETIC SELF-REVERSAL

A- A Review of the Literature

It is less than ten years ago that the possibility of self-reversal mechanisms was first given consideration in rock magnetism. Graham (1949) was the first to dispute the belief that reverse polarization of sedimentary rocks "in situ" is direct evidence of earth's field reversals in the past. His reason was that he observed both normally and reversely polarized rocks with a relatively thin but widespread Silurian sedimentary formation in Maryland, U.S.A. He argued that some physico-chemical changes had probably taken place in those parts of the formation where he had observed reverse polarization.

To show the theoretical possibility of such a physico-chemical mechanism, Néel (1951) postulated shortly after his now famous four possible mechanisms of self-reversal. Some of Néel's mechanisms have since then been tentatively used to explain particular cases of reversed polarization. A brief review of these mechanisms is made in the following paragraphs:-

(1) It may be that the rock contains a crystalline substance which has two sub-lattices, A and B, with the magnetic moments of all the magnetic atoms in lattice B oppositely directed to

those of lattice A. Substances of this nature exist in fact and they are called ferrimagnetics. Supposing that the spontaneous magnetization of lattice A, J_A, aligns itself with the ambient field, the resulting magnetization of the whole lattice will be $(J_A - J_B)$ at a given temperature. Néel imagined further that for some ferrimagnetic substances, the spontaneous magnetizations J_A and J_B react differently to changes in temperature. In particular, he imagined that J_B could become larger than J_A above a critical temperature which he called the <u>temperature of compensation.</u> If the temperature of compensation should turn out to be higher than ordinary temperatures at the surface of the earth, the ferrimagnetic in question would be polarized reversely upon cooling from its Curie point to room temperature in the ambient earth's field. Since Néel first formulated this mechanism, Gorter and Schulkes (1953) were able to synthesize a lithium-chromium ferrite ($Li_{0.5}Cr_{1.25}Fe_{1.25}O_4$) whose temperature of compensation is 100^oC. Thus, Néel's first mechanism is a physical possibility which may explain reverse polarization in igneous and metamorphic rocks containing certain ferrites of a very rare composition. On the other hand, such substances have not been identified in any of the reversely polarized rocks found so far.

(2) In his second mechanism, Néel assumed as possible the existence of a ferrimagnetic substance whose composition is such that J_A is always larger than J_B, independently of the temperature of the substance below its Curie point. If further J_A is less stable than J_B under some physico-chemical action, the rock would

become reversely polarized in the direction of J_B after this action has taken place. The physical possibility of this mechanism has not been realized to date and, according to Street (1954), chances are that it will never be.

(3) Néel's third mechanism is based on the interaction between two minerals of different Curie points in a rock. The coexistence of two minerals A and B of different Curie points is commonly observed in igneous rocks. For instance titaniferous hematite-magnetite intergrowths are reported in the description of many iron ore deposits. Let us assume that the Curie point of mineral A, θ_A, is higher than that of mineral B, θ_B. When such a mixture cools from a temperature $\theta_O > \theta_A > \theta_B$ to a temperature θ_1 where $\theta_A > \theta_1 > \theta_B$, mineral A becomes magnetized in the direction of the ambient field whereas mineral B remains unmagnetized at this temperature. If certain geometrical conditions are fullfilled, the demagnetizing field produced by mineral A is more intense in the space occupied by the grains of mineral B than the ambient field itself. Upon cooling below θ_B mineral B will thus become polarized in the direction opposite to that of the ambient field. Finally, the whole rock will be reversely magnetized if J_B is larger than J_A.

Laboratory experiments carried by Grabovski and Pushkov (1954) to prove the physical possibility of this mechanism were only partly successful. They aligned alternating plates of magnetite and of pyrrhotite parallel to the earth's field and heated them above the Curie point of magnetite (580°C.±). They then let the plates cool to room temperature i.e. past the Curie point of pyrrhotite (320°C.±). They found that the pyrrhotite plates were indeed reversely polarized after the cooling but that the overall polarization due to the pyrrhotite and magnetite combined was still normal.

An observation which proves the physical possibility of Néel's third mechanism was reported in 1912 by Smith and Guild (1912) and later by Smith, Dee and Mainford (1924). These authors showed that if an annealed steel rod is heated in a "magnetic vacuum" to about 250°C., its magnetic polarization is reversed after its cooling in the same magnetic-field free space. This was explained as due to the coexistence of iron carbide (FeC_3) and iron in the form of closely intergrown lamellae similar to those observed in mineral intergrowths. The iron carbide, also known as cementite, has a lower Curie point but a higher coercive force than the iron. When the rod is removed from the action of the earth's field, its end free poles reverse the spontaneous magnetization of the iron but hardly affect the magnetization of the iron carbide. Upon heating the rod slightly above the Curie point of the carbide (240°C.), the latter loses its remanent magnetization. When the rod is cooled again to room temperature, the carbide reassumes its magnetization but the latter is now opposite to its original direction, i.e. in the direction dictated by the end free poles. As the rock is set back under the effect of the earth's field, the end free poles lose their effect and the magnetization of the iron is then oriented opposite to that of the cementite. The net result is that the total polarization of the rod is reversed from its original state.

An actual case where Néel's third mechanism was postulated as the probable cause of reversely polarized rocks was reported by Balsley and Buddington (1954). Their conclusion was supported by the fact that "after heating above the Curie point one specimen containing the hematite-ilmenite mixture and cooling it in the earth's field, it was found to possess remanent magnetization opposite to that of the impressed field".

(4) The coexistence of two minerals of different Curie points is again assumed in Néel's fourth mechanism and the polarization of mineral B is also reversed by the demagnetizing field of mineral A as in the third mechanism. It is also assumed that the polarization of mineral A (whose Curie point is higher) is less stable than that of mineral B. The rock eventually becomes polarized in the direction of mineral B after mineral A either has been destroyed or has lost its magnetization.

A variation of this mechanism was suggested by Graham (1953) and by Asami (1956) for specific cases. In the first of these cases a magnetite-ilmenite intergrowth was assumed in the original rock and the latter was assumed to be originally normally polarized. Subsequently, percolating acidic waters are supposed to have partly oxydized the magnetite into maghemite. The latter was reversely polarized by the demagnetizing field of the former and since magnetite has a much lower coercive force than maghemite it would have eventually lost its polarization. The rock would have then adopted the reverse polarization of mineral B. Nicholls (1955) pointed out an objection to this mechanism: since maghemite forms from magnetite under temperature conditions much lower than its Curie point, its polarization would be of the isothermal type and consequently probably much less stable than that of the thermally polarized magnetite. Nevertheless, Haigh (1958) has recently proved both theoretically and experimentally that Nicholls views were not correct, i.e. that the magnetization acquired by the maghemite under these conditions referred to as "chemical" magnetization is much closer to thermomagnetization than to isothermal magnetization from the point of view of magnetic stability.

The case reported by Asami (op.cit.) refers to a low temperature exsolution of two phases of titanomagnetite from a solid solution of magnetite-ulvöspinel of intermediate composition. Asami observed both normal and reverse polarizations among 43 samples of basalts collected within an area of one meter square. From a thermomagnetic analysis he was able to show that the reversely polarized samples contained two different ferromagnetic minerals whose Curie points were 120° and 500° respectively. On the other hand, the normally polarized specimens were found to bear only one ferromagnetic mineral whose Curie point was in the vicinity of 370°C. He thus postulated a mechanism similar to Néel's fourth mechanism.

Since Néel first formulated the above mechanisms many others have been suggested by other workers and by Néel himself. In particular, Néel (1955) suggested possible self-reversals by diffusion involving ionic exchange between the two sub-lattices in a ferrimagnetic or by diffusion with complete change of composition. Gorter (1953) had achieved the diffusion of Al ions from the A sub-lattice in a ($NiFe_{2-m}Al_mO_4$) ferrite and he had observed a resultant reversal of spontaneous magnetization for this substance. An application of this mechanism to rock magnetism was suggested by Verhoogen (1956) for the case of substituted magnetites. The latter suggested that the role of Al in Gorter's experiment could be taken by Ti, Mg and Al ions in various proportions. No experimental proof is available so far to support Verhoogen's views.

Smelov (1957) introduced recently a new hypothesis to explain the negative polarization of the ore deposits in the Angara-Ilim region in Russia. According to this hypothesis, magnetite and magnesioferrite were first formed between 250°C and 400°C. In this range of temperatures magnesioferrite has a much higher permeability than magnetite and thus, relative to magnesioferrite, the latter is diamagnetic. Magnetite would then acquire a negative polarization in those conditions due to the presence of magnesioferrite. At lower temperatures the magnesioferrite would transform first into maghemite and finally into hematite under which state it loses almost all of its spontaneous magnetization. Magnetite remains relatively unaltered and it retains its reverse polarization which is then representative of the rock's magnetization as a whole.

The most outstanding body of experimental research done so far on self-reversal mechanisms was carried out between 1951 and 1958 by a group of Japanese scientists under the leadership of T. Nagata. The subject of their research was a reversely polarized dacitic lava found by Nagata (1951) on Mount Haruna in Japan. This rock has the extremely rare property* of reassuming its reverse polarization after being heated to 700^{o}C. in the laboratory and cooled in the earth's field. In the early stage of this research project it was found that the Haruna rock contains two very different ferromagnetic ingredients, namely a titanomagnetite of Curie point of 500^{o}C. and a ferromagnetic ilmenite whose Curie point is 200^{o}C. The origin of the reverse polarization was first attributed to the interaction of these two minerals. It was later established however that the intensity of the reverse magnetization was increased by leaching the titanomagnetite from the powdered rock. The origin of the reverse polarization was then assumed to be inherent in the ferromagnetic character of the ilmenite. A series of synthetic specimens of the ilmenite-hematite solid solution, $x(FeO \cdot TiO_2) \cdot (1-x)Fe_2O_3$ was then prepared to verify this possibility. It was found that reverse polarization is indeed a characteristic of the member ($x \doteq 0.5$) of this series. Conclusive evidence that

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*Balsley and Buddington (1958) report having found a similar rock in the Adirondacks, as mentioned previously.

this member of the ilmenite-hematite series has the inherent property of self-reversal is provided by the fact that reverse polarization is produced in a field as high as 17,000 oersteds. According to Uyeda, the mineral whose composition is given approximately by $0.5(FeO \cdot TiO_2) \cdot (0.5)Fe_2O_3$ is present in two phases which are intimately intergrown. The mechanism finally postulated by Uyeda (1958) is one in which "a kind of exchange interaction takes place over the phase boundary of two participating constituents which are the parasitically ferromagnetic titanhematite and the ferromagnetic ilmenite intermingled with good atomic coherency."

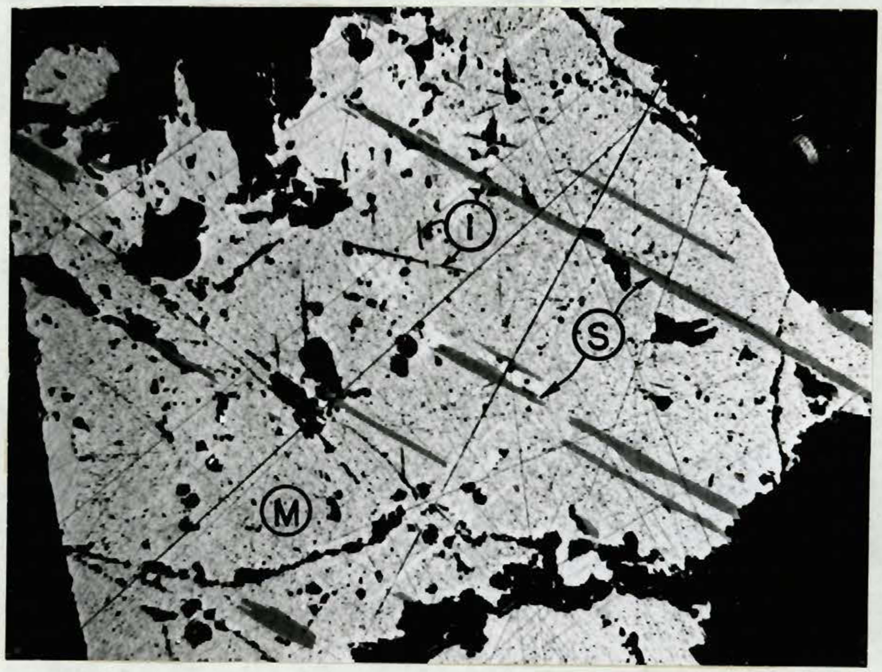
B- The Possibility of Self-Reversal Mechanisms in the Case of the Yamaska and Brome Mountains Rocks

Any attempt to discount the possibility of a self-reversal mechanism in the case of the Brome and Yamaska mountains rocks should be done with reserve. Firstly, it is doubtful that all the possible mechanisms have been described so far in the literature. Second, it may be that all traces of a mechanism which may have once been active in the rocks have completely disappeared from the rock as we see it today. Finally, the conditions required by some of these mechanisms may not be reproducible in the laboratory. Nevertheless, some of the mechanisms listed in the previous section are most likely not applicable to the present case whereas others are. At best, one can only estimate the probability that the reversely polarized rocks dealt with here were magnetized by a process different from the normal process of thermomagnetization in a field whose direction was opposite to that of the present earth's field.

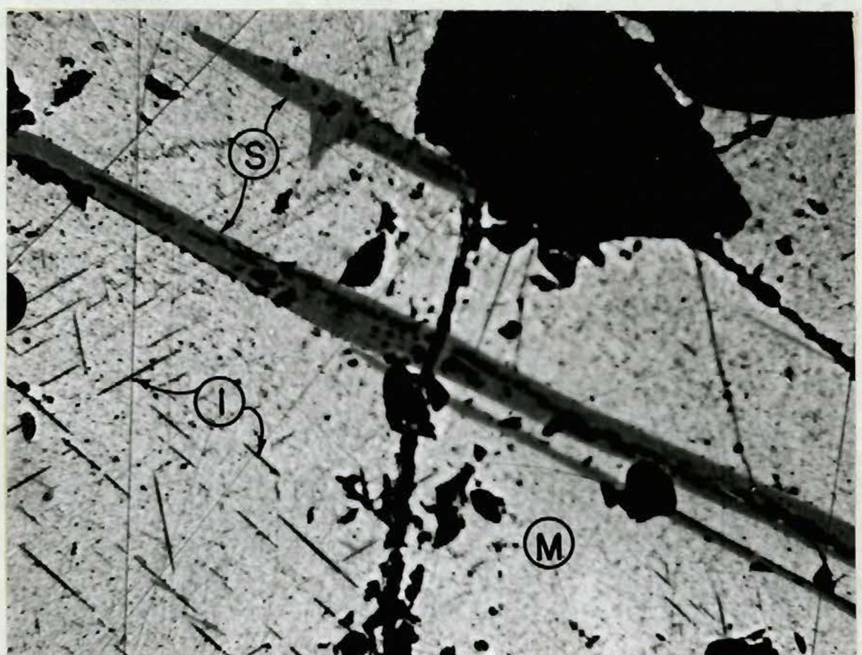
The results of Experiment No. 2, page 35, show that the reverse thermomagnetization of the rocks from Yamaska and Brome is not reproducible in the laboratory at the time scale of the experiment. This fact more or less eliminates the relevance of Néel's first and second mechanisms since the presence of the unusual ferrimagnetics required in the rocks for these mechanisms would almost necessarily call for the laboratory reproducibility of the polarization reversal.

Néel's third and fourth mechanisms require the coexistence in a rock of two ferromagnetic minerals of different Curie points. However, it can be shown mathematically that this condition is not sufficient to produce a magnetically antiparallel coupling between those two minerals. Uyeda (1955) made a study of some particular configurations favourable to this type of coupling. He studied the cases of concentric spheres and that of uniform mixtures of small spheres of two hypothetical minerals. In both cases he showed theoretically that there is no negative interaction. In the case of parallel plates of alternate constituents, he demonstrated that this configuration is compatible with the magnetic interaction of minerals. This texture is often encountered in natural rocks and the photomicrographs shown in Plate I below indicate that it is present in some of the specimens from Yamaska and Brome mountains. As far as it could be detected from the microscope examination, the regular pattern of streaks

PLATE I

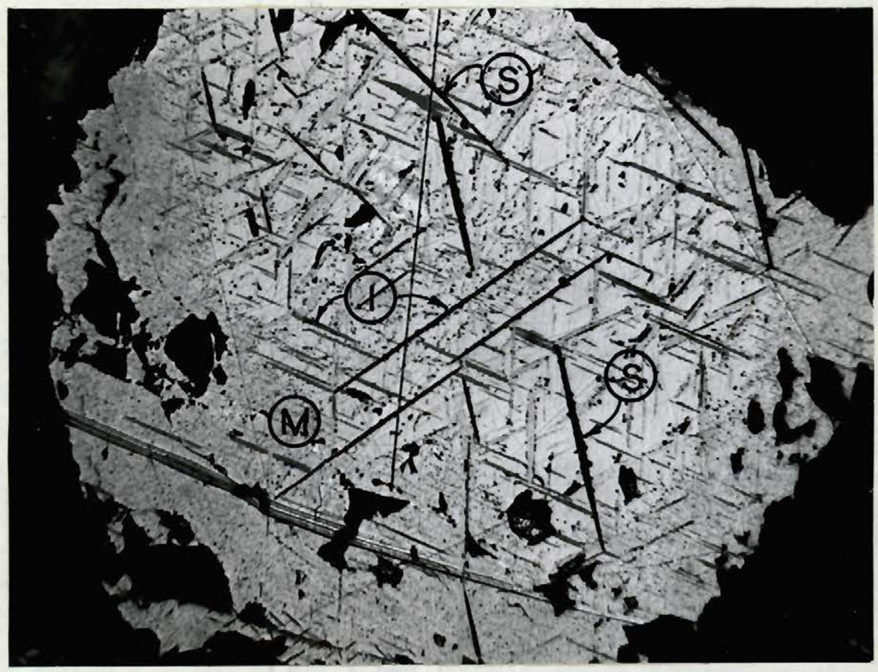


A- Specimen No. 37-B: Photomicrograph of opaque mineral grain showing exsolution lamellae of ilmenite (I) from magnetite (M) and MgAl Spinel (S) intergrowth; magnification X 400.

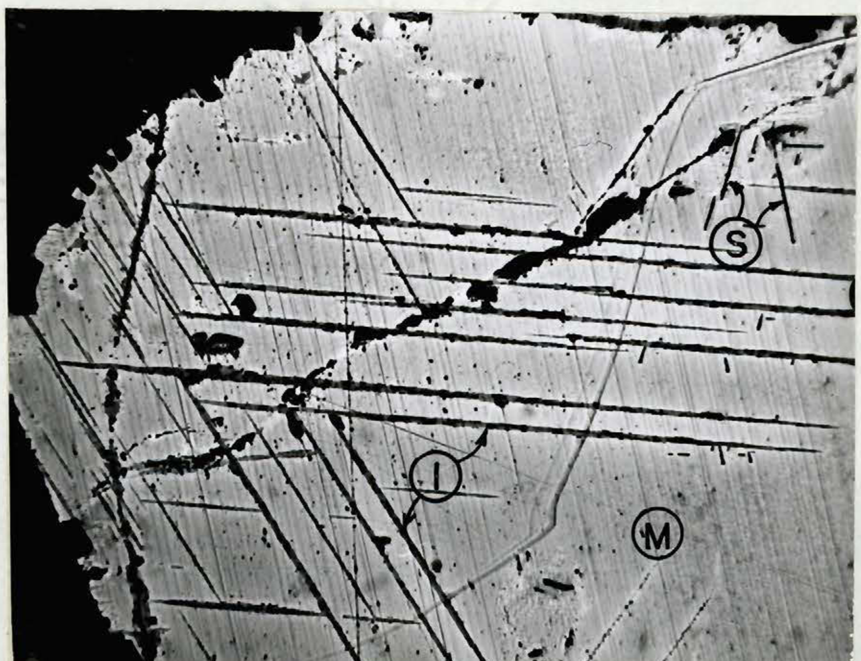


B- Specimen No. 38: Photomicrograph of opaque mineral grain showing exsolution lamellae of ilmenite (I) from magnetite (M) and MgAl Spinel (S) intergrowth; magnification X 400.

PLATE I (Cont'd)



C- Specimen No. 42: Photomicrograph of opaque mineral grain showing exsolution lamellae of ilmenite (I) from magnetite (M) and MgAl Spinel (S) intergrowth; magnification X 400.



D- Specimen No. 71: Photomicrograph of opaque mineral grain showing exsolution lamellae of ilmenite (I) from magnetite (M) and MgAl Spinel (S) intergrowth; magnification X 400.

PLATE I (Cont'd)

E- Specimen No. 74: Photomicrograph of opaque mineral grain showing exsolution lamellae of ilmenite (I) from magnetite (M) and oxidation of magnetite into hematite (H) along fissures; magnification X 400.

F- Specimen No. 105: Photomicrograph of opaque mineral grain showing exsolution lamellae of ilmenite (I) from magnetite (M); magnification X 400.

over the more uniform background consists in exsolved ilmenite or titaniferous hematite along the cleavage planes of magnetite or titanomagnetite. The question remains whether the ilmenite is of the ferromagnetic type or whether it is paramagnetic. Apart from the exsolution pattern observed at low magnification, Nickel (1958) reported recently the existence of an exsolution of magnetite from ulvöspinel in specimens from Yamaska mountain. The scale of this structure is very fine, however, and its detection was possible only through electron microscope observation. At this stage, therefore, it seems that the case dealt with could be explained by either of Néel's third or fourth mechanism. The variation of Néel's third mechanism suggested by Graham (see p.61) does not seem to apply in the present case since practically no deuteric action is indicated on any of the polished sections examined.

As to the mechanism of diffusion suggested by Néel (1955), where ionic exchange takes place between the two sub-lattices of a ferrimagnetic, it may not be possible to verify its applicability in the present case either with the information in hand or with further laboratory tests. The time scale involved in the migration of the ions may be far beyond the laboratory scale.

Smelov (1957) requires the presence of hematite as one of the ferromagnetic constituents in the rock for his mechanism. From the polished sections alone it is not possible to establish whether this mineral is present as αFe_2O_3 or as a member of the ilmenite-hematite series. This mechanism is therefore classified as possible for the time being.

Finally, a mechanism similar to that submitted by Uyeda to explain the reverse polarization of the Haruna rocks is not probable in the present case since the rocks behave differently upon being heated and cooled in the earth's field. This conclusion would be more certainly stated if we could establish whether or not the stipulated member of the ilmenite-hematite series for this mechanism is present in the rocks from Brome and Yamaska mountains.

In conclusion, a certain number of the known mechanisms seem possible in the present case but no one can be suggested as probable. More information is required concerning the chemical composition of the minerals in presence in the majority of the cases.

It is relatively easy to distinguish between magnetite, ilmenite and hematite by etching tests on the polished sections, but it is not so feasible to determine a specific member of the ilmenite-hematite or ulvöspinel-magnetite solid solutions. In the present investigation this type of information is of first importance since it is now recognized that the ferromagnetic properties of these minerals vary linearly with their composition.

Chevallier, Bolfa & Mathieu (1955) and Akimoto (1957) have established the relationships existing between the composition of the members of the series $x(FeO \cdot TiO_2) \cdot (1-x)Fe_2O_3$, their Curie points and their lattice constants. Their results were obtained from carefully synthesized compounds which were chemically analyzed.

A summary of their combined results for the Curie points vs compositions is given below. The Curie points θ are given in C°.

x	0	0.1	0.2	0.3	0.4	0.5	0.6	0.664	0.7	.708	0.8	0.82	0.9
θ_c	675	590	500	410	320	230	140	150*	050	060*	-40	-50*	-150

Akimoto (op.cit.) has established further that the members for which $.55 > x > 0$ are feebly ferromagnetic, those for which $.75 > x > .55$ are ferromagnetic and those for which $.75 < x < 1$ are paramagnetic.

