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DEPARTMENT OF MINES AND TECHNICAL SURVEYS

BULLETIN 90

PALAEOMAGNETIC STUDY OF THE SUDBURY IRRUPTIVE

S. R. Sopher

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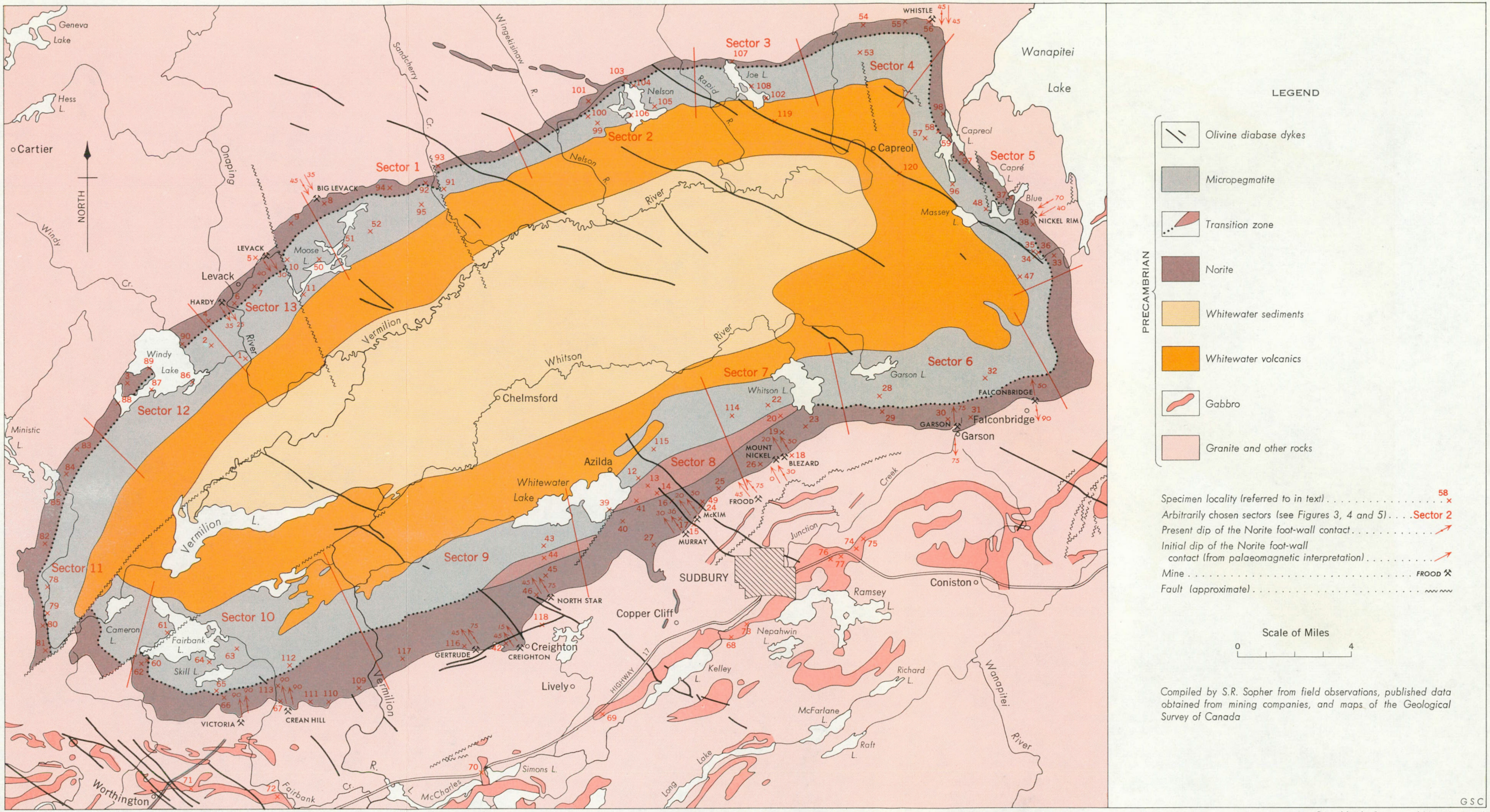

FIGURE 1. Geological sketch-map of the Sudbury Basin showing locations of specimens and sectors referred to in text

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PALAEOMAGNETIC STUDY OF THE SUDBURY IRRUPTIVE

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By
S. R. Sopher

DEPARTMENT OF
MINES AND TECHNICAL SURVEYS
CANADA

63064-0—2

PREFACE

For more than half a century the origin of the Sudbury irruptive has been a matter of contention. Much argument has centred around whether the irruptive owes its present attitude to emplacement into a folded structure or to folding after emplacement. The palaeomagnetic investigation reported here suggests that the irruptive was, in fact, emplaced into an original basinal structure but was subsequently folded.

This study successfully demonstrates the value of palaeomagnetism as a tool for some structural problems.

The author, when a graduate student temporarily employed by the Geological Survey of Canada, undertook the study as part of his graduate requirements at Carleton University, Ottawa.

J. M. HARRISON,
Director, Geological Survey of Canada

OTTAWA, July 24, 1961

Bulletin 90 — Paläomagnetische Untersuchung der Sudbury-Tiefengesteine. Von S. R. Sopher.

Beschreibt paläomagnetische Untersuchungen von Gesteinen aus dem Sudbury-Becken in Ontario, die darauf hinweisen, daβ die basischen Gesteine in eine ursprüngliche Muldenstruktur eindrangen und anschliessend gefaltet wurden.

Бюллетень 90 — Палеомагнетические исследования садбурийского ирруптивного тела. Автор: С. Р. Софер.

Описывает палеомагнетические исследования горных пород садбурийского бассейна в Онтарио, которые указывают, что основные породы были внедрены в уже существовавшую бассейнообразную структуру и впоследствии смяты в складки.

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PALAEOMAGNETIC STUDY OF THE SUDBURY IRRUPTIVE

Abstract

The palaeomagnetic study of the Sudbury irruptive illustrates the value of palaeomagnetic investigations as an aid in solving certain geological and structural problems. The north and south ranges of the Sudbury irruptive are found to have undergone a relative folding of approximately 30 to 40 degrees after emplacement. The east and northeast parts of the irruptive have been folded as well towards the inside of the basin. The amount of folding is insufficient to support Collins' hypothesis of an originally flat body or Hamilton's hypothesis of an extrusive origin. A modification of Wilson's funnel-shaped intrusion hypothesis appears to fulfil satisfactorily the geological and geophysical requirements.

The coordinates for the palaeo-geomagnetic pole positions for the irruptive rocks are found to be appreciably different from those for the olivine diabase dykes. In some places where the diabase intrudes the norite, the resultant direction of magnetization conforms locally with that of the dykes. Correlation with pole positions from other North American Precambrian rocks indicates that a considerable time interval separated their respective times of intrusion, the diabase dykes being the younger.