For the series $y(TiO_2 \cdot 2FeO) \cdot (1-y)Fe_3O_4$, Pouillard (1950) and Akimoto (op.cit.) have established similar relationships. Their combined results for the Curie points vs compositions are given below. The Curie points are given in C°.

y	0	.08**	0.1	0.1	0.2	0.25**	0.3	0.4	0.42**	0.5	0.6	0.7	0.8
θ_c	580	524	510	485	450	468	380	320	220	250	190	120	50

Although these data are subject to a certain error, it is certain that they can be used to great advantage in determining the approximate composition of a member of these series from its Curie point.

For this purpose and for the purpose of detecting the possible coexistence of minerals of different Curie points in the rocks from Yamaska and Brome mountains, the construction of a Curie point meter was considered desirable at this point of the present study. The details of this construction and the results obtained with the instrument form the subject of the next Chapter.

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* after Chevallier & al.

** after Pouillard

CHAPTER V

CURIE POINT DETERMINATIONS

According to Weiss's theory of ferromagnetism, a ferromagnetic substance is subdivided into elementary domains which are polarized in random directions but whose intensity is the same for all domains at a given temperature. This intensity of magnetization, known as the spontaneous magnetization, varies only with temperature for a given substance. The temperature at which the spontaneous magnetization is equal to zero is called the Curie point of that substance. The Curie point of a ferromagnetic substance corresponds therefore to the temperature at which the magnetic susceptibility of that substance vanishes.

Curie points have been determined by several scientists who used different types of magnetic balances for their determination. A complete review of these observations would be beyond the scope of this chapter and it would involve the description of many devices which were not used in the present project. Among the best known Curie point measuring devices we shall only mention the torsion balance type of P. Curie (1895), the translation balance of Foëx and Forrer (1926) and the ordinary magnetic balance of Pacault (1946). Nagata (1953) suggests also the adaptation of the astatic magnetometer for Curie point determinations.

The instrument originally designed by Pierre Curie was modified by Forrestier and later by Chevallier and Pierre (1932). An instrument similar to the one built by Chevallier and Pierre was used in the present study.

The essential components of this instrument comprise a torsion balance, an angle recording device, an electromagnet and a heating element. The main differences between Chevallier's instrument and the writer's are in the electromagnet pole pieces and in the recording device. Before entering into the detailed description of each component, an explanation of the working principles of the instrument will be given first.

A- Basic Principles of the Instrument

A T-shaped structure which is suspended at point O (see Fig. 13) by a fine copper wire is balanced in the horizontal plane by the sample and by the two counterweights at the extremities of the "T". A mirror which is linked rigidly to the "T" at the point of suspension lies in the vertical plane. When the electromagnet is energized by a sufficiently high direct current (of the order of 0.2 ampere), the sample is attracted towards the bottom of the heating element because of the field gradient resulting from the shape of the electromagnet pole pieces. As a result, the "T" rotates by an angle θ about point O and the mirror deflects a narrow two-inch-high light beam by an angle 2θ from its original position. The amount of light travelling past the two V- shaped openings (whose sections are shown in Fig. 13) is controlled by the angle θ of displacement of the "T". This light

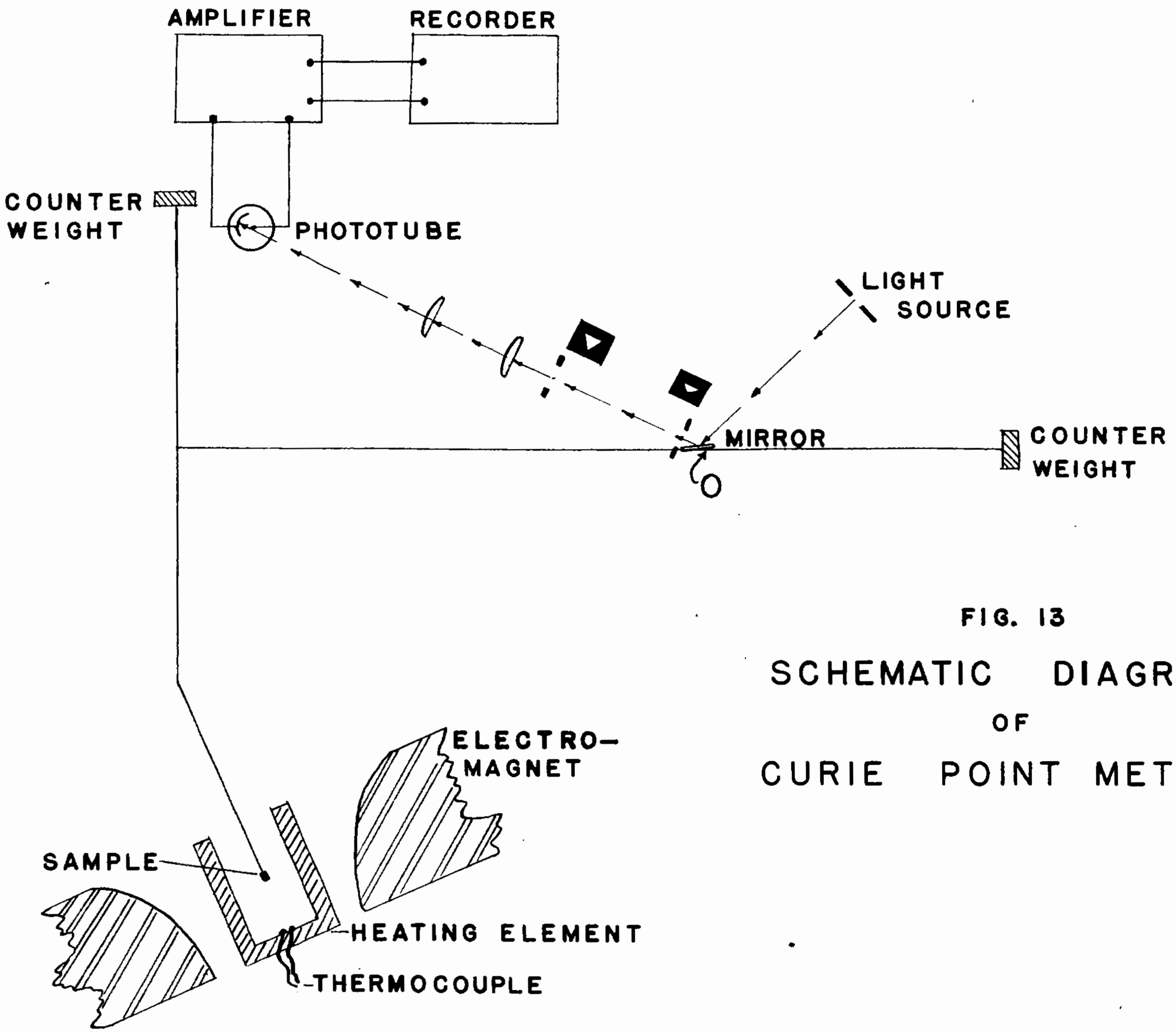


FIG. 13

SCHEMATIC DIAGRAM OF CURIE POINT METER

is further concentrated by a system of lenses onto the screen of a phototube. The output of the phototube is amplified through a current amplifier which feeds into an Esterline-Angus graphic ammeter.

In order to simplify the discussion, we shall assume temporarily that the specimen contains only one ferromagnetic mineral. As the temperature of the specimen is raised by means of the heating element, its magnetic susceptibility increases slowly and gradually. When the specimen reaches its Curie point, it is no longer attracted by the electromagnet due to the disappearance of the spontaneous magnetization in the domain. The torsion impressed on the suspension wire is sufficient to restore the "T" to the position it occupied before the electromagnet was energized. When the "T" is in this position, the light reflected by the mirror is completely intercepted, being reflected outside the V-shaped openings. The output of the phototube is immediately reduced to zero and the information is automatically recorded by the graphic ammeter. If the specimen is later permitted to cool, the reverse process takes place.

The above described cycle may be repeated several times without the fear of masking previous records as would happen with Chevallier's instrument which depends on photographic recording. When the sample under consideration contains more than one ferromagnetic mineral, this advantage soon becomes important. Another advantage of this type of recording over the photographic recording is that the operator can follow the displacement of the sample

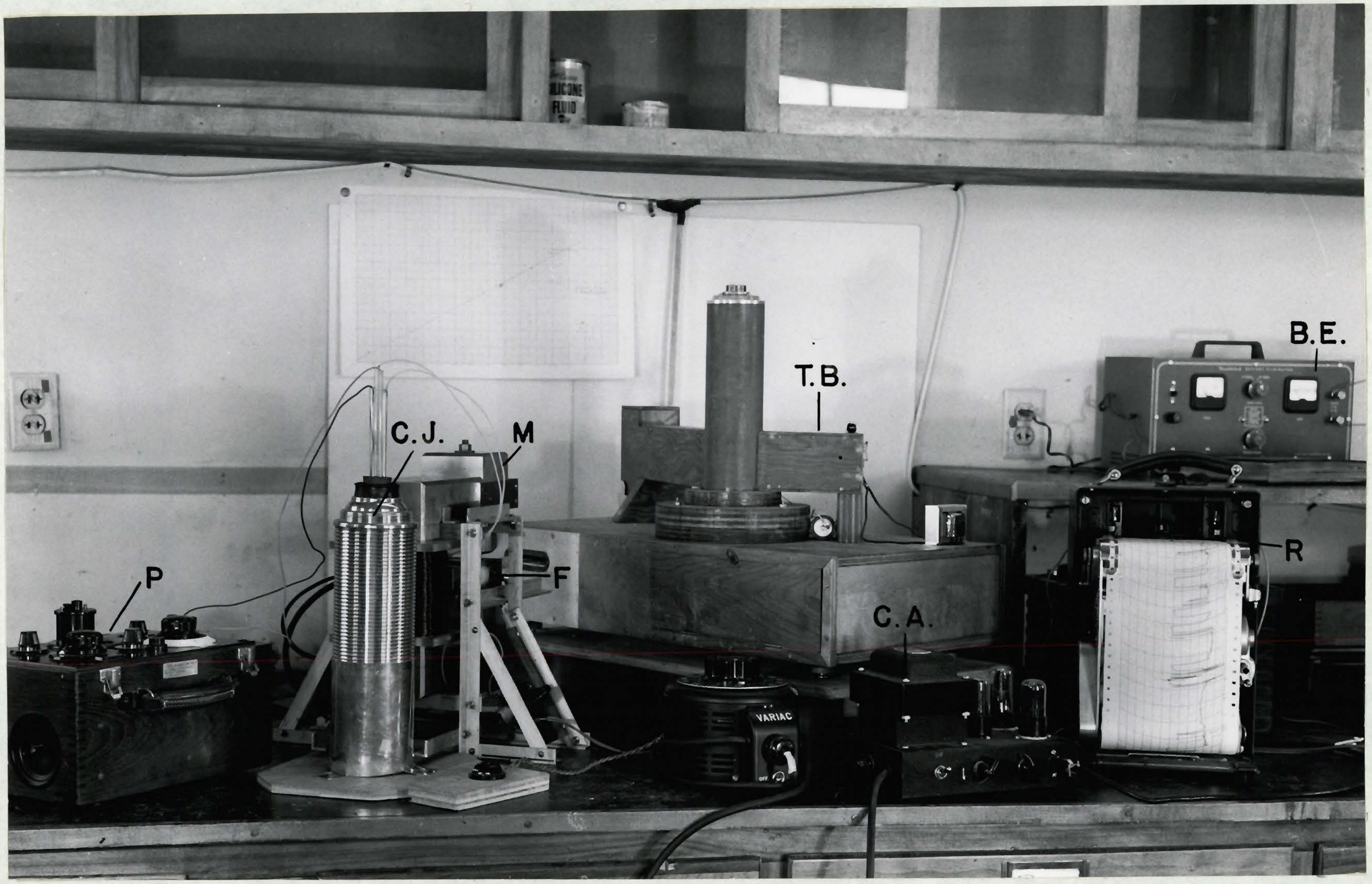


Fig. 14: CURIE POINT METER ASSEMBLAGE

P :	Cambridge Potentiometer	M:	Electromagnet	T.B.:	Torsion Balance
C.J.:	Cold Junction	F:	Heating Element	C.A.:	Current Amplifier
B.E.:	Battery Eliminator			R :	Recording

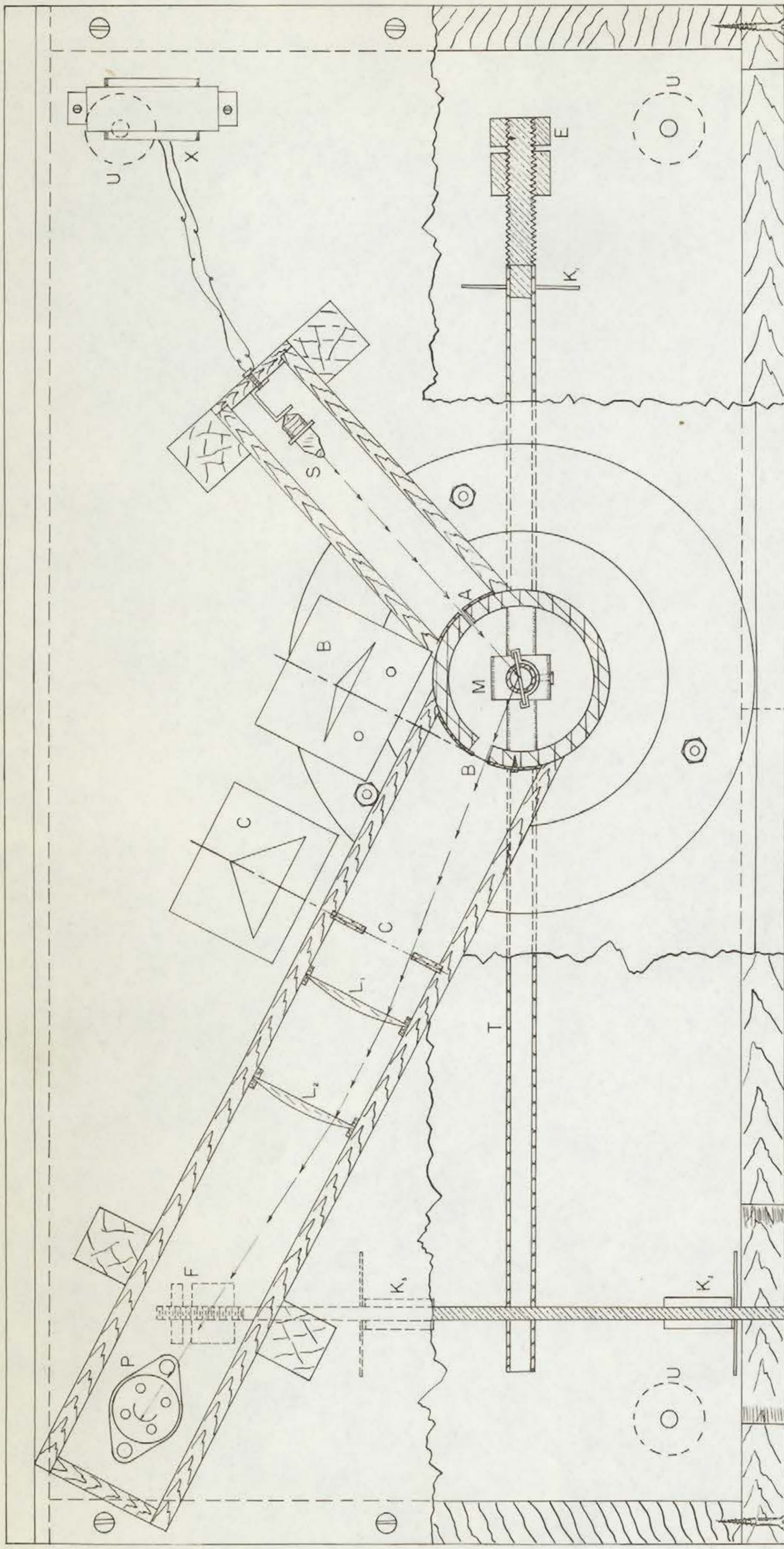
directly from the record during the operation.

B- The Components

(i) The Torsion Balance - The torsion balance whose design is reproduced in Figs. 15 and 16 consists essentially of an adjustable suspension Y and Z, a torsion wire W, a beam and cross-beam T, a damping mechanism D and V a specimen holder H, a levelling mechanism U to set horizontal the base of the instrument and two sets of counterweight E and F to balance the "T" in the horizontal plane. Except for H and the adjacent part of the cross-beam, the moving mechanism is held in a closed container in order to prevent effects from air displacements in the room. K_1 , K_2 and K_3 are used to control the parallelism between the "T" and the base of the instrument.

Two adjustments are possible by means of the suspension, namely the height of the "T" with respect to the base of the instrument and the equilibrium position of the same member in the horizontal plane when no magnetic force is impressed on the specimen.

The suspension wire is passed through pinholes along the axes of the setscrews Z to which it is soldered. The upper setscrew is locked to the suspension by means of another setscrew coaxial to it and the lower one is tightened against the aluminum tubing of the "T". The free length of the wire is exactly 12 inches and its diameter is 0.2019 mm. (Gauge No. 32 B&S). Assuming a rotation of 4^0 for the "T" about its point of suspension, i.e. a linear displacement of 21.2 mm. for the specimen, it is easy



TORSION BALANCE
FOR
CURIE POINT METER
DEC. 1957
A.L.
PLAN VIEW
SCALE IN INCHES
ALUMINUM
BRASS
BAKELITE

FIG. 15

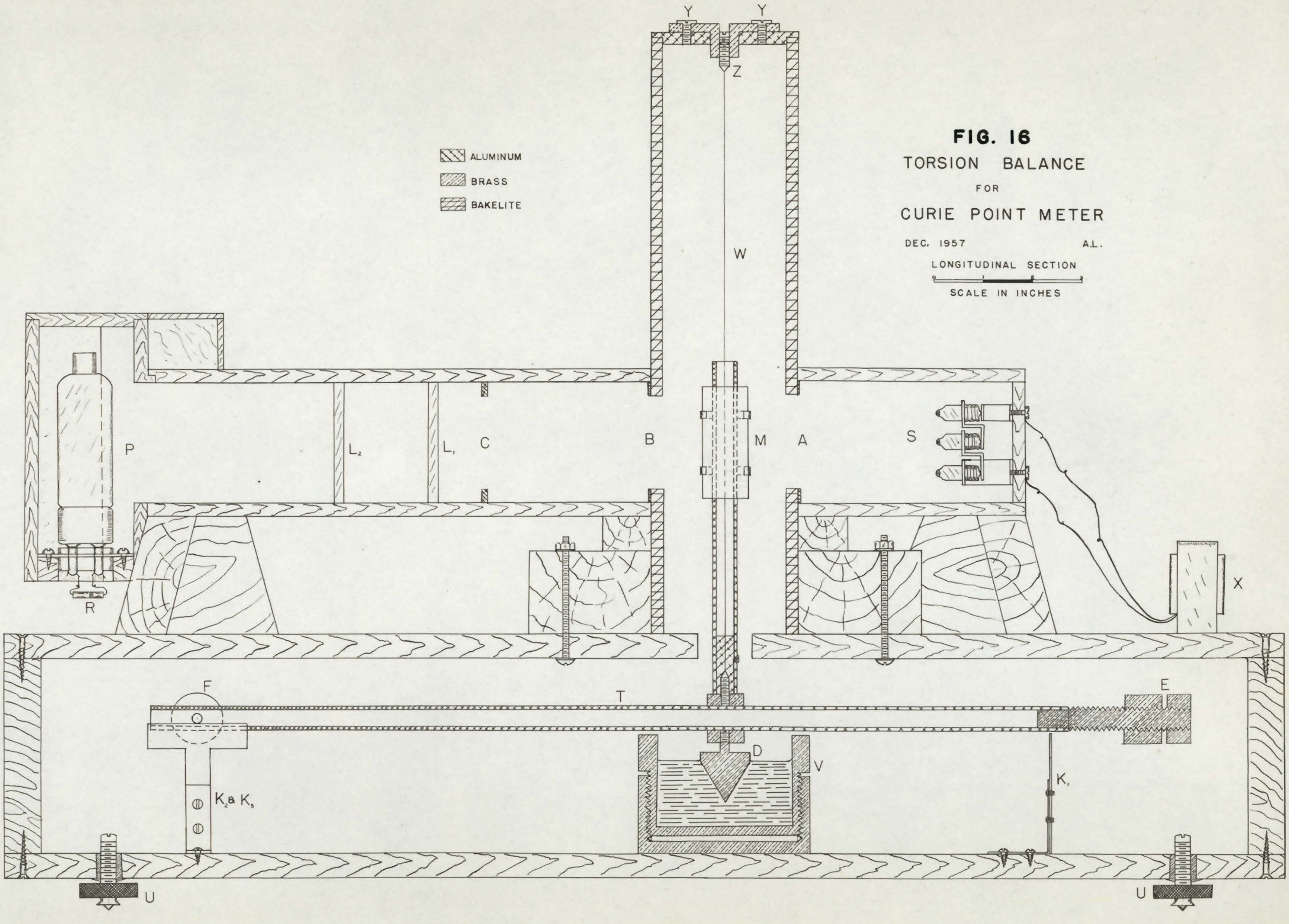


FIG. 16
TORSION BALANCE
FOR
CURIE POINT METER
DEC. 1957 A.L.
LONGITUDINAL SECTION
SCALE IN INCHES

to calculate the elastic couple impressed upon the twisted wire. The magnitude of this couple is given by the application of the formula*:

$$(1) \qquad \Upsilon = \frac{\pi C \Theta R^4}{2L}$$

where Υ is the couple in dyne-cms, R the radius of the wire in cms, Θ the angle of torsion in radians, L the length of the wire in cms, and C the torsion modulus of the material forming the wire. In the present case the value of C is of the order of 4×10^{11} according to tables**. Then:

$$\Upsilon = \frac{\pi x 4 x 10^{11} x 4 x (.01)^4 x 1}{57.5 x 2 x 12 x 2.54} = 14.3 \text{ dyne-cms.}$$

Since the arm of the couple is 30.5 cm long, the minimum force impressed on the specimen to cause the assumed 4^0 torsion of the wire is 14.3/30.5 or 0.475 dyne. The action of a force of that magnitude is easily detected by the present torsion balance as will be shown in the description of the following experiment.

A single crystal of magnetite weighing 10.34 milligrams was set in the specimen holder and the electromagnet was energized by a direct current of 0.2 ampere. Although very small, this quantity of magnetite was attracted by the electromagnet by a force larger than 0.475 dyne since the "T" was rotated by the full range of 4^0. As the energizing current was discontinued the "T" reassumed its original position by the action of the torque stored in the wire.

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*Frank, N.H., Introduction to mechanics and Heat, McGraw-Hill Book Co., New York and London, 1939 - page 273.

** ibid., page 374.

This shows that the size of the specimen whose Curie point is to be determined may be relatively small*, with the advantage that the entire specimen reaches very quickly a uniform temperature upon being cooled or heated.

The stem of the "T" was made of aluminum tubing in order to satisfy the requisites of light weight, rigidity and non-magnetic character. Since Fig. 15 was drawn, a slight modification was made to the sample end of the cross-arm. The silver holder and the adjacent brass rod were replaced by two loops of platinum wire inserted at the end of a pyrex rod. The insulator I was replaced by a copper sleeve joining the pyrex rod to the rest of the cross-arm.

In order to provide the "T" with extra stability in the horizontal plane in the event of small disturbing vertical vibrations, its center of gravity was lowered by the addition of a brass cone D which dips in high viscosity silicone oil. This provides at the same time a damping mechanism for the horizontal rotation of the "T". The amount of damping may be adjusted by changing the relative height of the oil surface.

(ii) The Recording System- This system may be divided into two distinct sections, namely the optical and the electronic section.

The components of the former are represented in Fig. 15 above. The light source S consists of three No. 222 flashlight lamps connected in series to the secondary of a 115/6.6 volt transformer X. The primary of the latter is connected to the output

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* The average weight of the rock specimen was of the order of 300 mg.

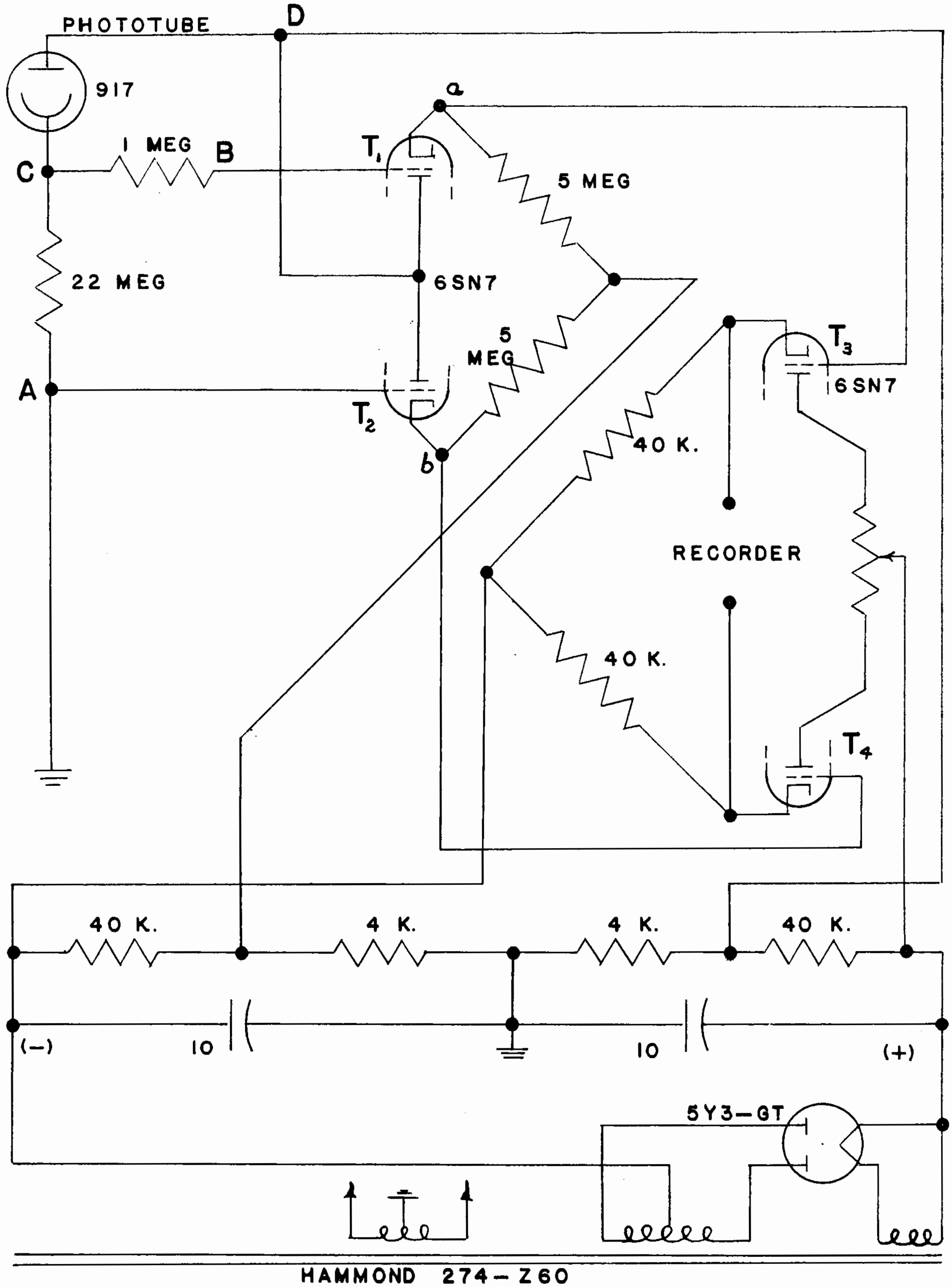

FIG. 17 – CIRCUIT DIAGRAM OF STABLE CURRENT AMPLIFIER

of a constant voltage Sola transformer in order to eliminate any variation in the light source intensity which would be caused by line voltage fluctuations. The light is beamed through a one millimeter slit A on the median line of the mirror M. Depending upon the position of the "T", more or less of this light is permitted to pass through the V-shaped openings B and C. The purpose of the two lenses L_1 and L_2 is to focus this light on the screen of the phototube P. They are identical cylindrical plano-convex lenses which have a focal distance of 154 mm., their focus lying on the median line of the mirror and on the screen of the phototube respectively.

The phototube used is the vacuum type No. 917. A 22 megohm output resistor was selected for the tube, this resistance permitting a linear response of the tube as well as a sufficient input voltage for the current amplifier. The latter is diagrammatically shown in Fig. 17 along with the power supply of the circuit. This circuit was adapted to the present needs from a circuit originally designed by Rively (1948). The main feature of this amplifier is its stability in the event of line voltage variations. This was verified in the laboratory by connecting the primary of the transformer to the output of a Variac. It was found that variations of 20 volts, which are considered as severe for line voltage fluctuations, were not perceptible on the trace of the recorder.

(iii) <u>The Electromagnet</u> - If a volume dv of material whose magnetic volume susceptibility is k is set in a magnetic field H, it will acquire a magnetic moment $\bar{M}$ which is determined by the relation:

$$(1) \qquad \bar{M} = \left[k\bar{H}/(1+Nk)\right](dv) \quad *$$

where N is known as the demagnetizing factor of the volume and is a function of the particle's shape **.

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

$$(2) \qquad W = MH\cos\theta = \bar{M}\cdot\bar{H}$$

where θ is the angle between the dipole and the magnetic 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:

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

The force impressed on the particle in any direction "s" is then:

$$(4) \qquad F_s = -\partial W/\partial s$$

$$= \left[-2kdv/(1+Nk)\right]\left[H_x\partial Hx/\partial s+H_y\partial H_y/\partial s+H_z\partial H_z/\partial s\right]$$

and in particular if:

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

we get:

$$(6) \qquad F_x = \left[-2k/(1+Nk)\right]\left[H_y\,\partial H_y/\partial x\right]dv$$

By an appropriate design of the pole pieces of the electro-

---

*See Electricity and Magnetism by S.G. Starling, Cambr. Univ. Press, 5th edition, page 268.

**The value of N for a sphere turns out to be 4/3 and formulae to calculate N for other spheroids have been derived and may be found in Rock Magnetism by T. Nagata, Mazuren Co. Ltd., Tokyo, 1953, page 81.

magnet the product $H_y \partial H_y/\partial x$ can be made a constant over an interval of at least 20 mm. along the x axis and the conditions in (5) may be achieved at the same time. The force attracting the specimen would then be:

$$(7) \qquad F_x = K\left[k/(1+Nk)\right]$$

where K is a constant equal to $-2H_y dv(\partial H_y/\partial x)$.

It is known from experience 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, $\Phi(T)$. If f (T) is a function of T, differentiable in the interval $0 \leqslant T \leqslant \theta_c$, it is possible to evaluate $\partial F_x/\partial T$ for any temperature of that interval. Then:

$$(8) \qquad \partial F_x/\partial T = K\left[1/(1+Nk)^2\right]\partial k/\partial T$$

According to the available experimental data (see Nagata, 1953, page 44), when a ferromagnetic mineral is heated from room temperature to a temperature above its Curie point θ_c, its magnetic susceptibility k increases very slowly up to the Curie point and it decreases abruptly at this temperature. Mathematically, this may be expressed as:

$$(9) \qquad \left(\partial k/\partial T\right)_{T<\theta_c} 0, \quad \left|\partial k/\partial T\right|_{T=\theta_c} \gg 0 \quad \text{and} \quad \left(\partial k/\partial T\right)_{T>\theta_c} = 0$$

Introducing these data in equation (8) yields:

$$(10a) \qquad \left(\partial F_x/\partial T\right)_{T<\theta_c} \cong 0$$

$$(10b) \qquad \left(\partial F_x/\partial T\right)_{T=\theta_c} = K(\partial k/\partial T) \quad \text{,using } k \to 0 \text{ as } T \to \theta_c$$

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

From equations (10a) and (10b) it comes out that the force impressed upon the specimen at any temperature below the Curie point is constant for all intents and purposes and that it varies abruptly at the Curie point. Furthermore, from equation (7) $F_x = 0$ at the Curie point since k vanishes at this temperature.

The fact that ferromagnetic minerals may sometimes be polarized permanently in a direction which is not that of the y axis is negligible, considering that the polarization induced in the specimen by a field 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 $H_x = H_z \cong 0$ and $(H_y \partial H_y / \partial x) =$ Constant are fulfilled by the magnetic field.

The design of the electromagnet used for the present instrument is shown in Fig. 18. The shape of the pole pieces is similar to those described by Foëx and Forrer (1926) and by Pacault (1946).

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 in order to avoid distortions in the magnetic field.

The coil of the electromagnet (not shown in Fig. 18) was wound with No. 22 B&S gauge enamel coated wire and it contains approximately 2,300 turns. Its D.C. resistance is 39 ohms. The electromagnet is energized by one or two 12 volt car batteries.

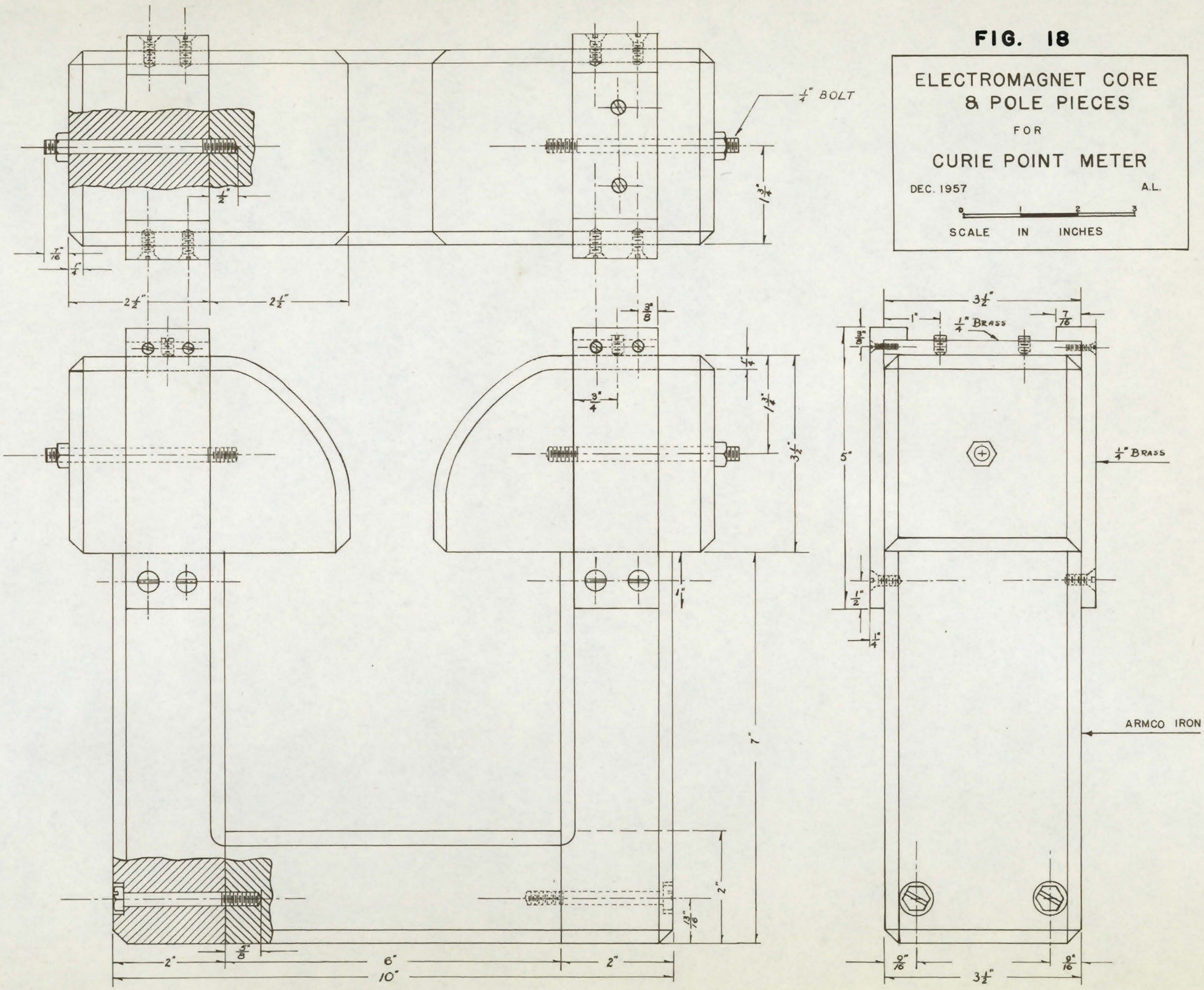

FIG. 18

ELECTROMAGNET CORE
& POLE PIECES
FOR
CURIE POINT METER

DEC. 1957 A.L.

SCALE IN INCHES

In this way the current in the coil may be adjusted to the required intensity by changing the voltage across the coil in steps of two volts from the batteries intermediate terminals and by means of a variable resistor in series with the coil for finer adjustments. When large currents are necessary (in the case of very weakly magnetic specimens) the batteries are made to "float" on a Heathkit battery eliminator. The average current used through the coil for the samples from Yamaska and Brome mountains was 0.25 ampere.

(iv) The Heating Element - Several requirements had to be fulfilled in the design of the heating element: 1- in order to make the magnetic gap between the pole pieces as short as possible, the height of the element had to be reduced to a minimum; 2- since the specimen (about 1 inch long) was to travel along a circular path, the inside width of the element had to be at least 1.5 inch; 3- the temperature in the element had to be as uniform as possible, at least in the region where the specimen was to travel; 4- provisions had to be made so that the specimen could be heated to 700°C. without risk of damaging the furnace lining; 5- provisions had to be made for the pole pieces of the electromagnet not to be appreciably heated by heat radiating from the element; 6- the installation or removal of the specimens without the need of handling the "T" manually was considered desirable in order to avoid damaging the torsion wire; 7- in the case of an electrically operated element, low A.C. current was required so that the magnetic field occasioned by it would not interfere with the field of the electromagnet; 8- the element had to be provided with a temperature

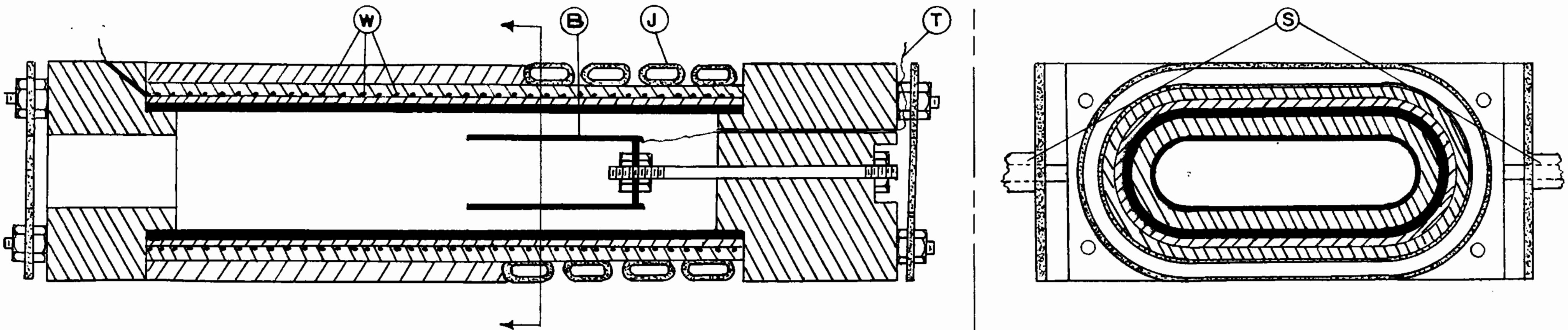

FIG. 19

HEATING ELEMENT

FOR

CURIE POINT METER

DEC. 1957 A.L.

0 1 2 3

SCALE IN INCHES

ASBESTOS

SOAPSTONE

COPPER

SILVER

measuring device indicating the temperature of the specimen at any time.

The heating element built after the design shown in Fig. 19 fulfills these requirements to a satisfactory extent. Items 1- and 2- were taken care of by the tabular shape given to the element; items 3- and 4- were satisfied partly by using silver for the lining and by adding the silver bell B around the space occupied by the specimen; condition 5- was taken care of by means of an aluminum shield around the element (this item is a modification from the original design shown in Fig. 19); the A.C. current does not need to exceed 2 amperes for the heating of the specimen up to 600°C and a relatively small number of turns (33 in all) of No. 20 B&S gauge Nichrome wire forms the element; to satisfy the desired condition 6- , the element is easily removed and replaced into the normal operating position, being mounted on tracks; finally, the temperature measuring device consists of a chromel-alumel thermocouple T which is connected to a Cambridge Potentiometer through a mercury cold junction held at 0°C. by melting ice in an ordinary thermos flask. The actual calibration of the thermocouple was done up to 500°C. and extrapolated for the temperatures ranging between 500 and 700°C. Below 500°C. a mercury thermometer was introduced in the region of the heating element normally occupied by the specimen and simultaneous readings of the thermometer and Potentiometer were made after the temperature indicated by the thermometer had stabilized. Five points equally spaced between 20° and 500°C. were established in this way during the heating as well as during the cooling of the element. The five points fell on a perfectly straight line on a temperature vs voltage diagram, thus justifying the extrapolation from 500°C. to 700°C. The heating and cooling curves were exactly the same. The possible error in temperature readings is of the order of 5°C.

C- <u>The Sample</u>

As mentioned previously, only a small quantity of material is required for Curie point determinations with the above described instrument. In order to prevent possible oxidation of the ferro-magnetic numerals, the solid sample is used in preference to the rock powder when the rock is sufficiently magnetic. Cylinders 3 mm. in diameter and 8 to 10 mm. in length are cut and polished on the grinding wheel with non magnetic abrasive. The samples are enclosed in 6 mm. sealed pyrex vials whose total length is less than one inch. Before the vials are sealed, the air and moisture are removed from them by means of a diffusion pump.

D- <u>Operation of the Instrument</u>

After the installation of the specimen in its 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 pushed towards the specimen until the latter almost touches the bottom of the bell B. The magnetic field is then temporarily released to verify that the specimen will be free to gain its original position when the Curie point is reached.

The next step consists in adjusting the intensity of the magnetic field 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 passage of the lower Curie point may not be noticed since the force acting on the higher Curie point mineral alone would be sufficient to keep the entire specimen in its position of maximum displacement.

The rate of increase of the temperature is kept at about 5°C. per minute by means of a Variac control. It is important to keep this rate relatively low in order that the instrument is given time to resolve two or more Curie points if they are present. Temperature readings are made every 4 or 5 minutes unless a noticeable break is indicated on the record. The instant 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 degrees C.

When the highest Curie point of the specimen has been observed, the temperature is slowly reduced and recorded until the lowest Curie point is indicated on the cooling curve.

E- Preliminary tests and Interpretation of the Records

Before Curie point determinations were made on the rocks from Yamaska and Brome mountains, a few tests were made with minerals of known composition in order to verify the suitability of the instrument and to obtain an estimate of its precision.

A few octahedral crystals of a magnetic, black mineral were extracted from a hand specimen of chlorite schist of unknown provenance. An X-Ray powder pattern confirmed that this mineral is magnetite*. As heat was applied to the specimen, its position remained unchanged until its temperature reached 580°C. At this temperature the force exerted on the specimen by the electromagnet vanished abruptly as indicated on a reproduction of the record in Plate II-A. As long as the specimen remained at a temperature above 580°C. the force remained null but it was abruptly restored at a temperature slightly below 580°C. This lag observed on the cooling curve is easily explained by the inertia of the "T".

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

As a second test, the Curie point of a sample of pyrrhotite** was determined. As indicated in Plate II-B, this specimen lost its magnetization at about 335°C. On the cooling curve, however, the specimen recovered completely its magnetic character only at 310°C.

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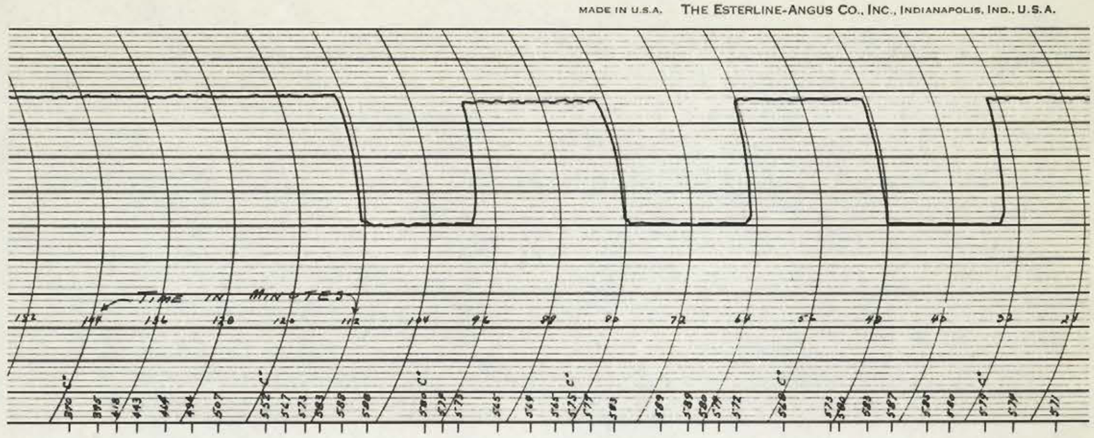
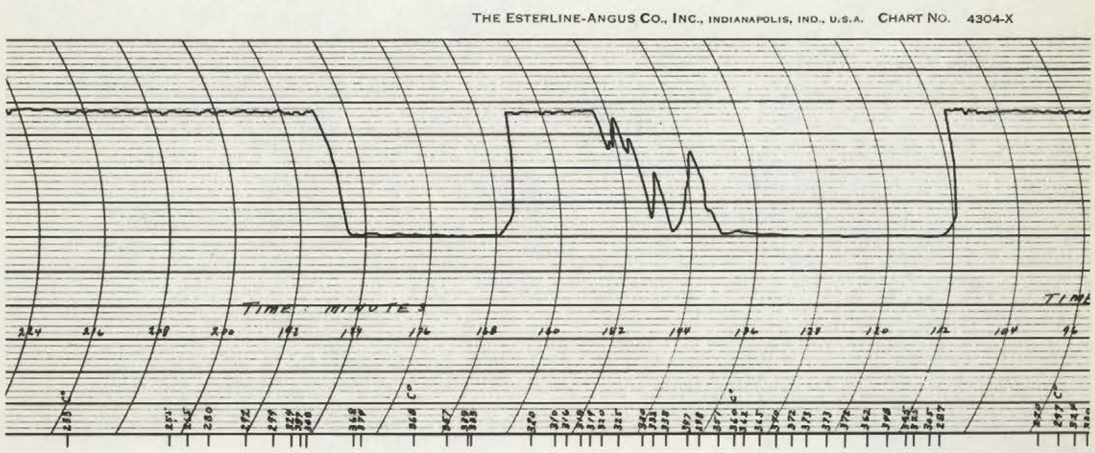
*This pattern was obtained through the courtesy of Dr. R.W. Traill of the Geological Survey. The lattice constant of the mineral was computed to $8.38_5 Å \pm 0.002$.

**This specimen comes from the Yellowknife mining area and was kindly given to the writer by Dr. R.W. Boyle of the Geological Survey.