Résumé

L'étude paléomagnétique des intrusions de Sudbury prouve que de telles études facilitent la solution de certains problèmes géologiques et structuraux. L'auteur a constaté que les parties nord et sud de ces intrusions ont subi, après leur mise en place, un plissement relatif d'environ 30 à 40°. Les parties est et nord-est ont de plus subi un plissement vers l'intérieur du bassin. Le plissement est trop faible pour corroborer l'hypothèse de Collins selon laquelle une masse horizontale aurait existé à l'origine ou celle de Hamilton selon laquelle ces roches seraient d'origine extrusive. Il semble que, pour satisfaire aux conditions géologiques et géophysiques, il faille modifier la théorie de Wilson, celle d'intrusions en forme d'entonnoirs.

L'auteur a constaté que les coordonnées des pôles paléo-géomagnétiques relatives aux intrusions, diffèrent sensiblement de celles des pôles pour les dykes de diabase à olivine. En certains endroits où la diabase est injectée dans la norite, l'aimantation de la norite emprunte par endroits la même orientation que celle des dykes. La mise en corrélation de la position de ces pôles avec les positions des pôles déterminées pour d'autres roches précambriennes de l'Amérique du Nord indique qu'un long intervalle de temps a séparé l'époque d'injection de la norite de celle de la diabase. Les filons de diabase sont les plus récents.

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INTRODUCTION

The Sudbury area is of interest not only for its mining activities but also for its outstanding structural, stratigraphic, and petrologic problems. The recently developed principles and techniques of palaeomagnetism now offer a new approach to the study of the structure of the Sudbury rocks. A recent study by P. Hood (1958)[1,2] indicated that there was a significant difference in magnetic orientation of samples of the irruptive collected from the north range as compared with samples from the south range. This discovery has led the present author to embark on a more extensive sampling of the entire rim of the irruptive as well as of some other related rocks.

The writer's study of remanent magnetism in the Sudbury irruptive rocks has provided new data on the relative amount of folding of the various rock phases there and also new data on relative age relationships between the norite, micropegmatite, olivine diabase, and the Sudbury gabbro. These data and interpretations of them are presented in the following pages.

Location

The Sudbury Basin is located just northwest of the city of Sudbury between north latitudes 46°20′ and 46°45′, and west longitudes 80°30′ and 81°45′. The nickel irruptive (Fig. 1) forms a high rocky rim around the margin of this basin and is exposed at the surface in the form of an elliptical ring 37 miles long, 17 miles wide, and from 1.0 to 3.6 miles thick.

Geologically, the Sudbury area is located within the Superior structural province that extends more than 600 miles from the west end of Lake Superior into the province of Quebec.

Description of the Irruptive and Associated Rocks

Irruptive Rocks

The Sudbury irruptive is composed of norite, micropegmatite, and a transitional rock type intermediate between the two. As these rocks have been described in great detail by Walker (1897), Coleman (1903), Phemister (1925 and 1937), Collins (1935), and others, only brief petrographic descriptions follow.

The *norite* is commonly much altered, but primary constituents are an orthorhombic pyroxene between hypersthene and bronzite in composition, mono-

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[1] A brief report of part of Hood's thesis, entitled *Palaeomagnetic Study of the Sudbury Basin* was published in the Journal of Geophysical Research, vol. 66, pp. 1235-1241, 1961, shortly after this bulletin was submitted for publication. *Ed.*

[2] Names and/or dates in parentheses refer to *References*, page 24.

clinic pyroxene, hornblende, biotite, plagioclase ranging from calcic labradorite to andesine, quartz, a micrographic intergrowth of quartz and feldspar, titaniferous magnetite, pyrite, and pyrrhotite.

The main constituents of the *micropegmatite* are a sodic plagioclase, orthoclase or microcline, quartz, and a micrographic intergrowth of quartz and feldspar (Collins, 1935). The feldspar in the intergrowth is composed of variable proportions of orthoclase, albite, and anorthite molecules. The ferromagnesian minerals are rare, and invariably so much altered that their original identity is uncertain. Titaniferous magnetite and ilmenite occur in smaller amounts than in the norite, although higher concentrations occur locally, especially in the north range.

The transition from norite to micropegmatite is abrupt and has led some geologists, Phemister (1925) in particular, to believe that the irruptive was the result of two separate intrusions.

Sudbury Gabbro

The Sudbury gabbro forms large sills and dykes in the Huronian and older rocks. Most of it is concentrated in sill-like bodies largely confined to areas of the Bruce Group. Such bodies are numerous in both Copper Cliff and Falconbridge map-areas, and most of them are several miles long.

The gabbro is a dark greenish, equigranular, fairly coarse-grained quartz gabbro, quite different in appearance from the norite of the nickel irruptive. Nevertheless, the quartz gabbro is itself a norite, as was pointed out by Coleman (1903) and Barlow (1907), for unaltered specimens carry faintly pleochroic hypersthene as well as augite and diallage. The relation of the gabbro to the norite has been described by Cooke (1946). The gabbro is older than both the norite and the olivine diabase dykes.

Olivine Diabase Dykes

These dykes in the Sudbury region are remarkable for their abundance and their parallelism. They are part of a system of dykes (Collins, 1935) that extends over an area at least 250 miles in diameter. Throughout this area they are characteristically numerous, parallel, and show few effects of later earth movements.

In the western part of the basin they strike at about 125 degrees, but their strike gradually swings to about 115 degrees in the eastern part of the basin. Very little is known about their dips, except that they are steep. They range in width from a foot or so to about 400 feet. They appear to fill simple tension fissures.

The olivine diabase is remarkably unaltered, unlike any other basic igneous rocks in the Sudbury district. It consists of "from 60-70% labradorite, about 20% augite, half as much olivine and accessory quantities of black iron ore, biotite and apatite" (Kindle, 1933). It is grey on fresh surfaces, but usually weathers reddish brown. The ferromagnetic minerals are mainly ilmenite, highly titaniferous magnetite, and pyrrhotite, in decreasing order of abundance. The magnetic intensity varies from dyke to dyke; dykes of lesser magnetic intensity contain a greater amount of ilmenite, although the total amount of the ferromagnetic constituents remains approximately the same. The magnetic content of the diabase locally affects the compass needle.

The dykes cut across all other formations and are definitely later than all folding and faulting within the area.

Hypotheses on Origin

Several hypotheses have been advanced in the literature reconstructing the original structure and attitude of the Sudbury irruptive. The five principal ones are as follows:

(1) the irruptive was originally a flat sill, and was later folded into its present shape (Collins, 1935);

(2) the irruptive was injected around a great downfaulted block of sediments (Knight, 1917);

(3) the irruptive is a funnel-shaped lopolith with a feeder at the bottom (Wilson, 1956);

(4) the irruptive is a volcano-tectonic depression surrounded by a ring complex of dyke-like and sill-like character (Thomson, 1956);

(5) the irruptive is of extrusive origin (Hamilton, 1960).

Hypotheses (1) and (5) involve major post-orogenic folding, whereas (2), (3), and (4) infer that the irruptive was emplaced in situ and that the present attitudes have remained substantially unchanged.

Acknowledgments

The writer wishes to express gratitude to all those who helped him in various phases of the work. In particular he wishes to thank L. W. Morley and A. Larochelle of the Geological Survey of Canada for their support and encouragement throughout the project; the geological staff of the International Nickel Company of Canada for their cooperation and collection of samples from their various mines; Professor T. J. S. Cole of the Physics Department of Carleton University; and J. L. Kirwan, who assisted in the collection of the oriented samples in the field.