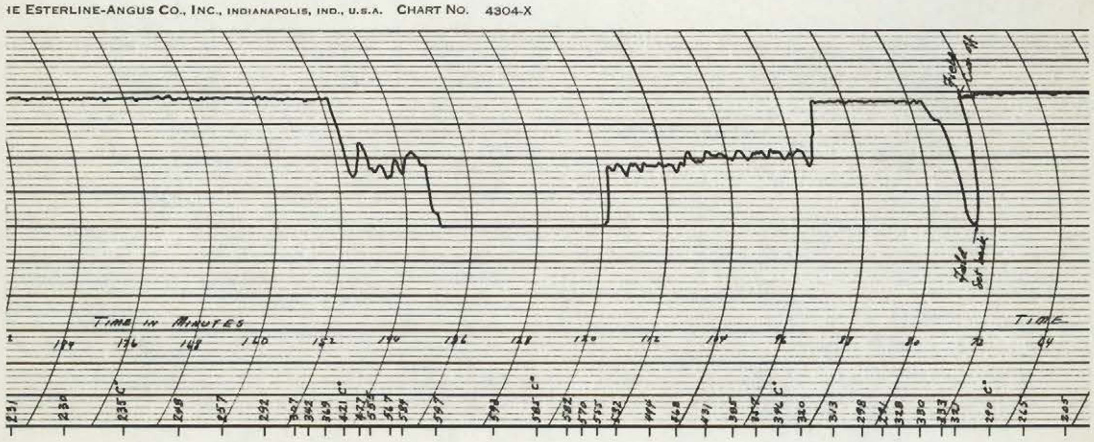
PLATE II



A- RECORD OBTAINED WITH CURIE POINT METER FOR A SAMPLE OF MAGNETITE



B- RECORD OBTAINED WITH CURIE POINT METER FOR A SAMPLE OF PYRRHOTITE



C- RECORD OBTAINED WITH CURIE POINT METER FOR A SAMPLE COMPOSED OF PART OF THE MAGNETITE AND PYRRHOTITE USED FOR A- AND B-

The heating-cooling cycle was repeated several times with the same specimen, with the same results each time. This phenomenon could be explained by a chemical or phase change which is reversible above the mineral's Curie point. It is also possible that a hysteresis phenomenon takes place in the mineral during the heating and cooling cycle. It is noted, however, that the lag is probably due partly to the inertia of the "T", as suggested previously for the magnetite case. Nagata (1953, p. 33) states 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°C. for the same series of minerals. Considering the additional fact that we do not know the exact composition of the mineral in hand, it is not possible to use it as a basis for estimating the accuracy of the present instrument.

A third test was designed to observe the type of curve which should be expected in presence of 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 sample is reproduced in Plate II-C. Two distinct breaks are indicated on the record and these breaks took place in the neighbourhood of 338 and 583° respectively. Considering that an accuracy of ± 5°C. is claimed for the temperature measurements, the above experiments show that the present instrument can be used to determine the Curie point of minerals to this accuracy and, more important in the present problem, to detect the presence of more than one ferromagnetic mineral.

F. Results and Interpretation

Curie points were determined for some of the specimens discussed previously in Chapters II and III. These are listed in table 6 below.

TABLE 6

CURIE POINTS OF THE FERROMAGNETIC MINERALS
PRESENT IN SPECIMENS FROM YAMASKA AND BROME MOUNTAINS

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	-	-	-

The first conclusion that can be derived from these results is that the ferromagnetic minerals present in the rocks from Yamaska and Brome Mountains vary over a wide range of

*Specimens whose photomicrographs appear in Plate I.

**Gradual drop from 462° to 535°C. and sharp drop at 535°C. .

composition as indicated by the number of Curie points encountered.

The presence of a mineral having a Curie point higher than 580°C. was not detected in any of the specimens tested. On the other hand, hematite (Curie point, 680°C.) is indicated on the photomicrograph of specimen No. 74, Plate I-E. This paradox may be explained in different ways. It is noticed that the hematite is of deuteric origin and formed by oxidation of the magnetite along fissures in the latter. First, it is possible that the part of the specimen used in the Curie point determination was free of such oxidation in contrast to the part of the specimen used for the polished section. Second, it is possible that the mineral identified as hematite under the microscope is in reality a non-magnetic impure iron oxide mineral. More plausible, perhaps, is the following explanation. On the one hand, the magnetic susceptibility of hematite is hundreds of times smaller than that of magnetite and, on the other hand, the amount of hematite in Specimen No. 71 is considerably smaller than that of magnetite, as indicated by the photomicrograph. It is possible that the component of magnetization due to the hematite was negligible in comparison to the component due to magnetite and that the Curie point could not resolve the former.

Similarly, the fact that the photomicrographs of specimens Nos. 37-B, 38, 42 and 74 indicate the presence of exsolution in those specimens although only one Curie point was observed for them may be explained either by the insufficient amount of the exsolved mineral or by its non-magnetic character. The second of these hypotheses seems more probable since for specimen No. 105 (Plate I-F) the quantity of exsolved material is considerable although only one Curie point was recorded.

The case of specimen No. 71 is somewhat unusual among the specimens studied. The continuous drop in magnetism from 462°C. to 535°C. and the sharp drop at 535°C. are interpreted as the result of an exsolution of ilmenite from a titanomagnetite whose Curie point is 462°C. It is possible that exsolution took place to different degrees in the different grains of the specimen. The result would be a rise in the Curie point of each grain up to a maximum of 535°C., the composition of which mineral would not allow any further exsolution under a specific set of conditions.

From the microscope observations as well as from the range of Curie points observed it is very probable that the "iron ore minerals" are in fact members of the ulvöspinel magnetite series rather than members of any of the two discontinuous solid solutions ilmenite-hematite. The actual composition of each of these specimens could be established approximately with the aid of Akimoto's results which are tabulated on page 72 of the preceding Chapter.

G. Conclusions

It is noticed that all the specimens examined under the microscope bear signs of exsolution whereas most of the Curie point determinations are indicative of only one ferromagnetic mineral in the rocks dealt with. On the other hand, the rocks are relatively stable magnetically and reversely polarized. Thus, there seems to be no relationship between the coexistence of two minerals of different Curie points in some of the specimens and the fact that they are reversely polarized. It is still possible, however, that a multicomponent mechanism is present in the rock but that it is on such a fine scale that it could not be detected by either the Curie point meter or by the ordinary ore microscope. In fact, Nickel (1958) described recently a sample of "magnetite" from Yamaska Mountain in which he was able to see a very fine exsolution of magnetite from ulvöspinel by means of the electron microscope. Therefore, it seems reasonable to retain the possibility, however remote, that a bicomponent mechanism, similar to those postulated by Néel may have caused the reverse polarization in the rocks from Yamaska and Brome Mountains.

On the other hand, it is not apparent that a unicomponent mechanism such as the one developed by Uyeda for the Haruna rocks can explain the present reverse polarization. First, as pointed earlier, the ferromagnetic minerals present are by all evidence not members of the $FeO \cdot TiO_2 \cdot Fe_2O_3$ which is a necessary condition in Uyeda's mechanism. Second, the Yamaska and Brome rocks differ from the Haruna rocks in that they polarize normally when heated and cooled in the earth's field.

The mechanisms suggested by Balsley & Buddington, Graham, Verhoogen and Smelov also do not seem to apply in the present case because only in one occasion was evidence of deuteric action observed under the microscope.

Therefore, from the Curie point determinations there is no definite evidence established to permit stating whether or not a self-reversal mechanism was responsible for the reverse polarization case under study. The same determinations indicate however that the chance that such mechanism was involved is relatively small.

CHAPTER VI

MAGNETIC MEASUREMENTS OF OTHER RELATED ROCKS

A. Collection of Specimens and Measurements

From the conclusions of the last chapter alone, it would be difficult to ignore completely the possibility that a self-reversal mechanism is the explanation of the reverse polarization of the rocks from Yamaska and Brome Mountains. As a further attempt to elucidate the problem, remanent magnetization measurements were made on rocks related to the above, either spatially or genetically. These rocks include metasediments collected as close as possible to their contacts with the igneous cores and rocks from other intrusive bodies belonging to the Monteregian Hills series. The sites of collection of these specimens are indicated in Fig. 20 (see pocket).

The collection of the specimens and their preparation for magnetic measurements were done according to the general procedure described earlier, with slight modifications. Whenever possible, a solar compass* was used in place of a Brunton compass

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*Manufactured by Bendix Aviation Corp., Teterboro, N.J., U.S.A.

to establish the azimuth of the arrows drawn on the specimens "in situ". The vertical faces of the cubes were cut either parallel or perpendicular to the vertical planes through the arrows, instead of being cut parallel and perpendicular to the astronomic meridians as done for the specimens discussed in previous chapters.

When the magnetization of the rocks was sufficiently strong it was measured by means of the spinner type magnetometer according to the method described in Chapter II. The magnetization of some specimens was too weak however to be measured with this instrument and in those cases use was made of an astatic magnetometer*. A description of an instrument of this type may be found in an article by Collinson et al. (1957).

B. Results and Interpretation

The actual magnetometer readings are listed in Table A-2 in Appendix II and a summary of the results appears in Table 7 and Fig. 21 below. The figures given in Table 7 are the means of figures obtained for the two or three cubes of a given sample. When the direction of magnetization of the different cubes belonging to the same specimen differ by more than 25°, the average is not listed in Table 7 because the rock in question is then considered as unstable magnetically. The intensities of magnetization of the cubes measured with the astatic magnetometer are not listed because the work involved in the calculation of these figures

*This instrument was kindly put at the writer's disposal by Mr. Jean Roy of the Dominion Observatory and most of the measurements were made by Mr. Robert Black.

TABLE 7

SUMMARY OF MAGNETIZATION MEASUREMENTS OF ROCKS RELATED TO THE ABOVE FROM YAMASKA AND BROME MOUNTAINS

Sample No.	Location **	Number of Cubes	Before Magnetic Washing			After Magnetic Washing		
			Declination	Inclination	Intensity emu/cu in $X10^{-5}$	Declination	Inclination	Intensity emu/cu in $X10^{-5}$
1-A*	Y	2	204°	+57°	---	210°	+56°	---
1-B*	Y	2	032	+36	---	052	+39	---
2-A	Y	2	---	--	586	332	-06	---
2-B*	Y	2	303	-02	2,680	---	--	---
3*	Y	2	265	-40	---	159	-30	---
4*	B	2	---	--	---	---	--	---
5-A	B	2	353	+50	270	012	+28	---
5-B	B	2	307	+66	---	---	--	---
6*	B	2	103	-16	---	048	-71	---
7-A	S	2	---	--	---	---	--	---
7-B	S	3	018	+05	56,033	003	+41	2,710
7-C*	S	2	002	+65	---	---	--	---
8	B	2	---	--	---	---	--	---
9*	B	2	173	+27	---	283	-26	---
10	S	3	118	-63	448	134	-62	294
11	S	3	281	+13	4,483	---	--	621
12	S	2	114	+16	557	150	-38	796
13	R	2	333	+44	651	314	+53	434
14	R	3	223	-03	1,617	166	-38	576
15*	R	2	---	--	---	050	+46	---
16	R	2	217	+82	20,900	337	+72	6,590
17	R	2	340	+32	19,150	335	+64	4,685
18	H	3	143	+11	235,167	146	+12	125,300
19	H	2	---	--	---	297	+23	---
20*	H	2	316	-67	316	169	-61	---
21	H	2	267	+70	2,690	150	-52	641
22	H	2	189	-04	19,375	147	-18	417
23*	BN	2	---	--	1,495	267	+56	---
24	BN	2	349	-43	14,850	180	-61	2,490
25	BN	3	000	+06	10,200	167	-51	595
26	BN	2	170	-68	4,310	042	-84	515
27	BN	2	169	-60	7,240	151	-66	745
28*	BN	2	176	-47	---	150	-51	---
29	R	2	215	-44	4,930	---	--	---
30	J	2	333	+57	5,960	340	+57	3,430
31	J	3	106	+19	82,500	---	--	3,060
32	J	3	332	+59	9,180	343	+57	6,107

*Metasediments
**Y- Yamaska; B- Brome; S- Shefford; R-Rougemont
H- St. Hilaire; BN- St. Bruno; J- Johnson.

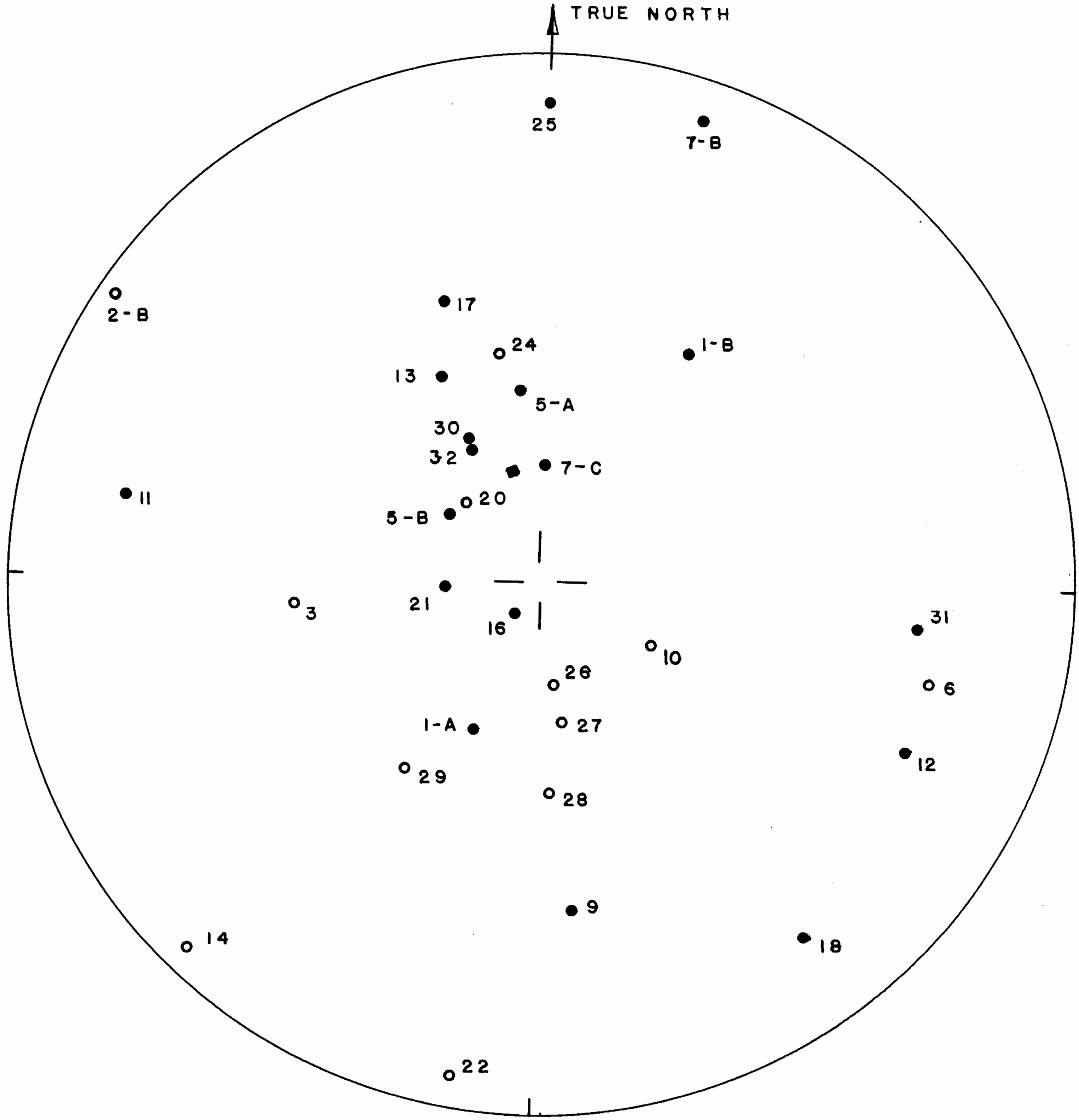

Fig. 21 Stereogram of Magnetization Vectors for 30 Samples of Rocks Related to Yamaska and Brome Mountains, before Magnetic Washing.

● : pointing down

o : pointing up

■ : direction of present earth's field

was not justified by their utility. These intensities are all less than 100×10^{-5} emu/cu.in.

An examination of Fig. 21 reveals a considerable scatter in the directions of magnetization of these rocks. Nevertheless, it is interesting to note that at least some of the sedimentary rocks (e.g. specimens Nos. 3, 6 and 28) and some of the intrusive rocks (e.g. specimens Nos. 10, 26, 27 and 29) are polarized almost parallel with the reversely polarized Yamaska and Brome rocks discussed earlier. On the other hand, other intrusive rocks (e.g. Nos. 32, 30) had a polarization almost parallel to the direction of the present earth's field.

As in the case of the rocks from Yamaska and Brome Mountains previously discussed, it seemed that the random distribution of polarization directions was possibly the result of the simultaneous presence in some of the rocks of several components of magnetization of different stability. The rocks were then subjected to the treatment of magnetic washing according to the technique described in Chapter III. The amplitude of the maximum demagnetizing field was set at 228 Oersteds.

The magnetometer readings obtained after magnetic washing are listed in Table A-2 in Appendix II and a summary of the results is given in Table 7 and Fig. 22. This summary was computed as described in the previous page.

As indicated by a comparison of Figs. 21 and 22, the treatment of magnetic washing had the effect of decreasing the scatter

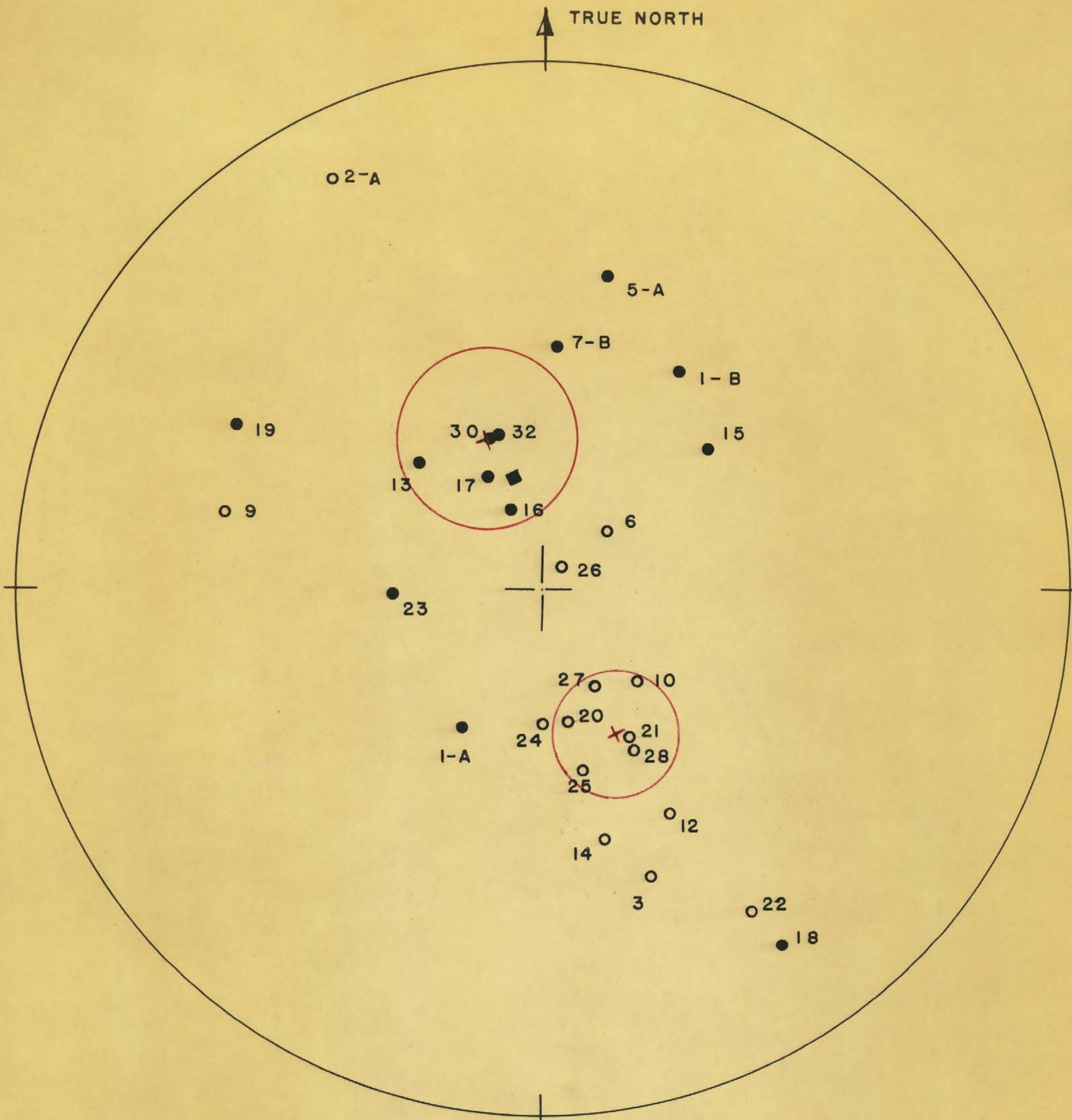

Fig. 22 Stereogram of Magnetization Vectors for 28 Samples of Rocks Related to Yamaska and Brome Mountains, after Magnetic Washing.

● : pointing down

o : pointing up

■ : direction of present earth's field

in the directions of polarization of the rocks under consideration. It is also shown in Fig. 22 (still more strongly than in Fig. 21) that the directions of polarization have a tendency to cluster into two main groups one of which has its mean pointing upward and southeasterly whereas the other has its mean pointing downward and roughly northwesterly.

Before attempting to calculate these mean directions and to establish their palaeomagnetic significance, it seems pertinent to discuss the suitability of the individual specimens for palaeomagnetic studies.

1- Specimens from Yamaska Mountain (Nos. 1-A, 1-B, 2-A, 2-B and 3)

Specimens Nos. 1-A and 1-B, both metasediments, were collected less than 5 feet from one another and less than 10 feet from the akerite contact on the west side of the mountain. They have both a very stable polarization as indicated by the negligible effect the treatment of magnetic washing had on them. The consistency from cube to cube for each specimen is also excellent. On the other hand, their direction of magnetization differ by as much as 90°, which suggests that the specimens may have been magnetized by lightning. It is considered as doubtful that these specimens can be used reliably for palaeomagnetic purposes.

Specimens Nos. 2-A and 2-B, which are also baked sediments, were collected less than 10 feet from one another and less than 20 feet from the akerite contact on the east side of the mountain. The instability of specimen 2-B is indicated by the random shift of its magnetic vector after magnetic washing. On the other hand, the stability of specimen 2-A was tested by measuring its magnetization repeatedly over a period of a few days. It was found that the latter changed appreciably each time according to the position it occupied in the mean intervals with respect to the earth's field. These two specimens were then eliminated from the list of specimens suitable for palaeomagnetic purposes.

Specimen No. 3 is a metasediment collected about 50 feet from the essexite border on the southeast side of the mountain. Its magnetic stability, although not perfect, is considered as sufficient for palaeomagnetic purposes.

2- Specimens from Brome Mountain (Nos. 4, 5-A, 5-B, 6, 8 and 9)

Specimens Nos. 4 and 8 are obviously inconsistent as indicated in Table A-2 and it would be misleading to consider their mean directions as significant in terms of palaeomagnetism.

Specimens 5-A and 5-B were collected within a radius of 10 feet from an outcrop of syenite in the northeastern part of the mountain. Specimen 5-A is a fine-grained rock whereas specimen 5-B is the coarse-grained. The instability of specimen 5-B is shown by the random shift of its magnetization from cube to cube after magnetic washing. The stability of specimen 5-A is indicated on the other hand by its excellent consistency from cube to cube after the same treatment. For these reasons the former was rejected from the list of suitable samples and the latter was added to it.

Specimen No. 6 is a metasediment collected less than 10 feet from the essexite contact in the southern part of the mountain. It was considered as magnetically stable on account of its good magnetic consistency after magnetic washing.

Specimen No. 9 is of sedimentary origin and it was collected at least $\frac{1}{4}$ mile from the assumed igneous contact in the northern part of the mountain. The magnetization of this specimen is consistent from cube to cube and it is thus considered as stable. However, due to its considerable distance from the igneous contact, it is probable that the magnetization left in it after magnetic washing is not related to the intrusion of the igneous rock. On this basis this specimen will not be considered in the present study.

3- <u>Specimens from Shefford Mountain</u> (Nos. 7-A, 7-B, 7-C, 10, 11 and 12)

Specimen 7-A was taken from a dyke cutting through the essexite mass from which specimen 7-B was collected. The two specimens were collected within a radius of 20 feet. The former was found to have a very weak and unstable magnetization whereas the latter is relatively strongly magnetized, its magnetization showing all signs of stability.

Specimen 7-C was collected from a limestone outcrop about five hundred feet from the nearest exposure of essexite. Its magnetic stability is relatively poor and its magnetization is probably not related to the intrusion of the mountain core. For these two reasons this specimen was considered as unsuitable for the present study.

Specimens Nos. 10, 11 and 12 were collected from the igneous core on the east side of the mountain. Specimen No. 11 is considered as magnetically unstable unlike specimens Nos. 10 and 12.

4- <u>Specimens from Mount Rougemont</u> (Nos. 13, 14, 15, 16, 17 and 29)

Specimens Nos. 13, 14, 16 and 17 were collected from the igneous mass and are considered as magnetically stable, in view of the consistency of their magnetization from one cube to another after magnetic washing. Specimen No. 15 was collected from the sediments near the igneous contact and it is considered as magnetically stable. Specimen No. 29 was collected from the igneous mass in the northern part of the mountain. After magnetic washing the magnetization of one of its cubes pointed steeply upward whereas that of the other pointed downward. For this reason this specimen is considered as unsuitable for the present study.

5- <u>Specimens from Mount St. Hilaire</u> (Nos. 18, 19, 20, 21 and 22)

Specimens Nos. 18, 19, 21 and 22 were collected from the igneous mass and proved to be magnetically stable after magnetic washing. Specimen No. 20 was collected about 20 feet from the igneous core on the west side of the mountain. Its magnetic stability after magnetic washing is indicated in table A-2.

Specimen No. 18 was unique in having an extremely strong magnetization which persisted in the specimen even after submitting the latter to a demagnetizing field of over 300 oersteds. This indicates that the specimen was polarized either by thermal or lightning effects. To verify the plausibility of the second of these possibilities, a simple experiment was carried out on the specimen. Cube No. 18-2 was heated to above 700°C. and kept at this temperature for one hour after which it was allowed to cool slowly in the ambient earth's field. Its magnetization was then measured. The resulting thermomagnetization was $5,560 \times 10^{-5}$ emu/cu in. in comparison with $228,500 \times 10^{-5}$ and $102,200 \times 10^{-5}$ emu/cu in. as obtained for the same cube before magnetic washing and before heating respectively. If we compare these results with those quoted in experiment No. 2, p. 35, we see that in the latter case the total intensity of magnetization of a cube of essexite from Yamaska mountain was hardly changed whereas in the present case the intensity of magnetization of cube No. 18-2 was reduced to 5% of its original value by the same treatment. Furthermore, the value of $5,560 \times 10^{-5}$ emu/cu in. is much closer to the intensities of other essexite samples collected throughout the Monteregian Hills. Another reason for suspecting lightning polarization in the case of sample No. 18 is the fact that it was collected on the peak of the mountain, which is a site favourable for lightning polarization. On account of these facts, specimen No. 18 is rejected from the group of specimens whose stable component of magnetization may have a significance in terms of palaeomagnetism.

6- <u>Specimens from Mount St. Bruno</u> (Nos. 23, 24, 25, 26, 27 and 28)

Except for specimens Nos. 23 and 28, these specimens were collected from the igneous mass. After magnetic washing their magnetization proved to be stable. Specimen No. 23 was collected from the sedimentary rocks near the border of the intrusive and it is considered as magnetically stable. Specimen No. 28 was collected about 6 inches from the border of the igneous mass in proximity of specimen No. 27. Its good stability is shown by the figures listed in Table A-2.

7- Specimens from Mount Johnson (Nos. 30, 31 and 32)

These three specimens were collected from the igneous core of the mountain and specimens 30 and 32 are considered as magnetically stable.

C. Conclusions

In summary, of the number of specimens whose magnetization was measured, a certain number are considered unsuitable in terms of palaeomagnetism due to their magnetic instability. These are accordingly not represented in Fig. 22. Another group of specimens was found magnetically stable but unsuitable for the present study for the different reasons given in the above paragraphs. This group includes specimens Nos. 1-A, 1-B, 2-A, 9 and 18. The other specimens are considered magnetically stable and the direction of their magnetic polarization is most probably related to the direction of the earth's field at the time of cooling of the intrusives. This last group of specimens only will be considered in the remaining part of the present chapter.

It is clear from Fig. 22 that the magnetization vectors represented on the stereogram may be classified into two principal groups, namely those which are almost parallel to the direction of the present earth's field and those which are almost opposite to the same direction. The mean directions of these two groups* and the corresponding cones of confidence for 95% probability were calculated according to the method previously described in Chapter III. The crosses and large circles in red in Fig. 22 represent these mean directions. A measure of scatter was also calculated according to formula (2) on page 53. The computed values are summarized as follows:

	Mean Declination	Mean Inclination	θ Radius of Circle of Confidence	K Measure of the Scatter
Group I :	339.5°	$+56.5^{\circ}$	18.5°	7.9
Group II :	153°	-55°	12.5°	12.5

The palaeomagnetic significance of these figures will be interpreted in the next chapter. At this point it is interesting to note that the mean directions for each group are diametrically opposite to one another within less than 10°.

Another interesting fact concerning the above results is that among the magnetically stable and reversely polarized specimens of group II are rocks of sedimentary origin. This is strong evidence that the reverse polarization observed in the intrusive rocks is very likely not related to the particular mineralogic

*Specimens Nos. 1-A, 1-B, 2-A and 18 were not included in either of these groups.

composition or structure of these rocks but that it is the result of ordinary thermomagnetization at a time where the ambient earth's field had an orientation opposite to its present one. The conclusions arrived at in Chapter V also support this view even though favourable structures for self-reversal had been observed by microscope examination and evidence of the coexistence of minerals of different Curie points had been found for some of the specimens.

Another conclusion which can be derived from the above results is that the Monteregian Hills probably did not cool simultaneously but their cooling extended over an interval of time during which the earth's field was reversed at least once. It is not implied here that the Monteregian Hills are necessarily of different geological age but rather that their cooling took place at different rates and that different parts of any one intrusive may have reached the Curie point of magnetite at very different times. The slow rate of cooling of the igneous masses is also indicated by the development of large crystals in some of them. This would explain the coexistence of normally and reversely polarized rocks on some of the intrusives and the fact that all the specimens collected from Mount Johnson are normally polarized whereas all of those collected from Mount St. Bruno (except for No. 23) are reversely polarized.

CHAPTER VII

PALAEOMAGNETIC INTERPRETATION AND CONCLUSIONS

A. The Significance of Remanent Magnetism in Rocks

The fact that some rocks possess permanent magnetization was reported about a hundred years ago by Melloni (1853) but it was not until Folgheraiter (1896) had measured the remanent polarization of Etruscan vases (dated 600 to 800 B.C.) that the suggestion was made to use this property for determining the approximate attitude of the earth's magnetic dipole at different epochs of the earth's history. Shortly after Folgheraiter's results were published, however, Carlheim-Gyllenskjöld (1900) disputed their validity on the basis of the observations of the geomagnetic field for the past 500 years. In the light of later polarization measurements of Recent lava flows (Chevallier, 1925) and Recent varved clays (Johnson & McNish, 1938), it also appears today that Folgheraiter's results were erroneous. Nevertheless, from the measurements made by Brunhes (1901), not long after Folgheraiter's findings, it was established that the polarization direction of a rock formation could be consistently in strong disagreement with the direction of the present earth's field.

Thus the basis of "palaeomagnetism" was set early at the beginning of the present century but this branch of science remained almost unexplored until the beginning of the last decade. It would be beyond the scope of this Chapter to review all the palaeomagnetic work done since then and, furthermore, excellent summaries of this work were made up to 1956 by Runcorn (1955) and Blackett (1956). Some of the more recent work has already been mentioned and a review of work pertinent to the present study is given in section C of this Chapter.

All the conclusions derived from palaeomagnetic studies are based on the assumption that the direction of remanent magnetization of rocks indicates the attitude of the ambient earth's field at the time the rocks acquired their remanent magnetization. In the case of igneous rocks, if it can be shown that the main component of stable magnetization is due to thermomagnetization, there should be little doubt about the question. The experiment of cooling a rock from above its Curie point to room temperature has been carried out many times by different workers and each time the ambient field was found to have dictated the orientation of magnetization in the rock after the cooling. Furthermore, it has been shown by magnetization measurements of contemporaneous lavas (e.g. Chevallier, 1925) that the remanent magnetization of these rocks is consistently parallel to the direction of the ambient earth's field. Except for the isolated case of the Haruna rocks mentioned earlier (p.64) the polarity of the magnetization vector in the rocks has always been found to be normal. In the case of recently deposited sediments, such as varved clays, it has been observed* that the magnetization vector is always pointing to the magnetic North but that the angle of its inclination is often smaller than that of the ambient earth's field. Such mechanical factors as turbidity currents, particles size and shape and compaction are apparently the cause of this discrepancy.

Palaeomagnetic inferences depend also on the validity of the approximation that the earth's field is similar to that which would be produced by a dipole magnet placed at the center of the earth along the geographic axis. This approximation finds its justification in that the non-dipole components of the earth's field are averaged out over periods of 10^3 to 10^4 years and that the mean magnetic axis of the earth is coincident with its geographic axis over these intervals of time. This is suggested a priori by actual observations of the geomagnetic field during the past four or five centuries whereby it is found that the magnetic poles tend to revolve about the geographic poles once every 1,500 years or so. More convincing perhaps is the fact that the mean magnetic pole determined from the magnetization directions measured so far for Tertiary or younger rocks correspond closely to the present geographic pole. On this basis, from an estimate of the mean direction of polarization

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*Griffith's, D.H., King, R.F. & Wright, A.E.; Some Field and Laboratory Studies of the Depositional Remanence of Recent Sediments. Adv. in Phys. vol. 6, July 1957, No. 23, p. 306.

of a rock formation, one can estimate the position of the earlier geographic poles in terms of the present geographic coordinates of the sample locality at the time the rock acquired its remanent magnetization.

Thirdly, there is the question of polarity reversals within one rock formation of either sedimentary or igneous origin. This is the case with the Monteregian Hills rocks, as indicated in Chapter VI. It is mentioned above that there are good reasons to believe that the geomagnetic dipole is closely related to the axis of rotation of the earth. It has been suggested (e.g. Runcorn & Elsasser, 1954) that the earth's field may be generated by conducting fluid motions in the earth's core from a primary field. On a theoretical basis, Herzenberg (1958) established recently that such a mechanism could act as a dynamo producing a magnetic field extending outside the conductor, i.e. outside the earth's core. Furthermore, Allan (1958) recently demonstrated mathematically that if a mechanism of this type is actually responsible for the earth's dipole field, it is possible that the magnetic poles reverse without an accompanying reversal of the direction of rotation. Therefore, the fact that many igneous and sedimentary rocks have been observed to be reversely polarized "in situ" is compatible with the principles of Palaeomagnetism and does not destroy the validity of its inferences. On the other hand, even in the improbable case where all the reversely polarized rocks would be due to self-reversal mechanisms, at least the attitude if not the polarity of the earth's axis of rotation could be estimated from magnetization data. Thus, on this basis, a magnetization vector having a D of 170° and a I of 54° indicate the same pole position as another vector having a D of 350° and a I of -54.

Finally, it may be objected that the earth's field at a given point on the earth's surface may be distorted by the presence of a magnetic body or that the varying pole position with periods of about 1,500 years are not considered in palaeomagnetic studies. These objections would be very pertinent if palaeomagnetic inferences were derived from one or two samples collected within a very restricted area. However, when the same inferences are derived from a large number of specimens collected over widely separated areas, it is assumed that local causes of magnetic field distortions are averaged out. Furthermore, even in the case of a consanguinous rock series such as the Monteregian Hills, it must be realized that two different parts of the series may have cooled below their Curie point, at periods differing by as much as 10,000 years. It is thus assumed that both local and temporal causes of magnetic field distortions are averaged out if the specimens are collected in large enough number and over a wide enough area.

Holding the above assumptions true, magnetization data have been used as a tool for investigating problems such as polar wandering and continental drift or for determining the approximate age of rocks.

B. Method of Determining the Pole Positions

Assuming that the earth's magnetic field has approximately the configuration of a dipole field and given the inclination I of the magnetization vector of a rock sample, it is possible to determine the magnetic co-latitude of the sampling site by means of the dipole formula:

$$(1) \qquad \cot \psi = \tfrac{1}{2} \tan I$$

The geographic pole position (θ, ϕ) for the time at which the rock was magnetized may be computed in terms of the present geographic coordinates by the relations:*

$$(2) \qquad \cos\theta = \cos\theta' \cos\psi + \sin\theta' \sin\psi \cos D$$

$$(3) \qquad \sin(\phi-\phi') = \sin D \sin\psi / \sin\theta$$

where (θ', ϕ') are the co-latitude and longitude respectively of the collecting site position and D is the declination of the magnetization vector.

Graphical methods are well suited for the determination of θ and ϕ after the value of ψ has been calculated from the dipole formula (1). Graham (1954) described such a method, and another graphical method was used in the present study. The use of the latter method is illustrated in Fig. 23, by the working out of a hypothetical case. In this example it is assumed that the rock has a magnetization vector whose D is 300° and whose I is 60° while the sampling site is assumed to be at 40°N latitude and 85°West longitude. The magnetic co-latitude calculated from the dipole formula (1) is 49°. In Fig. 23 the center of projection corresponds to the projection of the collecting site and the present geographic pole is projected at point N_1. The magnetic pole lies along the line whose azimuth is 300°, at point M_1, 49° from the collecting site. If now the sphere is rotated by an angle of 50°

*See Creer, K.M. & al., (1957), p. 145.

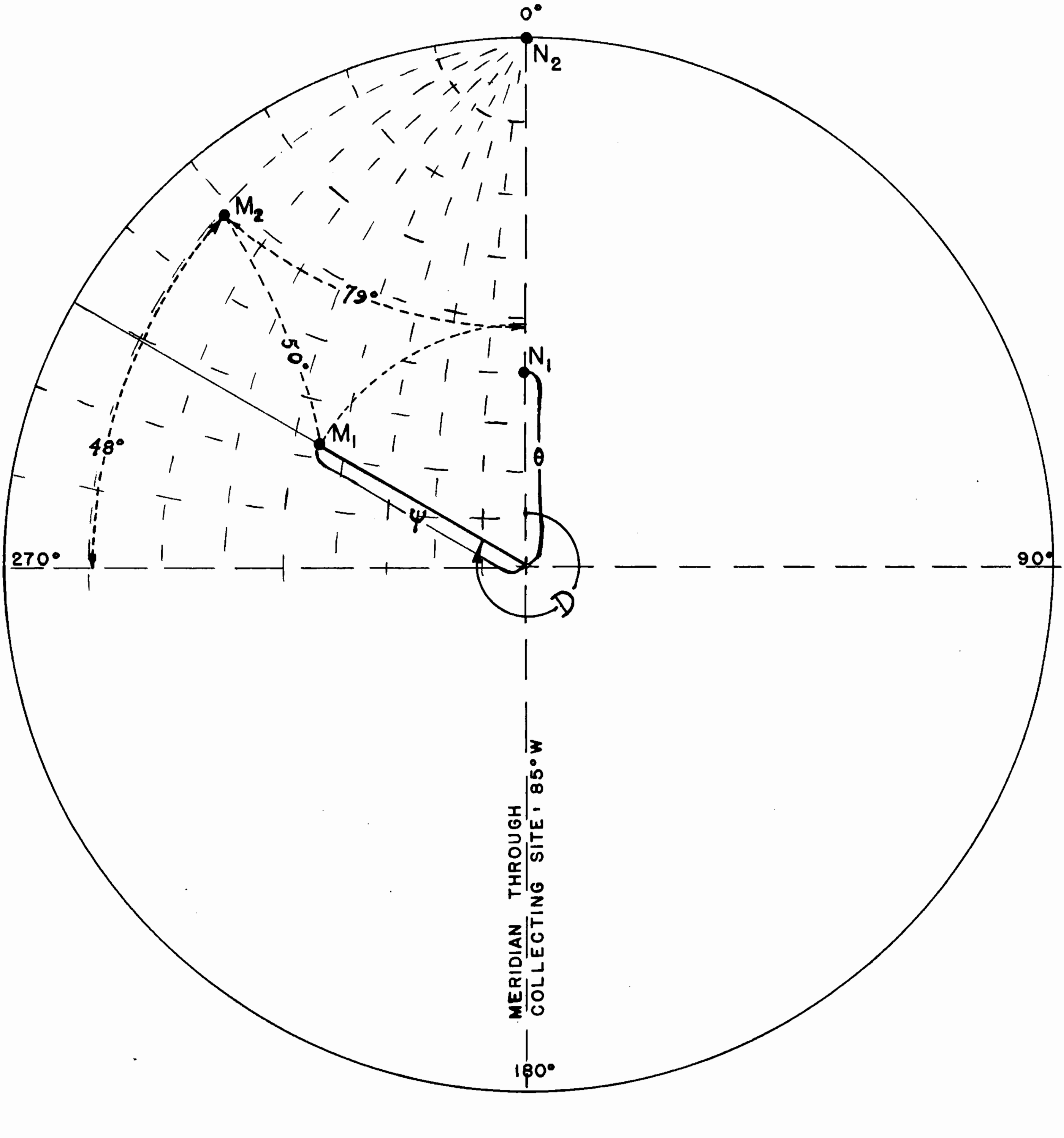

FIG. 23 - POLE POSITION DETERMINATION FOR HYPOTHETICAL CASE.
COLLECTING SITE = (40° N, 85° W)
MAGNETIZATION : D = 300°, I = 60°
POLE POSITION = (48° N, 164° W)

about the normal to the collecting site meridian, point N_1 is shifted to N_2 and point M_1, to M_2. Point M_2 corresponds to the magnetic pole position and it lies at 48°N latitude and 79° west of the 85°W meridian, i.e. at 164°W longitude.

Corresponding to the circles of confidence described about the mean polarization directions (Chapter III) are ovals on the globe inside of which the pole positions lie with a probability of 95%. The semi-axes $(\Delta\psi, \Delta\chi)$ of these ovals along and perpendicular respectively to the meridian joining the collecting sites to the pole positions are given by the expressions:*

(4) $$\Delta\chi = \alpha \sin\psi / \cos I$$

(5) $$\Delta\psi = \alpha \sin^2\psi / 2\cos^2 I = \tfrac{1}{2}\alpha(1 + 3\cos^2\psi)$$

where α is the radius of the circle of confidence (in degrees) corresponding to Θ in formula (2), p. 52, and I is the inclination of the magnetization. The semi-axes $\Delta\psi$ and $\Delta\chi$ may also be determined graphically, using a method analogous to that described for determining the pole positions.

C. Magnetization Measurements of North American Rocks

From the magnetization measurements made by various workers throughout the world, it is found that the pole positions inferred from Cretaceous or younger rocks correspond relatively closely to the present geographic poles, independently of the continent from which the rocks were collected. It is also found from the

*See Creer, K.M. & al. (1957), p. 145.

same results that, although the dipoles determined from these rocks are more or less parallel, their polarity is generally mixed within a given formation. On the other hand, it is noticeable that rocks older than Jurassic indicate magnetic (and therefore probably also geographic) poles substantially different from the present ones, and that rocks of approximately the same age but from different continents do not indicate the same pole positions. These facts are used to support the hypotheses of continental drift and polar-wandering. Because we do not know definitely the age of the Monteregian Hills, it could be misleading to compare the ancient pole positions indicated by their magnetization with similar data obtained from rocks from other continents, and to use this as evidence to study the above-mentioned theories. On the other hand, if the comparison is made with pole positions derived from dated rocks collected on the North American Continent, it should be possible to establish approximately the age of the Monteregian Hills, provided the latter prove magnetically stable.

Magnetization measurements have been made on this continent on a variety of rocks. Some of these rocks were found unsuitable for palaeomagnetic studies on account of their inconsistent or unstable magnetization. Among these are rocks measured by Hawes (1952), Morley (1952), Muehlberger & Baldwin (1958) and Balsley & Buddington (1958). On the other hand, other workers have found Pre-Cambrian or younger rocks whose magnetization was found to be consistent and very stable. A summary of these

TABLE 8

ANCIENT POLE POSITIONS INFERRED FROM NORTH AMERICAN ROCKS

Age	Formation	Mean Magnetization Direction			Collecting Site		Ancient Pole Position		Reference
		D	I	α	Lat.	Long.	Lat.	Long.	
1: Pliocene and Miocene	Columbia River Basalts	6°	+65°	9°	47N	118W	86N	53E	Creer, K.M. et al. (1957)
2: Cretaceous	Dakota Sandstone*	344	+62	7	36N	113W	77N	173W	Runcorn, S.K. (1956)
3-A: Triassic	Springdale Sandstone	338	+16	9	36N	113W	55N	107E	Irving, E.(1957C)
3-B: Triassic	Lavas near Holyoke, Mass.	10	+14	11	42N	73W	54N	90E	Du Bois, P. M. et al. (1957)
3-C: Triassic	Lavas and sediments of Connecticut	12	+14	15	42N	73W	55N	88E	Du Bois, P. M. et al. (1957)
3-D: Triassic	Brunswickian, N.J.	6	+28	3	41N	75W	63N	93E	Du Bois, P. M. et al. (1957)
4-A: Permian	Supai Beds (Graham's data)	330	-3	5	36N	113W	43N	113E	Irving, E.(1957C)
4-B: Permian	Supai Beds	133	+23	8	36N	113W	26N	119E	Runcorn, S.K. (1956)

* The published pole position (76.5N, 127E) was found incorrectly computed by Runcorn (op. cit.) from the given direction of magnetization of these rocks.

TABLE 8 (Cont'd.)

Age	Formation	Mean Magnetization Direction			Collecting Site		Ancient Pole Position		Reference
		D	I	α	Lat.	Long.	Lat.	Long.	
4-C: Permian	Supai Beds	146°	+8°	7°	36N	113W	39N	115E	Doell, R.R. (1955)
5: Pennsylvanian	Naco Sandstone*	150	-3.4	4	36N	113W	45N	112E	Runcorn, S.K.(1956)
6: Mississippian	Barnett Shales	-	-	-	-	-	41N	128E	Howell, L.G. and Martinez,J.D. (1957)
7: Silurian	Rose Hill Beds (Graham's data)	322	-39	5	40N	78W	19N	138E	Irving, E. (1957C)
7-A: Silurian	Clinton Iron Ore	-	-	-	-	-	35N	138E	Howell, L.G. and Martinez,J.D.(1958)
7-B: Cambrian	Wilburns	-	-	-	-	-	0	158E	Howell, L.G. and Martinez,J.D.(1958)
8: Precambrian	Portage Lake	282	+41	4	-	-	25N	170W	Du Bois,P.M. (1957)
9: Precambrian	Copper Harbour	294	+32	7	-	-	30N	176E	Du Bois, P.M.(1957)
10: Precambrian	Freda and None Such	285	-1	3	-	-	9N	169E	Du Bois, P.M.(1957)

*The published pole position (49N, 120E) was found incorrectly computed by Runcorn (op.cit.) from the given direction of magnetization of these rocks.

measurements appears in Table 8 together with references to the original reports. Ancient pole positions were derived from these magnetization directions and the former are plotted on a polar stereographic projection of the earth's northern hemisphere in Fig. 24. Because the Monteregian Hills rocks are certainly not older than Ordovician, the pole positions determined from the magnetization of Pre-Cambrian rocks reported by Graham (1953), Runcorn (1956), Doell (1955), DuBois (1957) and Howell & Martinez (1958) are not all reproduced in Fig. 24. In general the pole positions inferred by the directions of magnetization of these rocks are at low latitude North or South of the present Equator, and are comparable to the few examples plotted in Fig. 24.