The study was undertaken as a research project in the laboratories of the Geophysics Division of the Geological Survey of Canada and the Dominion Observatory in conjunction with the Geology Department of Carleton University.

SOME FUNDAMENTAL PRINCIPLES AND ASSUMPTIONS IN PALAEOMAGNETIC STUDIES

Earth's Dipole Field

A fundamental assumption in palaeomagnetic studies is that the geomagnetic field at the earth's surface averaged over a period of several thousand years can be represented by a geocentric dipole with its axis along the axis of rotation. Although this dipole field is considered to be stable, a comparatively irregular westward-drifting non-dipole field is believed to be superimposed on it. Runcorn (1959), in his model of the earth's field, represented the changes in the non-dipole field as the result of eddies at the core-mantle boundary and considered the westward drift as due to a smaller angular velocity in the outer layer of the core with respect to the mantle. As a result of this relative motion of the core and mantle, the non-axial components of both the dipole and non-dipole field should cancel when averaged over a sufficiently long time, i.e., about 5,000 to 10,000 years.

In the scope of the present problem, however, a multipole rather than a dipole hypothesis would not affect the interpretation of the data, as the area sampled covers an insignificantly small fraction of the earth's crust.

Types of Magnetization

Several components of magnetization may be superimposed in a rock. Because of this, geological interpretations of the magnetic measurements are critically dependent on the availability of techniques for distinguishing these components.

The most commonly encountered components of remanent magnetization in igneous rocks are (1) isothermal remanent magnetization (IRM); (2) thermo-remanent magnetization (TRM); (3) chemical magnetization; and (4) anhysteritic remanent magnetization.

The isothermal component of magnetization is acquired by a rock when it is subjected to a constant field at ordinary temperatures. The intensity of this component varies according to the time (t) elapsed since the rock's formation and is found by experiment to vary as log t. This type of magnetization, when subjected to a magnetizing field for a relatively long period of time, is also referred to as viscous magnetization.

The process of thermomagnetization occurs when a rock cools from above a critical temperature for its ferromagnetic constituents (Curie point) in a constant field. The magnetization thus acquired is parallel to the ambient field.

Chemical magnetization is acquired by magnetic minerals when they undergo a chemical change (e.g., reduction of hematite to magnetite) at constant temperature in a weak magnetic field.

Anhysteritic magnetization is impressed on a rock when it is subjected isothermally (below the Curie temperature) to a rapidly fluctuating magnetic field superimposed on a constant field. The type of magnetization acquired is identical to that encountered in nature when a rock is struck by lightning. Necessarily, the effects are limited to a few feet.

In order to distinguish and isolate the stable thermoremanent component of magnetization, several laboratory techniques have been devised. They have been reviewed by many authors (most recently by Cox and Doell, 1960) so that only the method used in the present study is described here.

Magnetic 'Washing'

The technique of magnetic 'washing' is based on the relative stability of the various components of magnetization under the effect of an AC field. It has been found experimentally (Rimbert, 1959) that by using an AC field whose amplitude slowly decreases to zero, the comparatively 'soft' magnetization (i.e., IRM) may be separated and removed from the 'hard' magnetization (i.e., TRM) without affecting the latter. The process is repeated with successively higher peak values of the alternating field until a stable condition is reached. This condition is related to the thermoremanent magnetization acquired by the rock when it cooled through the Curie point of its ferromagnetic constituents.

Difficulties in analyses arise, however, when chemical or anhysteritic components of magnetization are superimposed as well. Nevertheless, the thermomagnetic demagnetization curve of an anhysteritic component resembles the equivalent curve of a TRM component more so than the IRM curve and therefore aids in its recognition. Chemical magnetization is, however, very difficult to recognize and in practice igneous rocks considered likely to contain this type of magnetization are not suitable for palaeomagnetic studies.

Factors Influencing Remanent Magnetization

Other physical and chemical processes may have an effect on remanent magnetization.

The magnetic properties of minerals are not completely isotropic, that is, individual grains are not usually magnetized as easily in all directions. This property, called *magneto-crystalline anisotropy*, is related to the crystal lattice. As an example, a crystal of hematite is much more easily magnetized in the C-plane than along the C-axis. The shape of the individual grain also causes anisotropy. However, in an aggregate of minerals, such as is found in norite and olivine diabase, where the ferromagnetic constituents are randomly oriented, the net magnetization direction is that of the applied field.

Another cause for the non-coincidence of the vector of rock magnetism with the direction of the magnetic field, referred to recently as *anomalous remanent magnetization* (Cox, 1961), is the magnetic anisotropy resulting from mineral alignment in such foliated rocks as phyllites, schists, and gneisses (Brodskaya and Grabovsky, 1960; Daly, 1959). The remanent magnetization is found to be directed in the plane of schistosity even though the magnetizing field is applied

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at 90 degrees to the stratification. This phenomenon is thought to apply to the anomalous values found in some of the more foliated or schistose parts of the micropegmatite.

It has also been found that in the process of *magnetization involving a chemical change* (Haigh, 1958) a new orientation will be superimposed parallel with the ambient field at the time of magnetization. However, in igneous rocks, chemical alteration, unless complete, will not greatly affect the remanent magnetization; for example, the principal alteration product of the strongly magnetic titanomagnetites is usually the very weakly magnetic hematite.

Magnetic anisotropy may also result from *exsolution* as described by Hargraves (1959) for a hemo-ilmenite deposit. In the hemo-ilmenite grains discussed by Hargraves, the hematite is exsolved parallel with the basal plane of the ilmenite host. This preferred planar orientation coincided in attitude with that indicated by the maximum magnetic susceptibility. Erratic deviation in palaeomagnetic results may therefore be the result of anisotropy caused by hematite-ilmenite exsolution.

In rock magnetism, the term *magnetostriction* is generally used to describe the effect of change in magnetization resulting from mechanically applied elastic deformation. Stott and Stacey (1959) found that by a comparison of rocks under compressive stress with others that did not have any stress applied, the resulting thermoremanent magnetization measured after the stress had been removed was parallel in each case to the applied field. The rocks were heated above their Curie temperatures and allowed to cool to room temperature in the earth's field.

Coincidence of Magnetic Vector with Earth's Magnetic Field

It is assumed in palaeomagnetic work that the magnetization direction measured in a rock reflects the direction of the earth's magnetic field existing at the time the rocks were magnetized, and that the rocks were magnetized during their formation or soon after. Movement due to flow did not likely disturb the attitude of the vector of magnetization as the Curie point of the magnetic fraction was well below the temperature of solidification of the rocks.

Polar Wandering

Interpretation of magnetic data from rocks of different geologic ages has resulted in the speculation that polar wandering, whether geographic or magnetic, has taken place. Cumulative evidence suggests that not only has the entire crust migrated but also that the continents have themselves wandered relative to each other. However, these two concepts are still highly speculative and the results may be adequately explained by other causes. Nevertheless, whether the cause of polar wandering is the result of shift of the crust or of fluctuating non-dipole fields, rocks magnetized in substantially different field directions in a local area, such as at Sudbury, indicate that some geological time interval has elapsed between their respective emplacements. The exact interval of time cannot be given, however, without additional information.