D. Pole positions Inferred from the Monteregian Hills Rocks

The above described graphical method of computing pole positions and ovals of confidence was applied to the magnetization data obtained for the rocks from the Monteregian Hills discussed in the previous Chapters. Pole positions and ovals of confidence were determined separately from the mean direction of magnetization and circles of confidence of five different groups, namely: Yamaska (1)*, Yamaska (2), Brome, Related Rocks Normally Polarized** and Related Rocks Reversely Polarized. A summary of the computations appears in Table 9 and the pole positions and their corresponding ovals of confidence are represented in Fig. 24.

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*See page 53 for the meaning of symbols (1) and (2).

**See page 114.

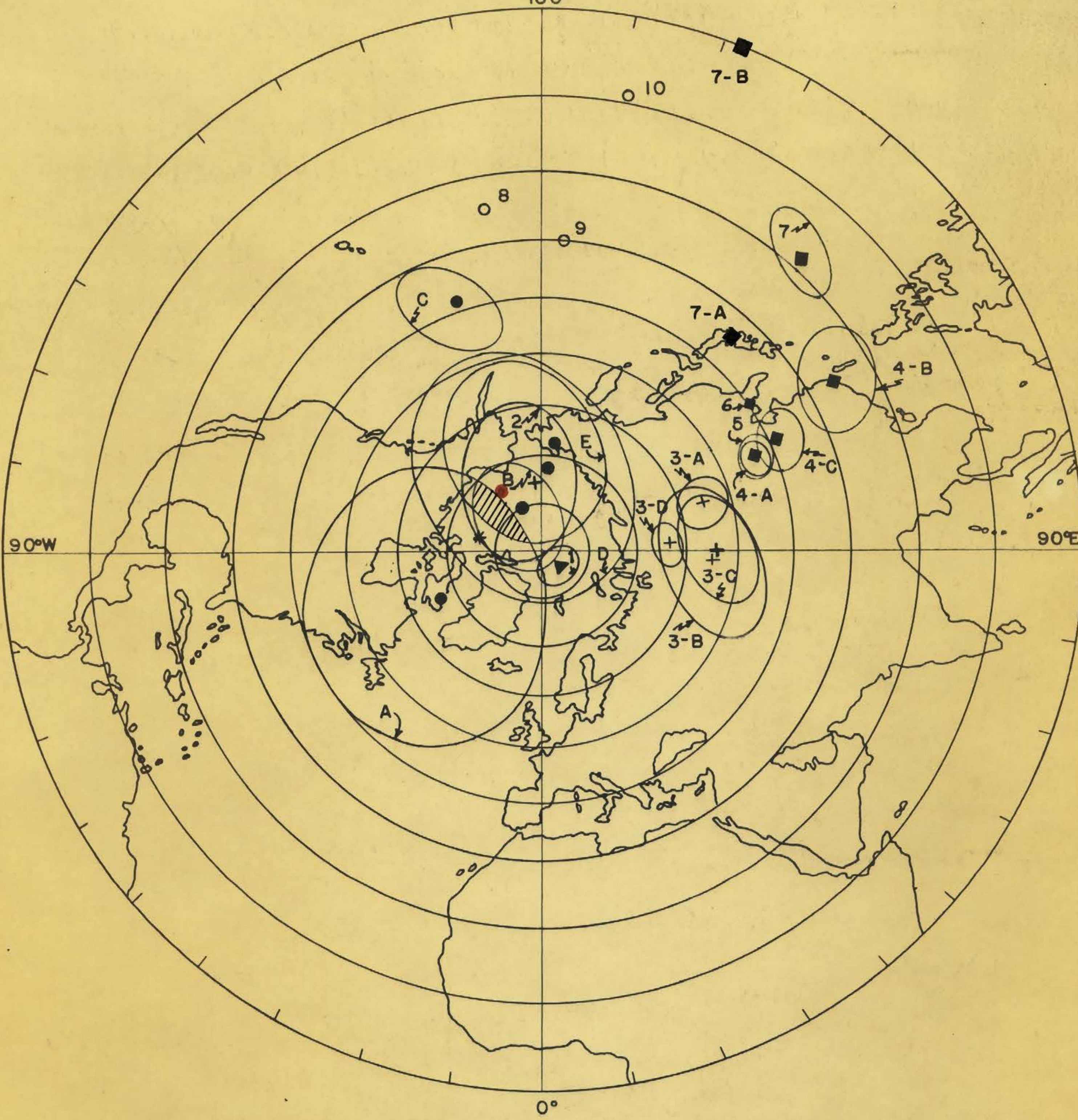

FIG. 24 – POLAR STEREOGRAPHIC PROJECTION OF ANCIENT POLES INFERRED FROM

▲ TERTIARY ROCKS + MESOZOIC ROCKS

■ PALAEOZOIC ROCKS o PRECAMBRIAN ROCKS

● MONTEREGIAN HILLS ROCKS

✳ PRESENT NORTH MAGNETIC POLE

— (LABELLING REFERS TO TABLES 8 AND 9)

TABLE 9

POLE POSITIONS INFERRED FROM THE MAGNETIZATION
OF MONTEREGIAN HILLS ROCKS

Group	Mean Magnetizations			Ancient Pole Positions			
	D	I	α	Lat.	Long.	$\Delta\chi$	$\Delta\psi$
A- Yamaska (1)*	190°	-79°	15.5°	67N	68W	25°	24°
B- Yamaska (2)*	167	-65	07.0	80N	153W	12°	9°
C- Brome	117	-46.5	08.3	38N	161W	11°	7°
D- Others, +ve	339	+56.5	18.5	73N	185W	26°	21°
E- Others, -ve	153	-55	12.5	67N	188W	19°	14°

E. <u>Interpretation of the Pole Positions Inferred by the Magnetization of the Monteregian Hills Rocks</u>

Exception being made of the Brome Mountain data, the pole positions derived from the magnetization directions of the Monteregian Hills rocks correspond almost to that of the present magnetic North pole, unlike other pole positions inferred from the magnetization directions of Triassic or older rocks.

On the other hand, the pole position suggested by the Brome Mountain rocks does not correspond to any of the pole positions computed so far from the magnetization directions of North American rocks. Because the Brome Mountain rocks were previously shown to be magnetically stable and consistent and because the oval of

*See page 53 for the meaning of symbols (1) and (2).

confidence about the corresponding pole position is relatively small, an explanation is required for this state of affairs. First it is noted that the specimens from Brome Mountain were collected over a rather restricted area, which would explain the relatively small oval of confidence about their corresponding pole position. On the other hand, the specimens were collected over an area sufficiently large to remove any possibility that the rocks could have been magnetized anomalously by lightning. Nor does it seems likely that the discrepancy is due to an error in the orientation of the specimens in the field or to an error introduced during the measurements because the number of specimens taken is sufficient to permit the assumption that these errors would cancel upon calculating the mean direction of magnetization. With these facts in mind, one possible explanation is that the rocks have been disturbed in block, subsequently to their magnetization. Although there is little geological evidence to support this hypothesis, it is recalled that Brome Mountain consists of a dual intrusion and that the rocks under discussion were collected in the part of the igneous mass which was intruded first. It is therefore suggested that the anomalous magnetization of the measured Brome rocks could be due partly to their disturbance during the second phase of the intrusion. This second phase of intrusion probably took place after the first intrusion had cooled because, according to Dresser (1906)*, it was injected between the essexite and the overlying sediments. Assuming that the pole

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*See page 10 of the present thesis.

position derived from the Brome rocks had been 160°W longitude and 60°N latitude (near the present magnetic North pole), their magnetization vector would have had a D of 140° and a I of -58°. As indicated in table 9, these two quantities are actually 117° and -46.5° respectively. The discrepancy between those two sets of values could be the result of a clockwise rotation of 18° about an axis normal to the plane striking North-South and dipping roughly 60°E. On the other hand there is no field evidence that the discrepancy between the expected and observed magnetization vectors could be due to the distortion of the earth's field by the presence of a very strongly magnetic body in the vicinity of Brome mountain. There is however the possibility that the part of the mountain from which the specimens were collected cooled over a relatively short interval of time as compared with the longer interval through which the cooling of all the Monteregian Hills took place; furthermore it is possible that the earth's field had an extreme attitude during this short interval of time and that this could account for part of the observed discrepancy between the expected and observed values of D and I. It is concluded that the pole position derived from the 11 stable specimens collected from the southern part of Brome mountain is probably not as representative of the mean earth's field attitude during the cooling of all the Monteregian Hills as are the pole positions derived from the 39 other stable specimens collected from different sites throughout the Monteregian Hills.

Among the 15 specimens collected on Yamaska mountain, those of the group labelled Yamaska (2) were previously considered (Chapter III) much more stable than those which do not belong to that group. For this reason, the pole position enclosed by oval A in Fig. 24 is probably not as reliable as the pole position encircled by oval B. However, the results obtained from both groups are compatible over a wide area in the vicinity of the present geographic North Pole.

Finally, the two groups of "Related Rocks" indicate pole positions which almost coincide. Although the ovals of confidence D and E are relatively large, the pole positions at their centers are probably more significant than any of the others because they reflect an average for rocks collected over a wide area, thus favoring the cancellation of discrepancies due to local disturbances in the ambient magnetic field at the time of their cooling or to subsequent movements in the rock. Again, the ovals of confidence about these two poles are compatible with ovals A and B over a certain area in the vicinity of the present magnetic pole.

Summing up the above paragraphs: 1- The Brome Mountain results are probably affected by local factors which appear to be mainly tectonic in nature. It is concluded that the pole position derived from these magnetization data alone are probably not indicative of the mean pole position at the time the Monteregian Hills cooled below 580°C.; 2- If the results obtained from the less stable ones among the Yamaska rocks are taken as valid, the most probable pole position inferred from all the magnetization data described in this thesis (the Brome rocks excepted) lies where the ovals of confidence overlap on the sphere (hachured area in Fig. 24), i.e. close by the present magnetic North pole, the Cretaceous pole of Runcorn and the Tertiary pole of Creer et al.;

3- If the less stable rocks among those from Yamaska as well as those from Brome are omitted from the discussion, then the most probable pole position lies inside the area of the globe which is enclosed in common by ovals B, D and E. This area is again about equidistant from the present and Tertiary poles and it contains the Cretaceous pole of Runcorn.

It might be objected that one is not justified to set aside the results of the Brome rocks or those of the less stable rocks among the Yamaska samples, and that the mean direction of magnetization of all the samples considered stable in this thesis should be used as a basis for the derivation of the most probable pole position. By assigning each of the A, C, D and E groups a weight factor equal to the number of specimens in its group (15, 11, 9 and 13 respectively), the mean direction of magnetization of all these samples was found to have a D of 327.5° and a I of 63°, the question of sign being disregarded. Using the method described in section B of this Chapter, the pole position was derived from this direction of magnetization and it was found to lie at 148°W longitude and 75°N latitude. This point is shown in red in Fig. 24. Again, it is noted that the pole position obtained on that basis is about half-way between the present and the Cretaceous poles and that it is relatively far from the Triassic poles.

It is concluded from the evidence that we have that the Monteregian Hills in general were probably not magnetized before the end of the Mesozoic. Furthermore, assuming that the rocks acquired their magnetization relatively shortly after the intrusion, it is suggested that their age is post-Triassic.

F. <u>Age Determinations of the Monteregian Rocks by Other Methods</u>

Heretofore, several attempts have been made to estimate the age of the rocks of the Monteregian Hills and of related rocks. A brief review of this work will be made, for comparison with the conclusion of the previous section.

Osborne (1935) used the halos surrounding zircon crystals in biotite as a means of comparing the age of the Nordmarkite rim in the northeast section of Mount Megantic with that of other intrusive rocks of known age. On this basis he concluded that the Nordmarkite rim was probably intruded during the Tertiary. Moreover, if the Mount Megantic Nordmarkite is genetically related to the Monteregian Hills series and if both were intruded at the same time, the latter may be considered as Tertiary, provided the method utilized by Osborne is reliable. It is generally accepted today however that this method of dating rocks is subject to considerable error and, on the other hand, there is no definite proof that the Nordmarkite of Mount Megantic belongs to the Monteregian Hills series. Therefore, Osborne's results cannot be considered here as a thoroughly sound basis for assuming the validity of the results described in the previous section of this Chapter.

Using the Helium method, Urry (1938) estimated the age of a Tinguaite sample from Mount Royal as 57 ± 1.5 million years. He also gives (ibid.) 60 to 80 million years as an estimate of the age of the same rock by the lead method. Urry gives no details describing the lead method be utilized. These age estimates would place the intrusion of Mount Royal and probably of the other Monteregian Hills near the end of the Tertiary or the beginning of the Mesozoic.

Urry's results were disputed by Lyons et al. (1957) in the light of results obtained by the lead-alpha method (also known as Larsen's method) for the zircon in biotite in a specimen of tinguaite from Mount Royal. Their estimate of 224 million years would place the intrusion of Mount Royal in the Carboniferous. In discussing the discrepancy between their results and those obtained by Urry, they state: "Because of the well-known difficulties inherent in the helium method, ... the odds that the Monteregian Hills are late Palaeozoic rather than Tertiary are overwhelming." On the other hand, Grunenfelder & Silver (1958) have shown recently that the lead-alpha method is itself subject to a considerable degree of error and that its tendency is to indicate ages older than the rocks actually have. Grunenfelder & Silver's conclusion is based on a comparison of the ages obtained for a given rock by the lead-alpha, (450 million years) the potassium-argon and the rubidium-strontium methods (250 to 290 million years).

Hurley & Fairbairn (1958) recently gave an estimate of

145 million years for the age of a sample of okaite from Oka, Quebec. This estimate was obtained by the potassium-argon method. If this rock is, as it is believed to be, related to the Monteregian Hills, the latter would therefore have been intruded during the Jurassic.

Dr. R.K. Wanless of the Geological Survey of Canada has just completed the age determination of a specimen of essexite from Brome Mountain by the potassium-argon method. According to his results, Brome Mountain and probably the other Monteregian Hills were intruded 115 to 140 million years ago*, i.e. during Cretaceous or Jurassic times.

It is interesting to note that the ages suggested from the observations of Osborne, Urry, Hurley, Fairbairn and Wanless are in fair agreement with those obtained from the magnetization data discussed in the present thesis whereas the age obtained by Lyons et al. (op. cit.) is in sharp disagreement with them. As mentioned above, indications that the age estimate of Lyons et al. is somewhat exaggerated. On the other hand the writer does not consider himself competent to discuss authoritatively the respective merits of the various radiogenic methods mentioned above, and therefore it should not be interpreted that in his mind the age indicated by the magnetization data can be used as a strong argument against the validity of the age estimate given by Lyons et al. However, it is suggested that if, when more data for plutonic rocks are available, the ages indicated by magnetization data correspond consistently

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*These results are reproduced here prior to their publication with Dr. Wanless' kind permission.

with the ages indicated by some proved radiogenic method, the former could be valuable as a rough and rapid check for the latter.

G. Summary

The negative anomalies indicated on the aeromagnetic maps of Yamaska and Brome Mountains first attracted our attention inasmuch as we were interested in finding their cause. The topography of the mountains was found to have little bearing on the "anomalous" polarity of the anomalies. The remanent magnetization measurements of a suite of oriented specimens from these localities indicated, on the other hand, that some of the specimens were reversely polarized "in situ". The problem then arose of why some of the specimens were reversely polarized and others normally polarized "in situ". It was found later that the normally polarized rocks were relatively less stable than the reversely polarized ones and that they had probably acquired their normal component of polarization subsequently to their cooling in the earth's field by an isothermal process. It was shown also that the reversely polarized rocks probably acquired the stable component of their remanent polarization at the time of their cooling in the ambient earth's field rather than by the effect of lightning. The next problem was to find whether the reverse magnetization was due to a reversal of the earth's field at the time the rock cooled or whether a self-reversal mechanism inherent in the rock mineralogical composition was responsible for this phenomenon. Observations of polished sections, and Curie point determinations were made first in an effort to elucidate this question. Although it was not possible to derive any definite conclusions from these observations, little if any evidence was found in them to support the view that a self-reversal mechanism was the cause of the present case of reverse polarization. The next approach to the problem consisted in determining the magnetization directions of oriented specimens collected on other Monteregian Hills and from sediments adjacent to the igneous cores of these mountains. Among the facts derived from these measurements, the reverse polarization of some of the sediments furnished almost incontroversial evidence that the present case of reverse polarization is not related to the mineralogical composition of the igneous rocks. The polarization reversals are rather probably related to the reversal of the earth's field from its present direction at the time the rock cooled. A statistical analysis of the magnetization direction measurements was made and from the mean directions of magnetization obtained, the positions of the magnetic poles at the cooling time of the rocks were computed in terms of the present geographic coordinates. These pole positions were then compared with the pole positions derived from the magnetization studies of dated rocks from other localities in North America. As a result of this comparison, it is concluded that the Monteregian Hills were probably intruded during the Cretaceous or later. Although we can decipher no magnetic indication that they could not have cooled during Jurassic time, they were not likely cooled during or before Triassic time according to the magnetic data. This conclusion is in fair agreement with age determinations made by different radiogenic methods.

H. Suggestions for Further Work

A large percentage of time was spent in the present study in designing and building basic laboratory equipment and in experimenting on the suitability of the Monteregian Hills rocks for palaeomagnetic studies. This necessarily limited the amount of time that could reasonably be spent on the collection, preparation and repeated measurements of a large number of field specimens. Even though it is felt that sufficient data were secured to suggest useful conclusions, it is without doubt that the magnetization measurement of a larger number of oriented specimens of this rock series would be highly desirable to strengthen the validity of these conclusions. Oriented specimens from Mount Royal, the Oka district, the basic rocks of Mount Megantic and from numerous dykes consanguinous with the Monteregian Hills series would supply adequate material for an extension of the present study. The work could also be extended to granitic rocks for which the age has been determined by either field evidence or by radiogenic methods.

The conclusions arrived at in the present study depend partly on pole positions derived from magnetization measurements of sedimentary or volcanic rocks which do not belong to the Monteregian Hills series. Because of this, the availability of more data of this type could have important bearings on the validity of the above-mentioned conclusions.

Finally, more detailed studies on the mineralogy of the ferromagnetic components contained in the Monteregian Hills series could possibly bring new light to the problem of their reverse magnetization "in situ". Curie point, saturation magnetization and coercivity are suggested as very diagnostic mineral properties for this type of studies

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APPENDIX I

It was stated in Chapter II that, theoretically, only two of the three sets of values (I_α , α), (I_β , β) and (I_γ , γ) are necessary to define completely the magnetization of a rock cube. More specifically, it can be stated that in theory only two of the three angles α, β and γ are necessary to determine the declination D and the inclination I of the magnetic vector. However, since an error of 5° is assumed possible in the measurement of the angles α, β and γ , if the determination of D and I is based only on two of these three angles, it is possible that the declination and inclination thus obtained differ by more than 5° from their true value. In order to reduce this error as much as possible, the three angles α , β and γ were used in the present study.

Since a graphical method was used to compute D and I, the same method will be used here to show that the possible error for D and I is considerably reduced if use is made of the three measured angles α , β and γ in this computation. Let us assume for example that the true declination of a magnetic vector is 130° and that its true inclination is 44°. It is easy to see on a stereographic projection that the theoretical values of α , β and γ would be 130°, 52° and 326° respectively for this vector. This is shown in Fig. A-1 below. In practice, however, the process is reversed, i.e. the three angles are measured and D and I are derived from

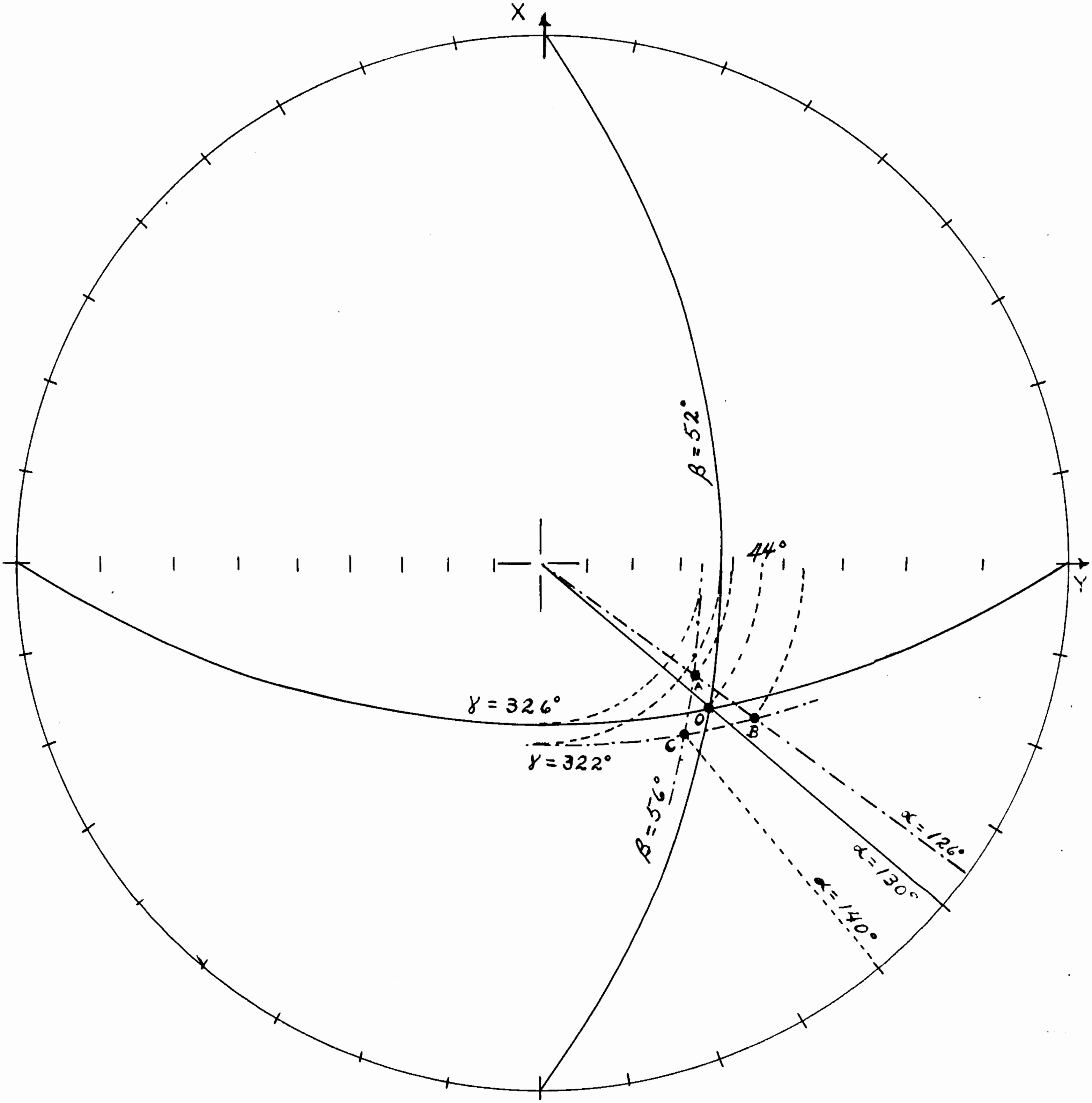

FIG. A–1. EXAMPLE OF DECLINATION AND INCLINATION DETERMINATION them. In the present case the measured angles could have been, say, 126°, 56° and 322° respectively, since a possible error of 5° is considered in the measurements. It is shown in Fig. A-1 that the great circles corresponding to these angles on a stereographic projection do not intersect at one point as it was the case before but that the intersections of any two of them form the corners of a spherical triangle ABC projected on the horizontal plane. If each of these corners is used to determine D and I (which would be equivalent to using only two of the three angles α , β and γ) the pairs of values obtained for D and I are (126°, 50°), (126°, 36°) and (140°, 45°) for corners A, B and C respectively. If it is equally probable that any of these pairs of values approaches the true values of D and I, the possible error in using any one of them is fairly large. We shall define the possible error as the difference in absolute value between the D and the I defining a given point inside the triangle ABC and the D and the I defining any one of the three points forming the corners of triangle ABC. It seems more probable that a point inside the triangle ABC will represent better the true values of D and I. In practice we do not know however how far off α , β , and γ are from their theoretical values and whether they are larger or smaller than the latter. For these reasons it is logical to distribute the error equally over each of them. On a stereographic projection this is done by revolving by an equal angle about its main diameter each of the circles representing α , β , and γ , respectively. The value of this angle is correct when the three great circles intersect at one point. In the present case it was found that the angle is 4^{o} and that it is clockwise in the case of α and γ but counterclockwise in the case of β. If the point O of intersection of the revolved circles is used to determine D and I, it is found that the latter are 130^{o} and 44^{o} respectively with a possible error of 10^{o} for D and of 6^{o} for I. As another example let us assume that the values of 133^{o}, 46^{o} and 331^{o} would have been the magnetometer readings for α, β and γ, respectively. The values of D and I obtained with these angles by the method described above are 129^{o} and 43^{o} respectively. Examples of this type could be set almost ad infinitum and there is no doubt that in certain cases, in particular when only one of the measured angles is off its theoretical value, one of the corners of triangle ABC could be used to determine D and I much more accurately than any point inside the triangle. Even in those cases however one would not know in general which of the three corners is to be used, and the possible error would still be smaller if a point at the center of the triangle would be used. An exception to this rule would be the case where it is probable that one of the three angles is more likely to be correct than the other two or vice versa. These cases are met when the magnetic vector is almost horizontal and vertical respectively. In the first case I_{α} is much larger than I_{β} and I_{γ}, and consequently angle α may be accurately better determined than angles β and γ. In the second case, the horizontal component is very small as compared with the vertical component and angle α may not be measured as accurately as angles β and γ.