SAMPLING PROCEDURE, LABORATORY EQUIPMENT AND TECHNIQUES

Sampling and Preparation of Specimens

In sampling the norite, transition rocks, and micropegmatite, the aim was to obtain a uniform distribution around the rim of the Sudbury Basin. However, overburden and some deeply weathered outcrops restricted the choice of specimens locally. Sampling was done mainly along roads and water routes. In all, 240 samples were collected from 120 locations on the surface, and 27 samples were collected underground from the properties of The International Nickel Company of Canada, Limited.

Sampling of the olivine dibase dykes and Sudbury gabbro was restricted to good outcrops along roads. Samples from underground workings of most of the operating mines of International Nickel were provided by the company.

The part of an outcrop to be sampled was selected according to ease of removal of the rock and to the flatness of its surfaces. Joint planes and fracture surfaces in situ were thus considered first.

The equipment used for obtaining samples included a sledge-hammer, chisels, carpenter's level, and both Brunton and solar compasses. A horizontal arrow was drawn on the outcrop surface with the aid of the carpenter's level. The downdip direction of the surface was also marked by a line perpendicular to the arrow. When a surface was overturned, the total angle from the horizontal was recorded, in which case the dip value would be greater than 90 degrees. The azimuth of the arrow was measured by both Brunton and solar compasses. The dip angle was determined with the clinometer of the Brunton compass. Two samples were collected from every outcrop. In the laboratory, two 1-inch oriented cubes were cut from each sample with the aid of a diamond saw. The orientation arrows were painted on the specimens and a transparent plastic was sprayed on the cubes to preserve the arrows and other identification marks.

Laboratory Equipment

The magnetic measurements in this study were carried out on either a 'spinner-type' magnetometer or an astatic magnetometer. The spinner-type was used to measure only the more intensely magnetized specimens whereas the astatic magnetometer was used for all others. All samples were 'washed' before a final stable direction was accepted.

Magnetic Washing Apparatus

The apparatus used in the present study was constructed by A. Larochelle (1958). A magnetic-free space was obtained by using two mutually perpendicular Helmholtz coils, with the vertical coil oriented in a N-S direction. The alternating demagnetizing field was produced by using a third Helmholtz coil, which is lowered and raised by a system of pulleys. This method of regulating the alternating field amplitude around the specimen is used instead of a rheostat because it has been found that an anhysteritic component may arise as a result of the discrete jumps that occur when the resistance of a rheostat is varied from loop to loop.

The specimens were 'washed' in three mutually perpendicular directions to ensure effective demagnetization evenly throughout. The alternating fields were increased in stages up to a maximum of 280 oersteds. Removal of the IRM components was considered to be achieved when the direction of magnetization remained stable after at least two 'washings' with successively increased peak intensities of the alternating current fields.

'Spinner-type' Magnetometer

The spinner-type rock generator used in the present study was built in the Geophysics Division of the Geological Survey of Canada. Instruments of this type have been fully described in the literature by several authors including Johnson, *et al.* (1948) and Hood (1958). The operation of the present instrument has been described by Larochelle (1958). Briefly, the apparatus operates on the principle that the residual magnetism of the rock induces an alternating voltage in a system of coils when the specimen is rotated close to them. The limit of resolution of the apparatus is indicated to be of the order of 10^{-4} emu. Repeated measurements show that the precision of angular measurements is within 3 degrees for declination and inclination.

Measurements involved spinning each cube about three mutually perpendicular axes in both clockwise and anti-clockwise directions. The determinations of declination (D) and inclination (I) were done graphically using a Wulff net, according to the procedure of Larochelle (1958). Both cubes from each sample were measured and a mean for the two vectors was obtained by allowing both poles to lie on a great circle and using the midpoint between them. A significant closure was encountered in some specimens owing to possible inhomogeneities in the distribution of ferromagnetic minerals. It is estimated, however, that the total error of this instrument and graphical procedure is approximately 4 degrees, as determined by repeated measurements on the specimens.

Astatic Magnetometer

Astatic magnetometers have been fully described in the literature by Collinson, *et al.* (1957), Blackett (1952), and others. The unit used in the present study was built by J. Roy of the Dominion Observatory and is fully described in his paper (*in press*).

A sensitivity of approximately 4.42×10^{-8} G/mm scale deflection has been achieved on this instrument. The precision of the angular measurements, as obtained by repeated measurements, is found to be within 2 degrees for declination and inclination.

Statistical Analysis of Results

In order to obtain an accurate estimate of the relative amount of rotation for the various segments of the irruptive, a mean vector for each of the thirteen arbitrarily chosen groups of data was computed. The reliability of this mean vector was established quantitatively by the methods of Fisher (1953) where a 95 per cent probability was assumed.

The directions of magnetization for each pair of cubes representing a specimen were averaged out and the average direction was plotted stereographically (Figs. 3, 4, 5) and are listed in Table I (*see* Appendix). The mean attitudes of these vectors are represented by X's and the large circles represent their circles of confidence (α), where—

$$\operatorname{Cos} \alpha_{(1-P)} = 1 - \frac{N-R}{R} \left\{ \left(\frac{1}{P}\right)^{\frac{1}{N-1}} - 1 \right\}$$

$P = 0.05$

$N =$ number of vectors

$R =$ length of the resultant vector.