The fact that very often the great circles representing the three angles α, β and γ do not intersect at one point is partly due to errors in the measurements but mostly to inhomogeneity in the ferromagnetic mineral distribution throughout the rock cube. This factor may be greatly eliminated however if the cube is spun both clockwise and counterclockwise about its three axes. Since the motor driving the spinner is an ordinary A.C. motor, its sense of revolution could not easily be reversed. The equivalent result was reached however by spinning the cubes first in the positions given in Fig. 4 of Chapter II for the clockwise angles and then in the positions shown in Fig. A-2 below for the counterclockwise angles. The latter will be referred to as α', β' and γ'. By a comparison of Figs. 4-B, 4-C and 4-D with Figs. A-2(A), A-2(B) and A-2(C) respectively, it is easy to derive that, for a homogeneous rock cube, $\alpha = 360^{\circ} - \alpha'$, $\beta = 360^{\circ} - \beta'$ and $\gamma = 360^{\circ} - \gamma'$. If the rock is not homogeneous, then:

$$\overline{\alpha} = \left[\frac{\alpha + 360^{\circ} - \alpha'}{2} \right] \quad \text{, etc.,}$$

where $\overline{\alpha}$ is a mean value for α.

The importance of magnetic inhomogeneity as a factor increasing the possible error in polarization measurements is illustrated by the following angles which were obtained in the measurement of cube No. 18-1 to which reference is made elsewhere in this thesis:

α = 009°	α' = 308°	$\bar{\alpha}$ = 030.5°
β = 004°	β' = 329°	$\bar{\beta}$ = 017.5°
γ = 057°	γ' = 270°	$\bar{\gamma}$ = 073.5°

By plotting the first of these sets of angles on a stereographic net and by using the method described in the previous pages to determine the most probable values for the inclination and the declination, a D of 29° with a possible error of 55° and a I of 13° with a possible error of 20° were obtained. On the other hand, by plotting the angles 360°- α', 360°- β' and 360°- γ', the most probable D obtainable from this data is 37° with a possible error of 33° and the most probable I is 11° with a possible error of 15°. Finally, if the mean values $\bar{\alpha}$, $\bar{\beta}$ and $\bar{\gamma}$ are plotted, a D of 32° with a possible error of 8° and a I of 12° with a possible error of 4° are determined as the most

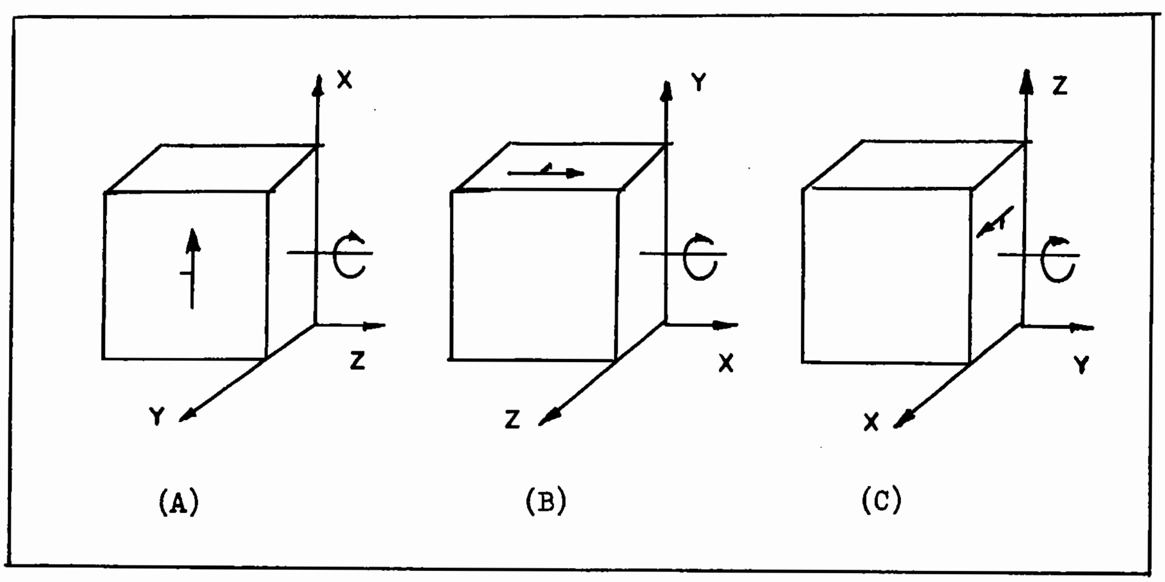

Fig. A-2: Cube positions for the measurements of α'(A), β'(B) and γ'(C).

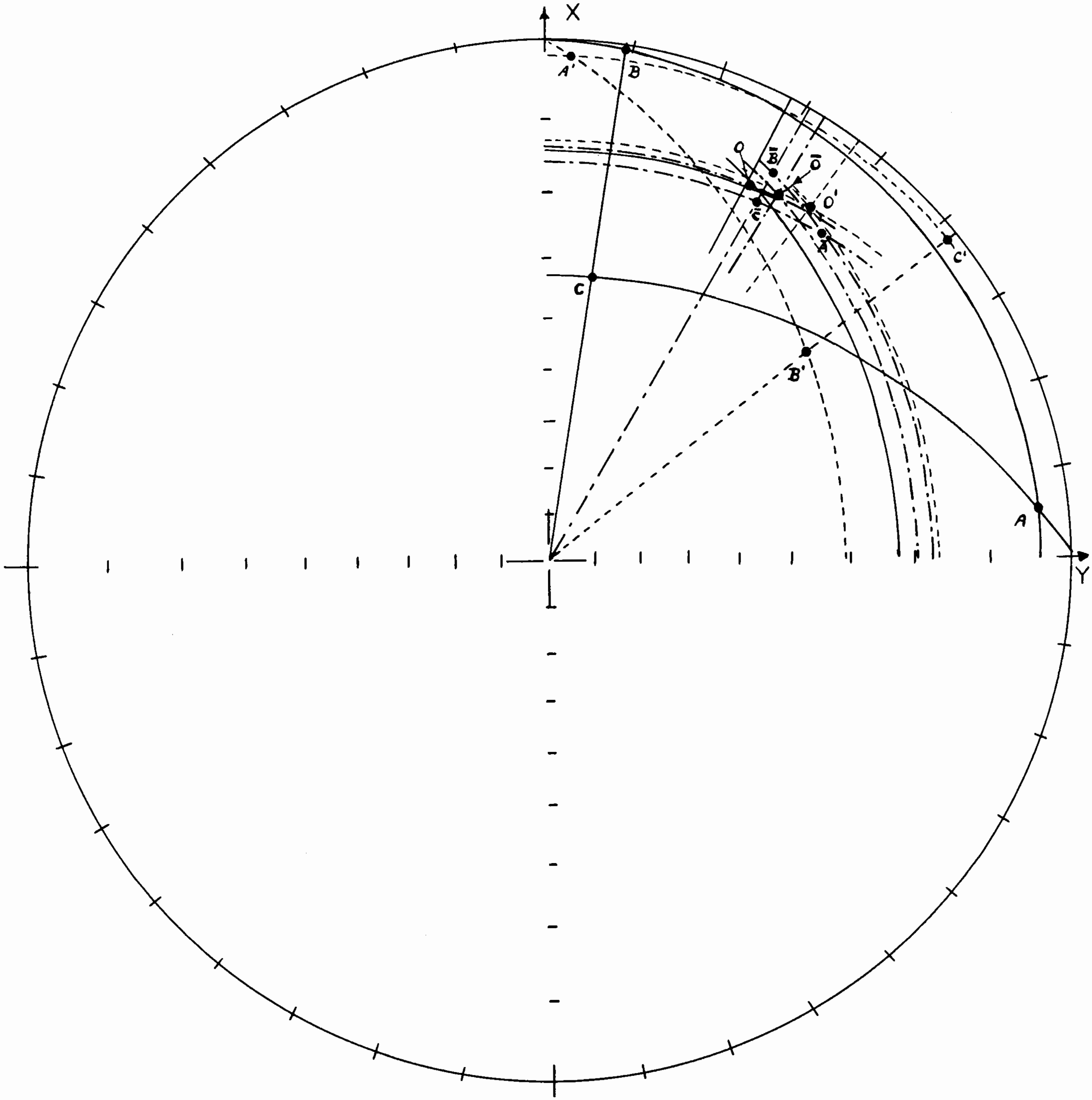

FIG. A-3: REDUCTION OF POSSIBLE ERROR BY CLOCKWISE AND COUNTERCLOCKWISE SPINNING OF CUBE NO. 18-1 probable declination and inclination of the magnetic vector of this cube. Fig. A-3 illustrates the above described operations.

The reduction of the data found in Table A-1 below was performed according to the principles developped in the previous paragraphs. Tables 2 to 5 inclusive of Chapters II and III give a summary of these results where the means of two or three cubes cut out of one sample are given as the most probable representation of the magnetization of that sample. The intensities listed in Tables 2 to 5 are also the arithmetic means of the intensities of the individual cubes representing each specimen.

TABLE A-1

REMANENT MAGNETOMETER READINGS FOR ROCKS FROM YAMASKA AND BROME MOUNTAINS

Cube No.	Before Magnetic Washing								After Magnetic Washing							
	α	β	γ	I_α	I_β	I_γ	D	I	α	β	γ	I_α	I_β	I_γ	D	I
36-1	143	003	265	4,800	3,000	3,000	140	+03	123	323	208	2,670	2,475	1,980	120	-38
36-2	148	015	265	3,570	1,950	2,100	150	+06	133	323	200	1,980	1,800	2,100	123	-43
37-1	163	318	241	11,920	11,076	12,700	158	-22	126	313	193	2,760	5,100	4,500	117	-51
37-2	168	308	238	11,230	11,230	13,510	162	-26	125	308	201	2,865	9,450	5,250	121	-51
37-B-1	128	348	233	9,266	13,350	8,670	121	-16	123	318	205	3,000	7,200	6,945	120	-42
37-B-2	131	348	239	14,230	13,416	10,233	125	-15	118	318	203	4,275	8,175	3,720	117	-42
38-1	148	333	236	5,770	5,148	5,148	142	-23	113	313	200	2,130	2,610	2,250	112	-46
38-2	146	330	241	6,396	5,928	12,355	143	-21	113	315	205	2,295	6,375	3,000	114	-43
38-B-1	118	338	208	4,992	5,772	8,049	111	-27	095	323	182	3,225	4,200	4,905	093	-42
38-B-2	126	343	220	11,169	11,169	11,169	119	-21	103	313	191	1,815	3,150	4,095	102	-48

TABLE A-1 (Cont'd.)

Cube No.	Before Magnetic Washing								After Magnetic Washing							
	α	β	γ	I_α	I_β	I_γ	D	I	α	β	γ	I_α	I_β	I_γ	D	I
39-1	153	336	248	37,515	28,536	42,066	148	-16	118	318	203	4,050	4,875	5,100	115	-42
39-2	128	346	233	23,493	22,632	15,559	121	-17	103	323	191	3,300	3,975	3,870	102	-40
40-1	008	103	065	35,301	30,135	38,437	358	+34	138	287	198	323	295	540	136	-67
40-2	018	098	060	27,367	22,140	30,258	004	+42	131	288	208	684	634	810	136	-59
41-1	018	103	076	2,095	1,980	2,682	001	+25	133	306	195	344	504	940	124	-56
41-2	053	086	053	1,865	2,160	2,441	028	+58	111	305	171	765	589	933	98	-64
42-1	038	243	121	86,100	50,430	95,940	045	-18	136	311	221	3,975	4,920	4,515	136	-39
42-2	035	336	118	85,485	52,275	95,940	041	-20	141	309	227	5,775	7,500	7,785	141	-37
43-1	148	323	238	38,130	37,884	46,494	146	-25	153	313	223	3,525	4,800	4,575	143	-34
43-2	151	316	230	34,440	34,440	49,815	147	-32	118	313	215	4,650	6,300	5,250	120	-39
43-3	153	321	231	38,130	41,205	51,660	147	-28	148	316	228	21,709	25,522	25,522	146	-32

TABLE A-1 (Cont'd.)

Cube No.	Before Magnetic Washing								After Magnetic Washing							
	α	β	γ	I_α	I_β	I_γ	D	I	α	β	γ	I_α	I_β	I_γ	D	I
44-1	145	323	231	7,176	8,767	7,800	141	-29	103	323	183	2,026	2,182	2,070	098	-45
44-2	146	330	228	6,240	6,302	5,678	139	-27	98	326	163	2,217	1,782	1,782	086	-45
44-3	151	326	236	8,268	8,330	8,268	145	-29	78	328	158	1,692	1,692	1,864	077	-31
53-1	078	353	176	720	601	799	088	-15	166	276	216	1,656	957	1,004	167	-55
53-2	083	013	153	702	468	342	082	-14	161	264	218	1,512	979	1,242	172	-63
55-1	256	220	206	1,249	1,965	1,854	252	-36	158	268	218	156	176	137	167	-61
55-2	268	220	193	1,062	1,360	1,314	264	-34	183	283	198	162	237	162	173	-61
67-1	146	308	213	18,096	34,320	15,930	140	-45	153	268	206	11,008	49,507	56,272	160	-72
67-2	150	308	223	22,755	29,766	30,135	146	-38	171	273	208	28,105	46,002	56,272	172	-64
67-3	146	298	218	20,418	30,381	33,825	147	-46	154	283	200	28,413	53,812	61,807	153	-65
71-1	218	248	211	21,621	27,362	30,420	217	-54	176	278	210	8,860	11,793	14,788	173	-54
71-2	223	248	204	21,653	38,745	40,897	222	-58	169	273	203	8,299	16,723	18,002	170	-68

TABLE A-1 (Cont'd.)

Cube No.	Before Magnetic Washing								After Magnetic Washing							
	α	β	γ	I_α	I_β	I_γ	D	I	α	β	γ	I_α	I_β	I_γ	D	I
72-1	213	261	203	23,119	55,965	59,163	211	-67	168	287	218	11,013	14,352	16,473	163	-48
72-2	208	261	203	14,664	76,875	83,025	205	-67	158	284	208	12,604	17,004	18,501	156	-59
74-1	117	311	199	19,593	27,456	30,264	115	-50	138	284	192	8,268	20,233	22,386	138	-72
74-2	108	318	198	20,904	16,692	15,288	108	-42	120	288	192	8,455	18,158	18,158	121	-69
87-1	063	083	058	3,044	3,667	4,743	040	+48	018	273	156	592	1,339	1,599	014	-68
87-2	058	086	043	2,562	3,480	3,863	040	+58	048	305	158	856	1,520	1,919	052	-74
87-3	043	078	053	2,830	3,480	4,093	029	+46	020	268	158	720	965	1,362	010	-52
103-1	235	135	337	53,074	53,136	39,913	239	+45	222	200	240	2,490	2,355	1,680	226	-17
103-2	240	141	337	52,336	51,352	38,007	244	+40	229	209	254	2,448	2,210	2,149	222	-17
103-3	242	144	333	53,935	55,657	37,330	244	+36	232	209	245	1,966	1,874	1,813	228	-20
104-1	018	316	105	51,229	12,177	54,612	018	-15	353	261	149	979	1,641	1,973	351	-55
104-2	018	308	107	56,395	22,816	57,933	017	-18	333	253	153	1,040	1,717	1,814	331	-58

TABLE A-1 (Cont'd.)

Cube No.	Before Magnetic Washing								After Magnetic Washing							
	α	β	γ	I_α	I_β	I_γ	D	I	α	β	γ	I_α	I_β	I_γ	D	I
105-1	148	265	188	643	1,763	2,248	213	-80	145	288	199	1,063	1,422	1,790	143	-65
105-2	188	262	206	1,303	2,196	2,822	191	-61	160	278	201	1,117	1,652	2,025	160	-68
105-3	118	295	190	1,494	2,657	3,225	118	-65	142	290	198	1,193	1,797	2,115	140	-64
111-1	316	133	043	2,004	3,595	3,557	316	+36	008	278	178	200	2,160	2,840	018	-82
111-2	321	133	043	2,317	4,131	3,863	320	+37	048	321	178	1,415	1,933	2,268	064	-53
111-3	325	131	038	2,409	5,431	5,278	320	+40	338	268	163	464	1,584	2,376	343	-75
113-1	260	163	343	23,985	24,907	20,295	263	+20	288	235	178	1,729	2,285	2,304	282	-62
113-2	278	183	351	16,605	16,605	8,917	268	+07	346	253	151	1,872	3,204	3,211	340	-54
113-3	263	163	338	19,680	19,680	11,992	263	+17	328	251	163	1,602	3,193	3,204	322	-64
120-1	220	251	207	13,350	30,150	30,150	219	-59	200	258	210	10,380	12,780	12,750	200	-59
120-2	223	240	196	11,316	27,675	27,675	230	-59	215	263	203	15,195	49,507	56,580	211	-68
120-3	218	239	178	9,225	25,092	26,814	235	-71	205	263	200	20,910	48,277	59,796	200	-70

TABLE A-1 (Cont'd.)

Cube No.	Before Magnetic Washing								After Magnetic Washing							
	α	β	γ	I_α	I_β	I_γ	D	I	α	β	γ	I_α	I_β	I_γ	D	I
121-1	238	263	196	15,675	25,522	24,907	230	-63	179	263	193	7,564	25,270	27,982	189	-70
121-2	238	259	203	9,655	21,525	22,017	229	-58	185	263	188	29,784	24,108	25,830	194	-75
121-3	232	247	202	10,639	24,231	24,292	230	-50	211	258	198	7,995	23,493	25,030	211	-69
138-1	091	058	025	1,220	1,584	1,123	070	+44	315	243	158	231	1,422	1,897	312	-57
138-2	091	066	028	1,274	1,882	946	076	+49	302	253	173	100	1,242	1,098	297	-73

APPENDIX II

For the specimens whose magnetization was determined with the spinner type magnetometer the inclinations and declinations with respect to the X axis were computed according to the graphical method described in Appendix I. The strike of the X axis was then added to the declination thus obtained and the sum corresponds to the true declination of the specimen.

In the cases where the magnetization was determined by means of the astatic magnetometer, the components I_x, I_y and I_z* were measured and the declination with respect to the X axis was calculated according to the formula:

$$(1) \quad \tan D = I_y/I_x ,$$

and the true declination was obtained by adding the strike of the X axis. The inclination was calculated according to the expression:

$$(2) \quad \cot I = I_x/(I_z \cos D)$$

The specimens, the strike of their X axes and the actual magnetometers readings are listed in Table A-2 below.

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*See fig 4-A, Chapter II for the significance of these symbols.

TABLE A-2

REMANENT MAGNETOMETER READINGS FOR OTHER RELATED ROCKS

Cube No.	Strike	Before Magnetic Washing								After Magnetic Washing							
		α	β	γ	I_α	I_β	I_γ	D	I	α	β	γ	I_α	I_β	I_γ	D	I
1-A-1	188	-	-	-	-	-	-	204	+63	-	-	-	-	-	-	210	+60
1-A-2	"	-	-	-	-	-	-	204	+51	-	-	-	-	-	-	211	+53
1-B-1	310	-	-	-	-	-	-	033	+37	-	-	-	-	-	-	032	+45
1-B-2	"	-	-	-	-	-	-	032	+35	-	-	-	-	-	-	032	+34
2-A-1	344	074	313	153	780	451	451	053	-40	-	-	-	-	-	-	334	-10
2-A-2	"	074	353	139	428	344	344	062	-11	-	-	-	-	-	-	331	-06
2-B-1	358	303	183	091	2,620	1,840	2,215	303	+02	-	-	-	-	-	-	228	-77
2-B-2	"	303	173	083	2,496	1,560	2,215	302	-05	-	-	-	-	-	-	306	-36
3-1	184	-	-	-	-	-	-	262	-41	-	-	-	-	-	-	163	-39
3-2	"	-	-	-	-	-	-	268	-39	-	-	-	-	-	-	154	-20
4-1	124	-	-	-	-	-	-	072	-01	-	-	-	-	-	-	082	+26
4-2	"	-	-	-	-	-	-	149	+49	-	-	-	-	-	-	268	+36
5-A-1	190	158	087	319	190	256	190	352	+56	-	-	-	-	-	-	012	+27
5-A-2	"	158	080	308	232	192	251	354	+44	-	-	-	-	-	-	012	+29

TABLE A-2 (Cont'd.)

Cube No.	Strike	Before Magnetic Washing								After Magnetic Washing							
		α	β	γ	I_α	I_β	I_γ	D	I	α	β	γ	I_α	I_β	I_γ	D	I
5-B-1	197	-	-	-	-	-	-	309	+63	-	-	-	-	-	-	118	+14
5-B-2	"	-	-	-	-	-	-	306	+70	-	-	-	-	-	-	152	+29
6-1	076	-	-	-	-	-	-	105	-10	-	-	-	-	-	-	051	-72
6-2	"	-	-	-	-	-	-	101	-22	-	-	-	-	-	-	045	-70
7-A-1	015	-	-	-	-	-	-	193	+73	-	-	-	-	-	-	326	-14
7-A-2	"	-	-	-	-	-	-	288	+69	-	-	-	-	-	-	298	-03
7-B-1	283	102	002	301	61,254	61,008	19,311	023	+05	090	040	000	2,322	3,222	1,661	013	+40
7-B-2	"	090	004	000	51,414	51,660	14,391	013	+04	069	048	020	1,845	2,280	1,785	352	+45
7-B-3	"	094	006	315	52,275	52,115	12,669	018	+06	080	035	367	2,025	2,625	1,815	005	+38
7-C-1	319	-	-	-	-	-	-	005	+68	-	-	-	-	-	-	355	+68
7-C-2	"	-	-	-	-	-	-	359	+63	-	-	-	-	-	-	032	+46
8-1	229	-	-	-	-	-	-	047	+06	-	-	-	-	-	-	092	-52
8-2	"	-	-	-	-	-	-	038	+44	-	-	-	-	-	-	059	+27
9-1	328	-	-	-	-	-	-	177	+24	-	-	-	-	-	-	280	-26
9-2	"	-	-	-	-	-	-	169	+30	-	-	-	-	-	-	287	-26

TABLE A-2 (Cont'd.)