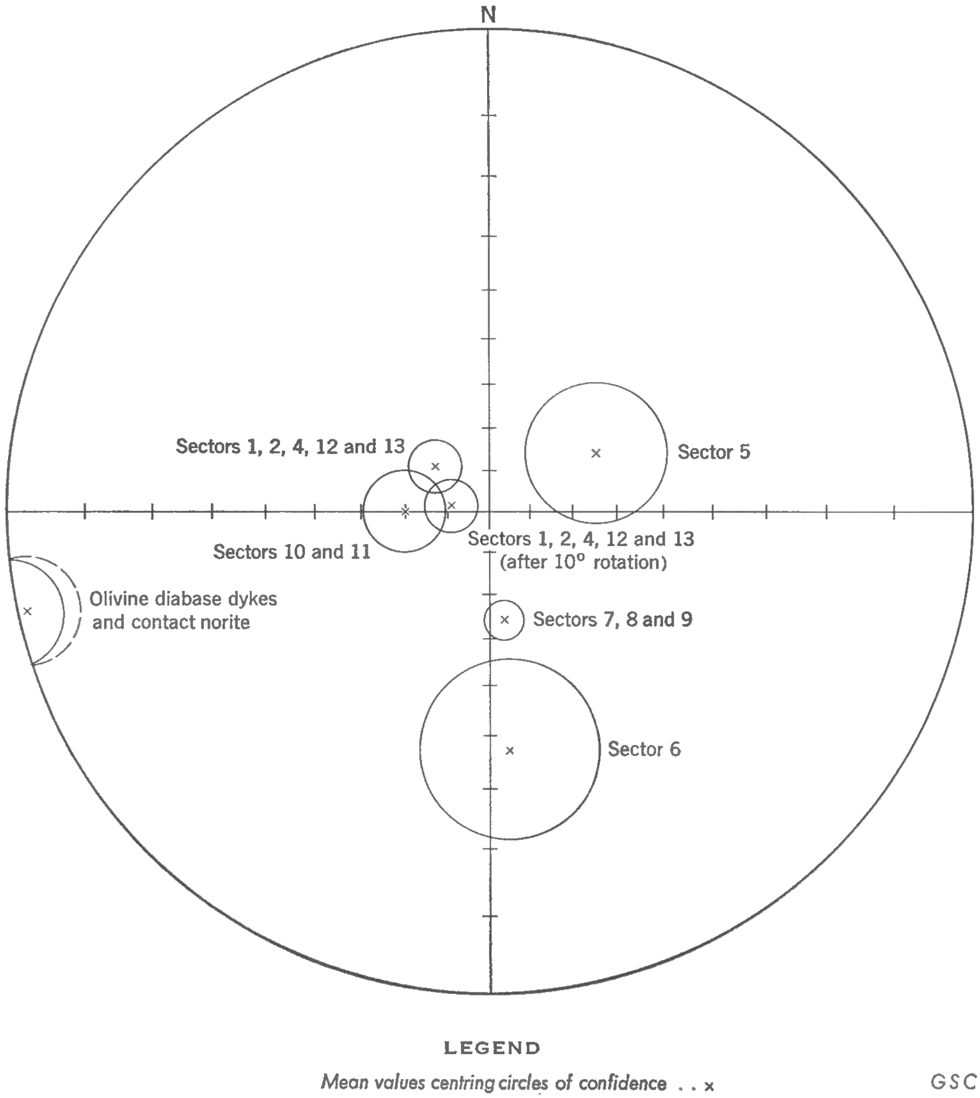


FIGURE 2. Generalized stereographic projection of palaeomagnetic directions.

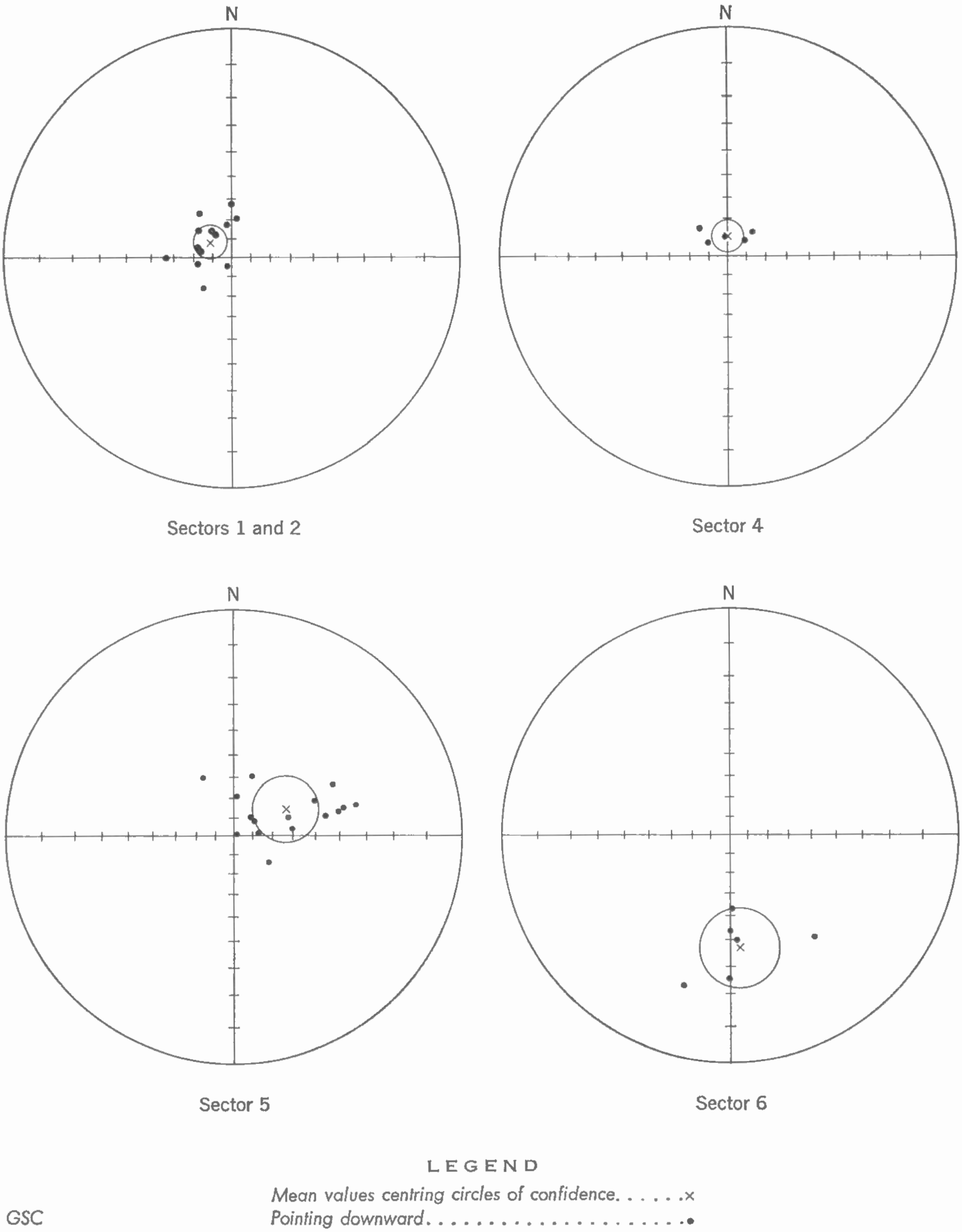
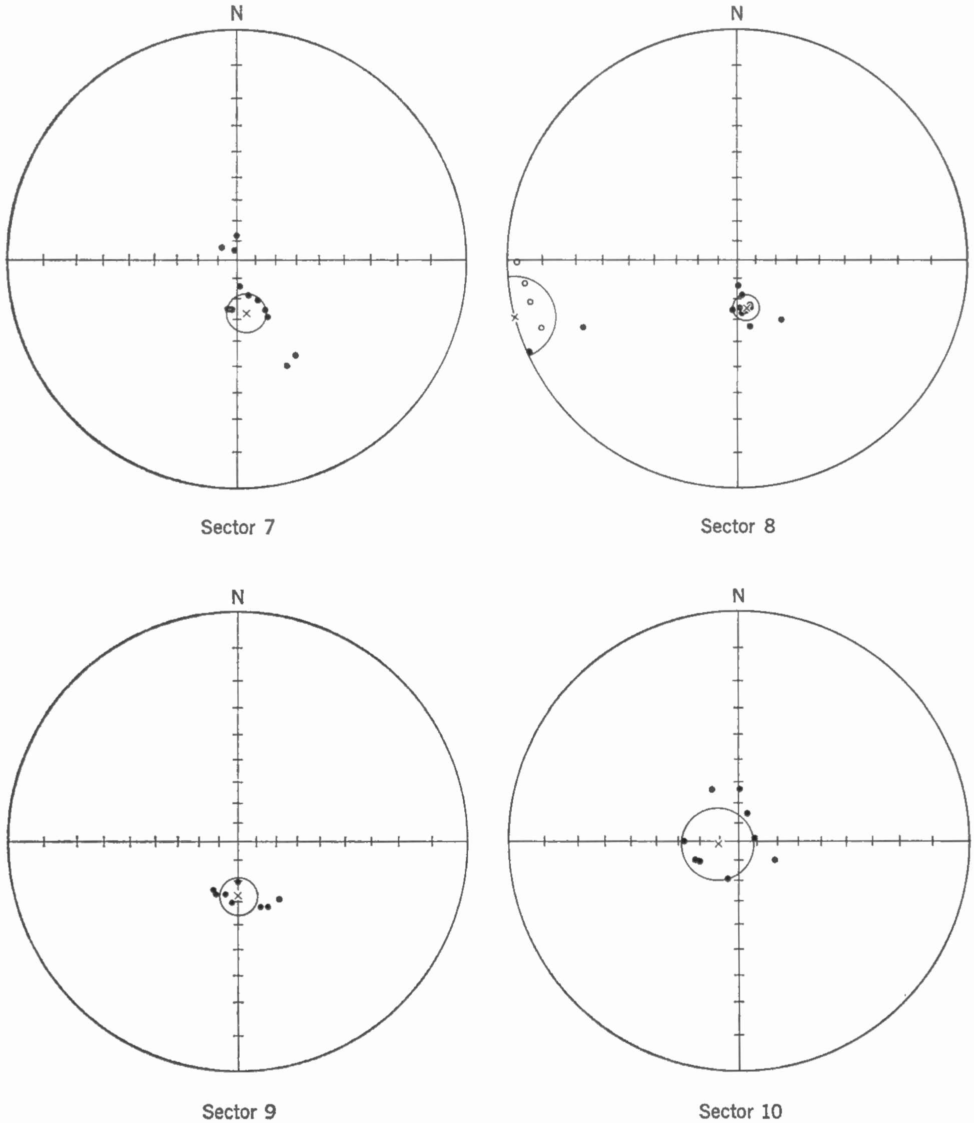