Cube No.	Strike	Before Magnetic Washing								After Magnetic Washing							
		α	β	γ	I_α	I_β	I_γ	D	I	α	β	γ	I_α	I_β	I_γ	D	I
10-1	070	038	292	160	342	343	615	111	-61	057	306	183	175	337	165	142	-65
10-2	"	044	279	164	126	266	176	112	-72	060	305	164	167	290	172	134	-54
10-3	"	058	304	163	256	590	428	130	-55	050	295	175	156	357	245	127	-68
11-1	333	302	160	058	4,462	4,150	3,182	274	+17	278	172	084	565	716	271	254	+01
11-2	"	303	158	078	5,460	4,462	3,869	284	+12	301	182	095	581	578	380	272	-03
11-3	"	306	162	081	3,120	2,621	2,621	284	+10	297	212	140	452	548	339	270	-30
12-1	170	304	168	065	481	481	252	112	+13	346	241	125	738	551	691	153	-31
12-2	"	307	155	059	627	459	352	117	+20	354	270	138	651	623	630	147	-45
13-1	180	148	065	319	619	635	643	332	+41	124	068	328	201	342	353	311	+54
13-2	"	146	074	319	329	428	428	334	+46	131	068	324	277	443	461	317	+52
14-1	200	028	353	078	1,530	956	1,316	239	+02	321	240	127	370	441	619	167	-37
14-2	"	024	344	084	1,759	688	1,461	216	-02	327	238	129	397	446	650	169	-38
14-3	"	019	338	029	1,446	727	1,568	216	-05	320	233	134	285	420	503	161	-39

TABLE A-2 (Cont'd.)

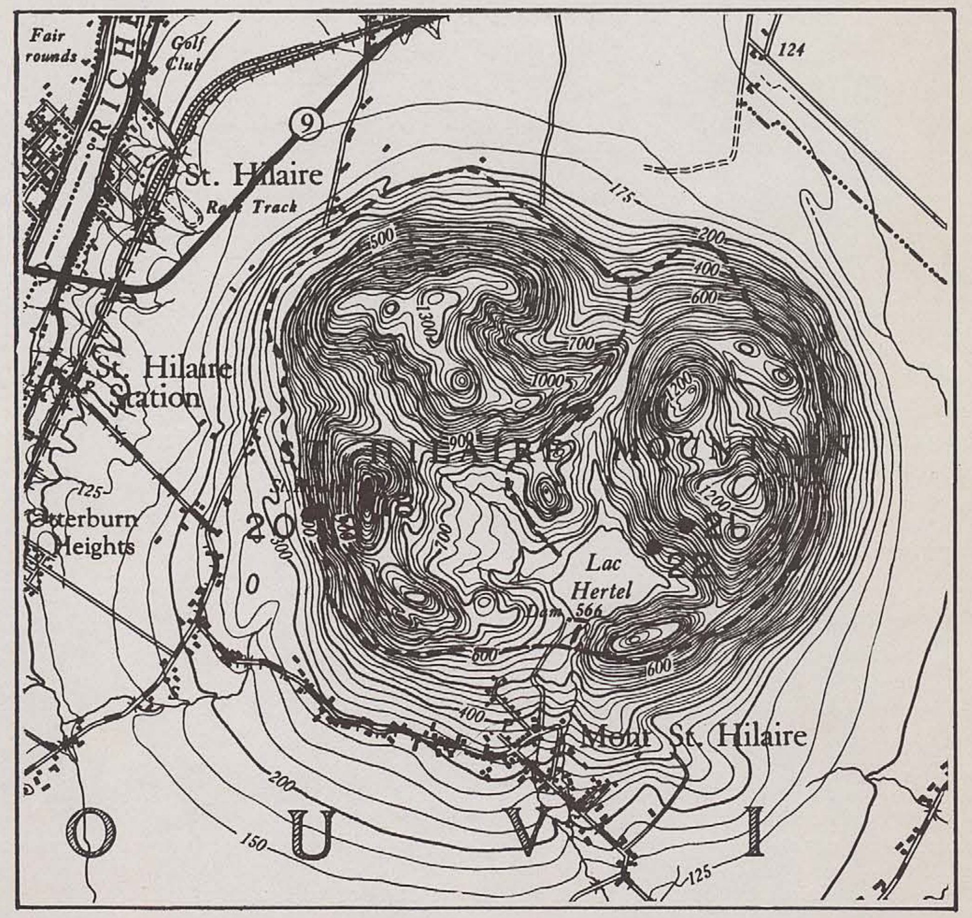
Cube No.	Strike	Before Magnetic Washing								After Magnetic Washing							
		α	β	γ	I_α	I_β	I_γ	D	I	α	β	γ	I_α	I_β	I_γ	D	I
15-1	207	-	-	-	-	-	-	074	+16	-	-	-	-	-	-	054	+36
15-2	"	-	-	-	-	-	-	080	+55	-	-	-	-	-	-	046	+57
16-1	225	080	073	353	6,211	18,573	18,696	217	+82	106	077	353	1,736	5,834	6,146	334	+74
16-2	"	081	073	352	6,273	19,557	20,541	218	+82	115	070	350	2,363	6,967	6,877	340	+70
17-1	060	277	143	018	15,621	18,450	10,332	340	+34	273	116	001	2,062	4,669	4,182	330	+64
17-2	"	278	148	018	16,359	20,172	10,332	340	+30	285	120	003	1,680	4,809	4,325	341	+63
18-1	111	030	018	073	192,478	186,472	191,620	143	+12	035	023	080	119,262	81,796	105,534	143	+11
18-2	"	030	010	082	187,330	186,757	185,900	142	+06	040	009	081	98,384	62,920	85,228	152	+07
18-3	"	031	025	068	202,202	194,766	200,486	144	+16	033	033	074	133,276	99,528	128,700	142	+17
19-1	310	-	-	-	-	-	-	299	+59	-	-	-	-	-	-	290	+19
19-2	"	-	-	-	-	-	-	-	+90	-	-	-	-	-	-	304	+26
20-1	066	253	258	183	158	241	371	320	+77	-	-	-	-	-	-	154	-60
20-2	066	253	246	200	238	202	331	313	-58	-	-	-	-	-	-	183	-61
21-1	250	012	082	010	2,621	1,840	2,215	268	+75	260	236	184	616	405	581	150	-59
21-2	"	005	073	015	2,496	1,560	2,215	266	+66	256	220	184	635	115	473	149	-46

TABLE A-2 (Cont'd.)

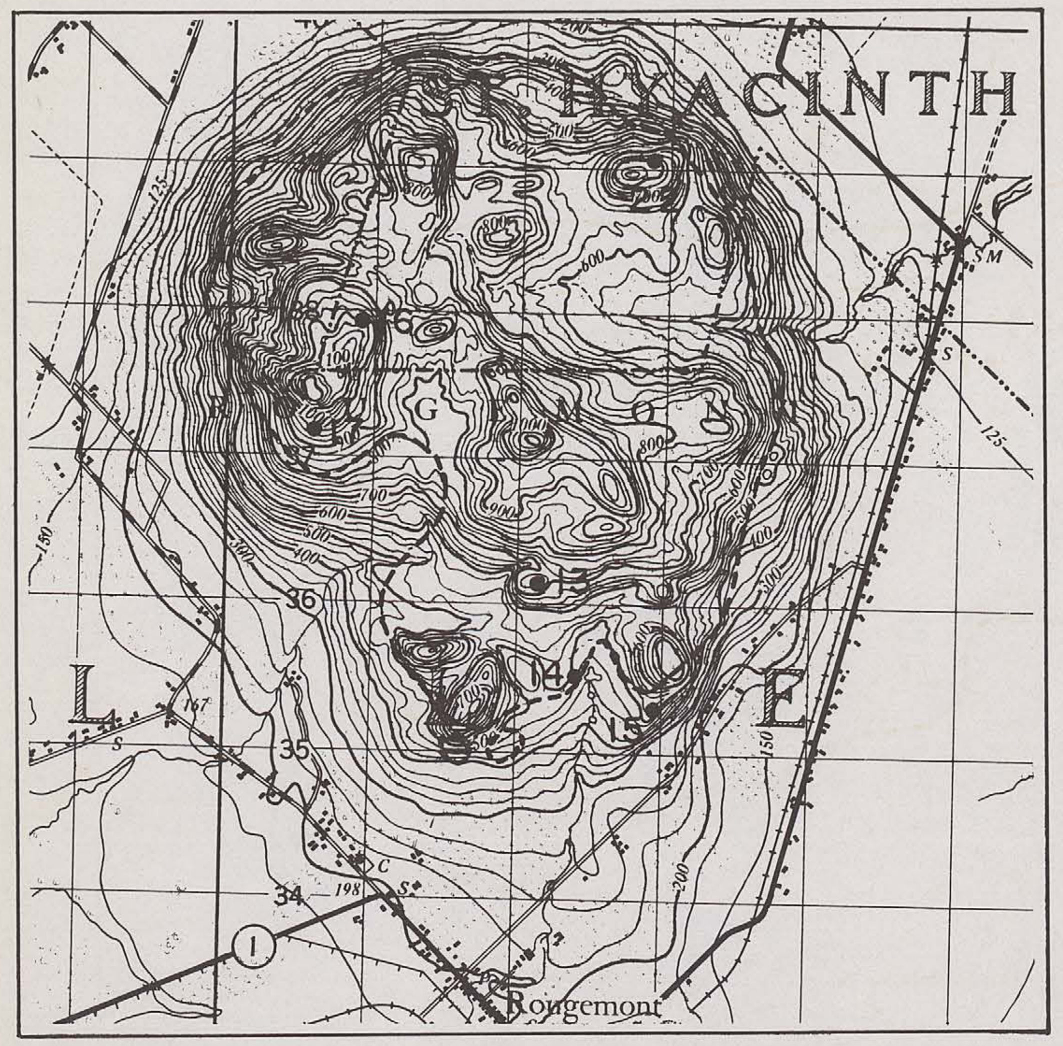
Cube No.	Strike	Before Magnetic Washing								After Magnetic Washing							
		α	β	γ	I_α	I_β	I_γ	D	I	α	β	γ	I_α	I_β	I_γ	D	I
22-1	349	194	187	262	18,033	6,240	17,597	188	-04	173	319	237	204	382	308	154	-16
22-2	"	194	188	258	20,374	6,895	19,219	190	-05	157	327	246	357	314	443	140	-20
23-1	063	144	068	303	1,116	1,178	1,362	215	+38	-	-	-	-	-	-	273	+52
23-2	"	106	024	318	1,354	1,392	765	171	+21	-	-	-	-	-	-	262	+60
24-1	146	199	247	223	10,888	11,606	12,918	347	-43	034	284	158	1,461	2,180	2,440	180	-65
24-2	"	199	237	217	12,074	10,920	14,009	352	-42	035	287	148	1,663	2,012	2,142	179	-56
25-1	123	237	172	284	10,265	9,890	4,742	001	+07	055	294	149	355	512	637	172	-52
25-2	"	240	168	282	10,015	10,015	5,772	002	+08	051	297	147	373	407	546	170	-50
25-3	"	238	172	274	9,110	8,174	4,649	357	+04	033	296	149	378	458	619	159	-52
26-1	015	148	278	206	2,738	4,085	3,733	168	-66	012	271	184	109	520	474	-	-90
26-2	"	155	275	201	2,594	3,832	3,840	173	-70	032	285	178	156	537	494	042	-77

TABLE A-2 (Cont'd.)

Cube No.	Strike	Before Magnetic Washing								After Magnetic Washing							
		α	β	γ	I_α	I_β	I_γ	D	I	α	β	γ	I_α	I_β	I_γ	D	I
27-1	271	263	247	190	1,384	2,815	2,493	169	-63	227	251	192	256	627	665	141	-69
27-2	"	262	242	191	4,238	11,544	10,857	169	-56	250	244	190	656	703	645	161	-63
28-1	340	-	-	-	-	-	-	183	-56	-	-	-	-	-	-	155	-50
28-2	"	-	-	-	-	-	-	170	-38	-	-	-	-	-	-	145	-52
29-1	345	237	230	203	2,157	3,044	2,876	215	-35	-	-	-	-	-	-	338	+42
29-2	"	223	232	197	3,794	6,045	6,075	216	-53	-	-	-	-	-	-	299	-55
30-1	145	188	093	327	2,915	4,184	6,180	332	+59	192	101	329	1,671	2,530	3,543	340	+56
30-2	"	191	097	325	3,570	5,460	6,000	335	+56	196	099	328	1,927	3,089	3,433	340	+59
31-1	041	061	014	039	102,388	106,964	74,360	109	+20	031	069	033	2,394	3,228	3,511	072	+53
31-2	"	058	016	048	77,506	77,506	41,756	104	+19	358	091	028	1,385	2,479	2,846	039	+60
31-3	"	060	015	053	45,387	43,050	24,108	105	+17	337	106	027	1,056	2,470	2,410	016	+59
32-1	102	232	113	333	5,895	7,530	7,530	330	+57	234	119	340	3,108	6,022	5,491	338	+57
32-2	"	233	115	338	5,580	8,640	8,655	333	+58	241	129	346	2,902	5,928	5,429	347	+53
32-3	"	238	110	339	6,600	8,760	8,775	334	+62	242	117	346	3,089	5,897	5,522	344	+61



MOUNT ST. HILAIRE (H)



MOUNT ROUGEMONT (R)

SHEFFORD & BROME MOUNTAINS (B&S)

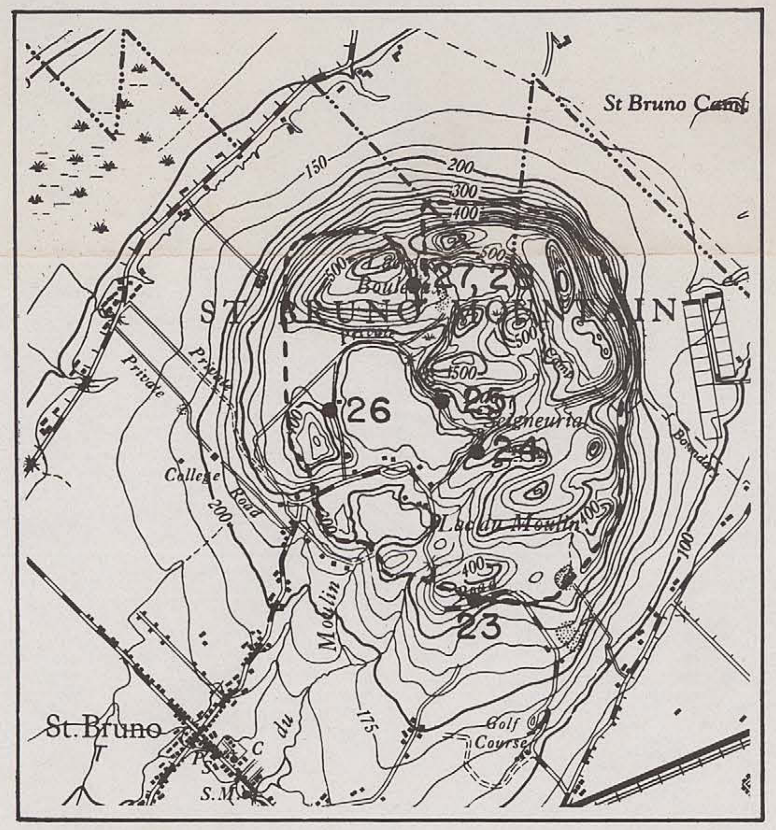
FIG. 20 - MAPS SHOWING SITES OF SPECIMEN COLLECTION

SCALE

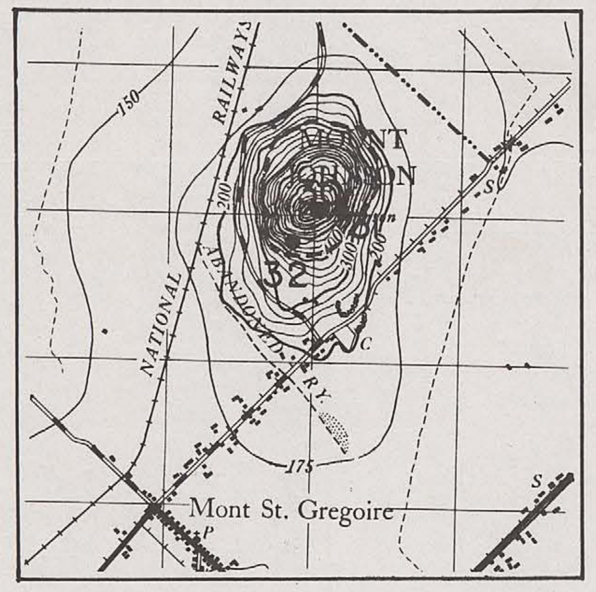
LEGEND

BOUNDARIES OF INTRUSIVE BODIES

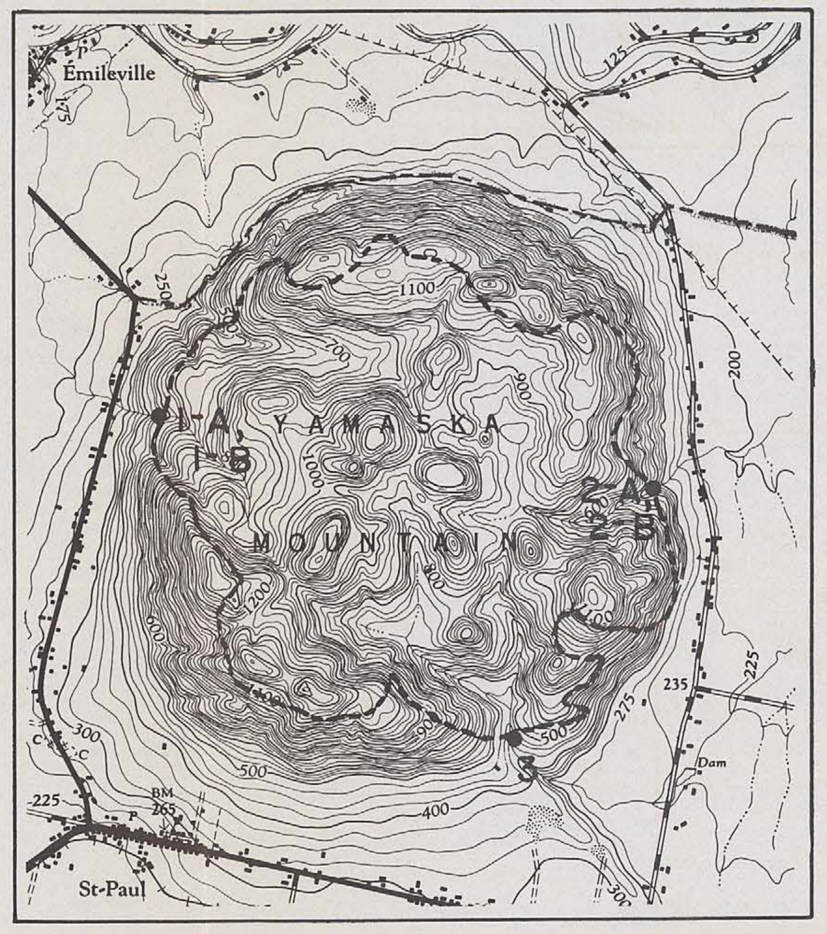
• 4 SITES OF SPECIMEN COLLECTION



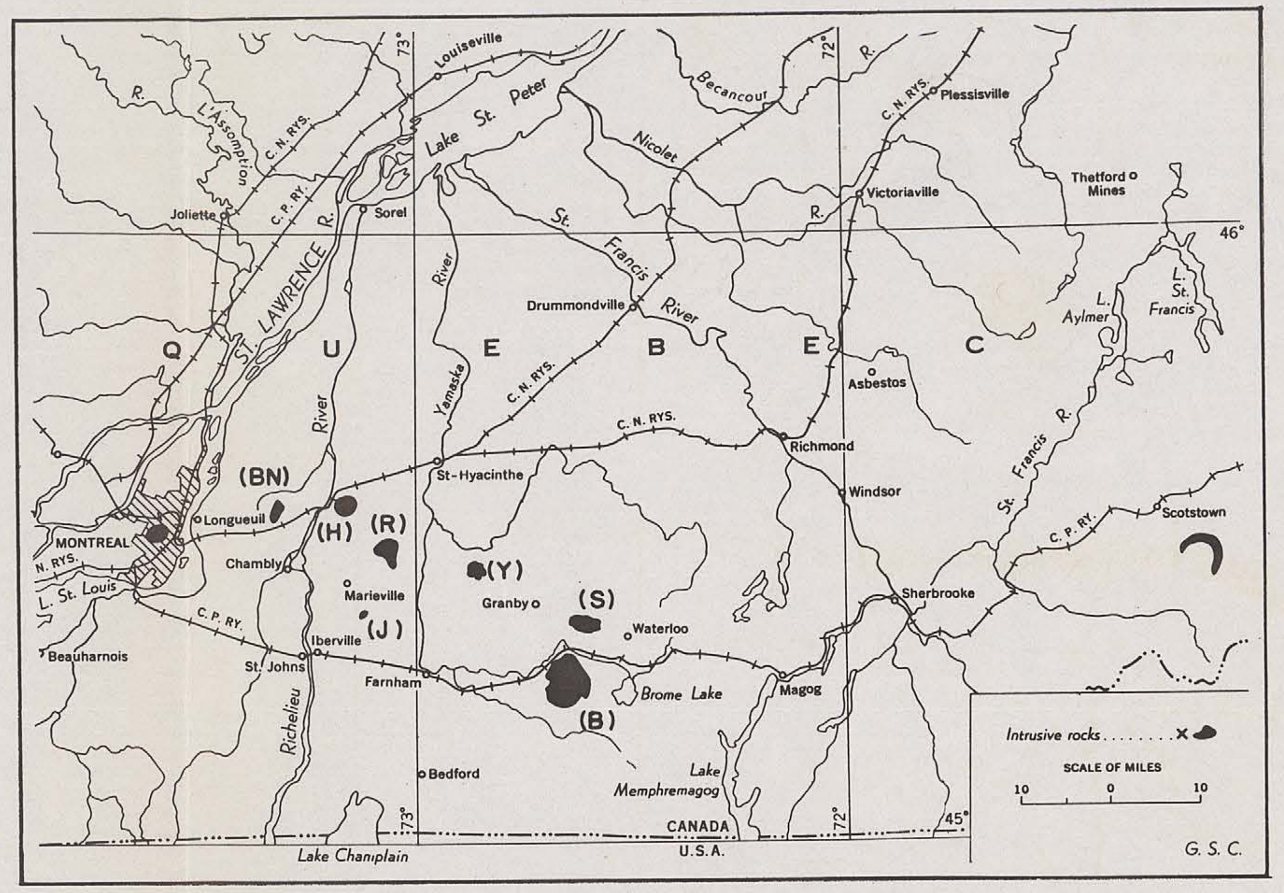
MOUNT ST. BRUNO (BN)



MOUNT JOHNSON (J)



MOUNT YAMASKA (Y)



REGIONAL MAP OF THE MONTEREGIAN HILLS