FIGURE 3. Stereographic projections of data for sectors 1, 2, 4, 5, and 6 (for location of sectors, see Fig. 1).



LEGEND

Mean values centring circles of confidence. . . . . .×
Pointing upward . . . . ∘
Pointing downward. . . . . •

GSC

FIGURE 4. Stereographic projections of data for sectors 7, 8, 9, and 10 (for location of sectors, see Fig. 1).

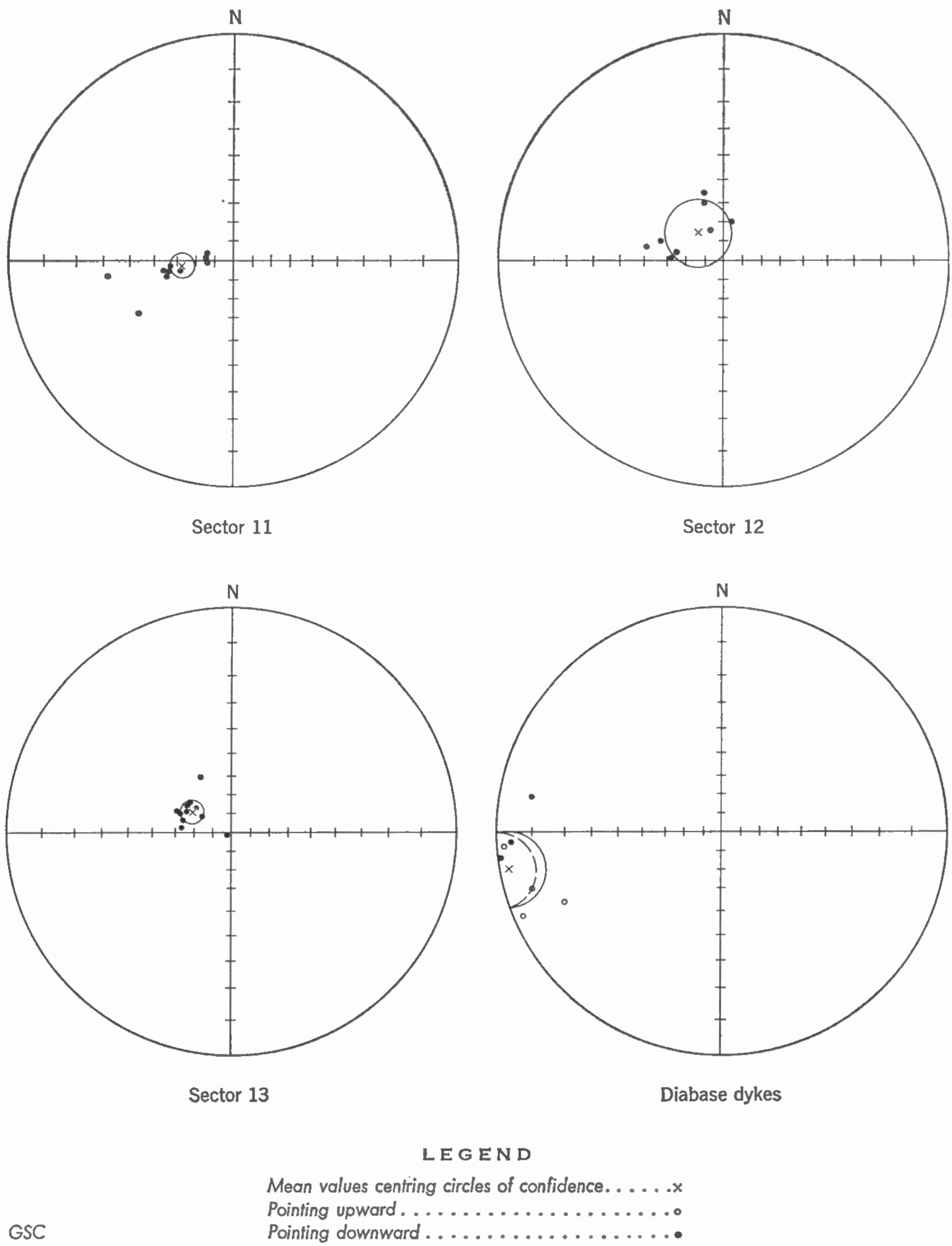


FIGURE 5. Stereographic projections of data for sectors 11, 12, 13, and diabase dykes (for location of sectors and dykes, see Fig. 1).

PALAEOMAGNETIC DATA AND THEIR INTERPRETATION

Data

In order to simplify the systematic study of the irruptive, it was found convenient to divide the elliptical Sudbury Basin into more or less equally extending arbitrary divisions or sectors. Thirteen sectors (*see* Fig. 1) were selected, each of which could be studied independently and compared with the others. A summary of the results as plotted on a generalized stereographic projection is shown on Figure 2.

Remanent Magnetism in the Norite and Micropegmatite

The stereographic projections (Figs. 3, 4, 5) show that there is a substantial difference in the magnetic orientation of specimens collected from the north and south ranges of the Sudbury irruptive. An average value for the north range was determined by combining sectors 1,2,4,12, and 13. The declination and inclination were found to be 310 degrees and +73 degrees, respectively, having a tight circle of confidence ($\alpha=5°$). Similarly, the average value for the south range was determined by combining sectors 7,8, and 9 for which the declination and inclination were 173 degrees and +64 degrees respectively, with α equal to 4 degrees.

The mean for sector 5, which envelops the eastern part of the irruptive, was found to have a declination and inclination of 63 and 62 degrees respectively. This mean differs considerably from that of either the north or south range and may be described to advantage as the 'east' range.

Similarly, in order to emphasize that the Falconbridge area (sector 6, Fig. 1) has undergone more than the average rotation for the south range, its mean direction has also been isolated in Figure 2.

It will be noted that the mean vectors of magnetization for sectors 10 and 11 (Figs. 4, 5) in the western extremity of the irruptive are almost coincident. As these sectors are facing each other, i.e., sector 10 is in the south range whereas sector 11 is in the north range, no relative rotation has taken place between them. A combined mean direction of magnetization for both sectors was also determined.

Remanent Magnetism in the Diabase Dykes and Norite (influenced by intrusion)

The mean direction of magnetization for the diabase dykes is defined by a declination and inclination of 260 and —2 degrees respectively. Occurrences of norite close to diabase dyke intrusions have an average value of 256 and 0 degrees for their respective declination and inclination. As this mean is almost coincident with that of the diabase, a combined value has also been calculated. This mean direction of magnetization is 258 and —1 degrees for declination and inclination, respectively.

Remanent Magnetism in Ore Samples and in the Sudbury Gabbro

As no stable condition of magnetization was reached for the ore samples, the directions of magnetization were not plotted stereographically. The initial directions of magnetization will be found in Table I (*see* Appendix).

The values for declination and inclination of specimens of the Sudbury gabbro are listed in Table I, but are not plotted stereographically because of their instability after magnetic 'washing'.

Interpretation of Palaeomagnetic Data

Evaluation of the Magnetic Properties of Various Rock Types

An evaluation of the magnetic properties of the various rock types has been attempted in order to substantiate the stability of the thermoremanent magnetization in the rocks. A correlation of the magnetic properties with the mineralogical characteristics has also been attempted.

Norite

The results of A.C. demagnetization show that the norite (surface and underground) is unusually stable magnetically, its isothermal contribution is negligible, and the TRM is not affected. Some of the samples had directions of magnetization substantially different from the mean vector of magnetization for the arbitrary divisions of the irruptive. Hood (1958) obtained similar anomalous results. The present writer has found, particularly in the norite sampled in sector No. 8 (Hood's samples S1-4, 5, 6) in the south range, that an olivine diabase dyke (shown on Geol. Surv., Canada, Map 871A) is in the immediate vicinity, running parallel with the new highway (not shown on Map 871A) and that the direction of magnetization of these 'anomalous' norites coincides with that of the diabase dyke. It is concluded, therefore, that intrusion of the later olivine diabase dykes has indeed affected the magnetization of the nearby norite. Temperature of intrusion is considered to be well above 600°C, i.e., above the Curie point of the titaniferous magnetite in the norite, the exact composition of which has not been determined.

A few reversely magnetized rocks (i.e., rocks with the north pole of the magnetic vector pointing up, but not necessarily involving a 180 degree rotation) were encountered, which were invariably restricted to areas in the eastern half of the north range as well as the eastern part of the irruptive. In most rocks the magnetization was not stable, but A.C. demagnetization changed the direction of magnetization so that they fell within the mean for the section. However, in one location, the reversely polarized magnetization is very stable with the inclination at a very steep angle. This phenomenon may be caused by anhysteritic magnetization perhaps resulting from lightning. The small percentage of these anomalous unstable samples suggests that they are not the result of the reversals of the earth's field, but rather are the result of some local phenomenon, such as the presence of titanomaghemite. This mineral was found by Akimoto and Kushiro (1960) to be the cause of instability in dolerite sheet swarms of the

Japanese Tertiary. It is suggested that chemical reactions (such as alteration or weathering) have destroyed the TRM to a greater or lesser extent and consequently the RM measured is mostly of an isothermal or a chemical origin.

A study of thin and polished sections showed that titaniferous magnetite and ilmenite in the Sudbury norite occur in several stages of alteration. In one of the few samples of norite that showed reversely polarized magnetism, the titaniferous magnetite was found in all stages of replacement or exsolution by or from the ferromagnesian minerals. This secondary magnetite and ilmenohematite is probably the cause of the reversely oriented magnetism, having a composition close to that of $xFeTiO_3$ $(1-x)Fe_2O_3$ with $x=0.5$, as found by Uyeda (1958) from a study of synthetic specimens covering the whole range of the series. Exsolution of 'titaniferous magnetite' along the cleavage directions of amphibole is particularly well developed in those samples of norite affected by the intrusion of the diabase dykes.

Norite Containing Massive Sulphides

Specimens of norite containing abundant sulphides (underground ore samples) were found to be characteristically unstable. Studies on the magnetic properties of pyrrhotite (Nagata, 1953; Rimbert, 1959; Uyeda, 1958) show that the TRM of this mineral is normally very stable against A.C. demagnetization and that the Q. ratio $\left(\text{defined as } Q=\frac{\text{TRM}}{\text{Induced Mag.}}\right)$ is especially high (100-200). The specimens analyzed in this study, however, revealed no such stability, which suggests that the magnetization measured on these specimens may have been mainly due to IRM rather than to TRM components. In order to show that this could be the cause of instability, a specimen was heated to about 360°C for an hour in an open system. The cube was allowed to cool to room temperature in the earth's magnetic field. The magnetization thus obtained was found to have an intensity about fifteen times as great as that measured before heating. A comparison of the demagnetization curves is shown in Figure 6. Although the experiment was undertaken under oxidizing conditions, examination of the specimen after heating showed that alteration (bluish tarnish) is restricted to the surface of the cube. Very little hematite was formed.

It is difficult to predict precisely the possible rearrangement of the elements that take place at 360°C under oxidizing conditions, but at most it may be reasoned that some loss of sulphur has taken place. In any case no new ferromagnetic minerals would be expected. If this is valid, reference to the study by Haraldsen (1937) on the variation of susceptibility with sulphur content (n in FeS_{1-n}) shows that a decrease instead of an increase in susceptibility, and therefore in intensity, would be realized.

The lack of stability and relatively low initial intensity of magnetization in the writer's specimens suggest that the magnetization of the pyrrhotite proceeded at temperatures below the Curie point of pyrrhotite (about 320°C). This does not invalidate the hypothesis of the well-known pyrrhotite-pentlandite exsolution phenomena that take place at much higher temperatures (500°C), but indicates

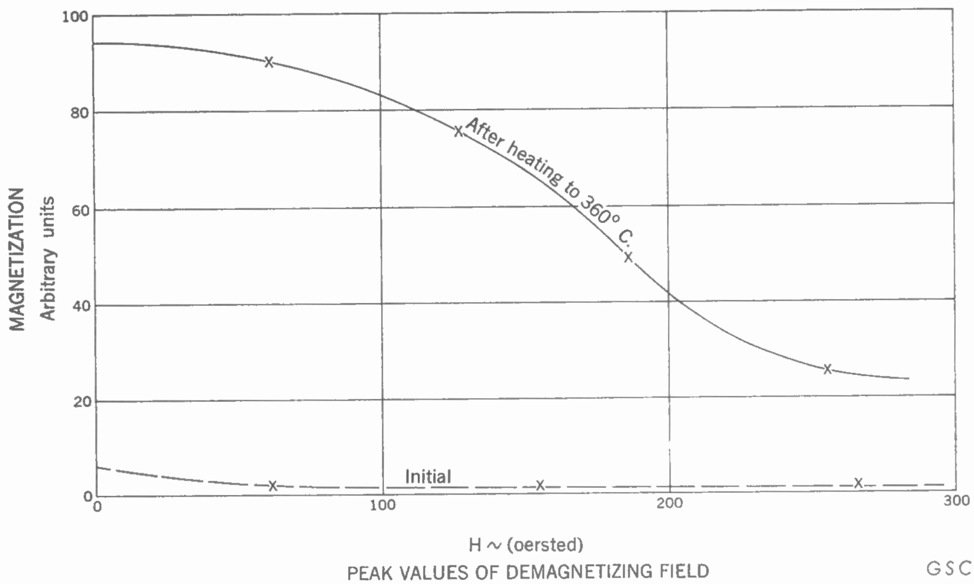


FIGURE 6. Comparison of demagnetization curves for norite containing massive sulphides, before and after heating.

that the final crystallization of much of the pyrrhotite in the Sudbury norite, perhaps after remobilization and reprecipitation, occurred at lower temperatures.

On the other hand, the decrease in intensity of the TRM component of magnetization with time (relaxation time) may have weakened the TRM component to such an extent that it was no longer separable from the IRM component. Because of this possibility, any conclusion on the cause of the instability of the sulphide-bearing norite must be regarded as tentative only.

In general, the content of titaniferous magnetite in the norite of the north range is thought to be greater than that in the norite of the south range, because of the differences in intensity of magnetization in the respective samples. However, grain size and the titanium content may appreciably affect the intensity.

Micropegmatite

The intensity of magnetization of the micropegmatite is substantially less than that of the norite. Chemical analyses accumulated by Collins (1935) show that the content of $FeO.Fe_2O_3$ and TiO_2 in the irruptive decreases in the direction of the micropegmatite as would be expected from the corresponding decrease in magnetic intensity found in the present work. Nevertheless, local concentrations of ferromagnetic constituents are common, especially in the north range. Although much of the micropegmatite was found to be stably magnetized, this rock type contains areas characterized by unstable magnetization. It is notable that in a study of the Pilansberg dykes, Gough (1956) found that the more feldspathic specimens gave directions widely different from the basic specimens. He also found that there was a large difference in stability between them, although a minority are similar to the more basic parts. In the present work, the samples of micropegmatite with stable magnetization and with the same direction of magnetization as the norite were used in the calculation for the mean directions of magnetization. As noted previously, the instability shown by some specimens may be due to a greater degree of alteration and oxidation that has destroyed most of the TRM. Consequently, the remanent magnetization measured in the unstable specimens is mostly due to an isothermal origin.

Olivine Diabase Dykes

The opaque minerals in the diabase dykes are characterized by euhedral ilmenite, titaniferous magnetite, and pyrrhotite. Most of these minerals are only slightly altered and contain surprisingly few exsolution lamellae. Inclusions of ferromagnesian minerals were observed in some specimens, which probably signify simultaneous or slightly post-olivine crystallization.

The vector of magnetization in the olivine diabase specimens was found to be significantly different from that in the norite, for the inclination is approximately horizontal in a direction very nearly perpendicular to the dykes. As the dykes are considered to be steeply inclined, it was suspected that some mechanism such as the alignment of crystal axes perpendicular to the dyke-country wall contact may be the cause of the anisotropy. However, a study of polished sections in directions parallel and perpendicular to the direction of magnetization did not reveal any obvious correlation such as the parallelism of exsolution. Where exsolution was observed, the lamellae were of such minute width that they were not easily discernible, but appeared to be arranged in a rhombohedral pattern.

A.C. demagnetization tests showed that two components of magnetization were present in these rocks. The soft component (isothermal remanent) was removed with an A.C. field of approximately 250 oersteds, leaving a relatively hard (thermoremanent) stable component.

Strangway (1960) in his study of several diabase dyke swarms in the Canadian Shield found that the stable component of magnetization is in general approximately parallel with the plane of the dykes, and concluded that the TRM component of magnetization no longer represented the true direction of the earth's magnetic field at the time of emplacement of the rock. Although he found anomalous results (direction of magnetization being closely perpendicular to, rather than parallel with, the plane of the dyke) from olivine diabase dykes sampled at one location in the Sudbury area, he dismissed the findings as probably due to unstable weak components of magnetization. The present study shows that from three dykes sampled, a stable direction of magnetization was reached after A.C. demagnetization, the final intensity of magnetization remaining close to the initial value.

The similar direction of magnetization in samples of norite collected near olivine diabase dykes to that in the dykes supports the hypothesis that the stable direction of magnetization in the olivine diabase dykes was caused by the earth's field at the time of formation rather than by a hypothetical mechanism operating simultaneously in the dyke as well as in the norite. Therefore, the swarm of olivine diabase dykes sampled by the writer is suitable for palaeomagnetic studies, whereas those studied by Strangway evidently are not.

Two samples (118S and 118K) obtained by the writer from a quartz-bearing greenstone dyke were found to have a direction of magnetization differing considerably from that of the norite, and at the same time to have a negative direction of magnetization. Although this may mean that they were intruded at different times, further sampling is necessary before any conclusion can be reached.

Sudbury Gabbro

Preliminary investigation indicated that most of the gabbro contained only a very small percentage of ferromagnetic minerals. Intensities of magnetization for many specimens were found to be too low for measurement after successive A.C. demagnetization. Furthermore the specimens proved to be very unstable magnetically. Because of these two conditions the gabbro specimens are merely listed in Table I and the directions were not plotted stereographically. The writer's megascopic and microscopic studies showed that secondary sulphides were concentrated along cleavage directions in the gabbro. Any secondary pyrrhotite thus formed would contain an isothermal component of remanent magnetization, which is necessarily unstable. A further study of these rocks is recommended.

Ancient Geomagnetic Pole Positions

Calculations of palaeo-geomagnetic pole positions are primarily dependent on the most reasonable, if not unique, reconstructed model of the geological structure. Interpretational ambiguities frequently arise and, if serious, necessitate the development of a new structural model. Calculations of palaeo-geomagnetic pole positions from the writer's specimens of the Sudbury rocks have been based on the assumption that the north range did not undergo any obvious change in original attitude. To cover the possibility that the north range was folded about 10 degrees an alternative model has been assumed and a 'corrected' pole position calculated to suit this model.

In order to present the data in terms of the geocentric dipole that would produce the measured field direction, the relationships

$$\text{Sin } \theta' = \sin \theta \cos p + \cos \theta \sin p \cos D$$

$$\text{Sin } (\phi' - \phi) = \sin p \cos D / \cos \theta'$$

D = declination of magnetic vector

I = inclination of magnetic vector

θ' = latitude of geomagnetic pole

ϕ' = longitude of geomagnetic pole

θ = latitude of collecting site

ϕ = longitude of collecting site

where p is calculated from the dipole formula $\cot p = \frac{1}{2} \tan I$, were used.

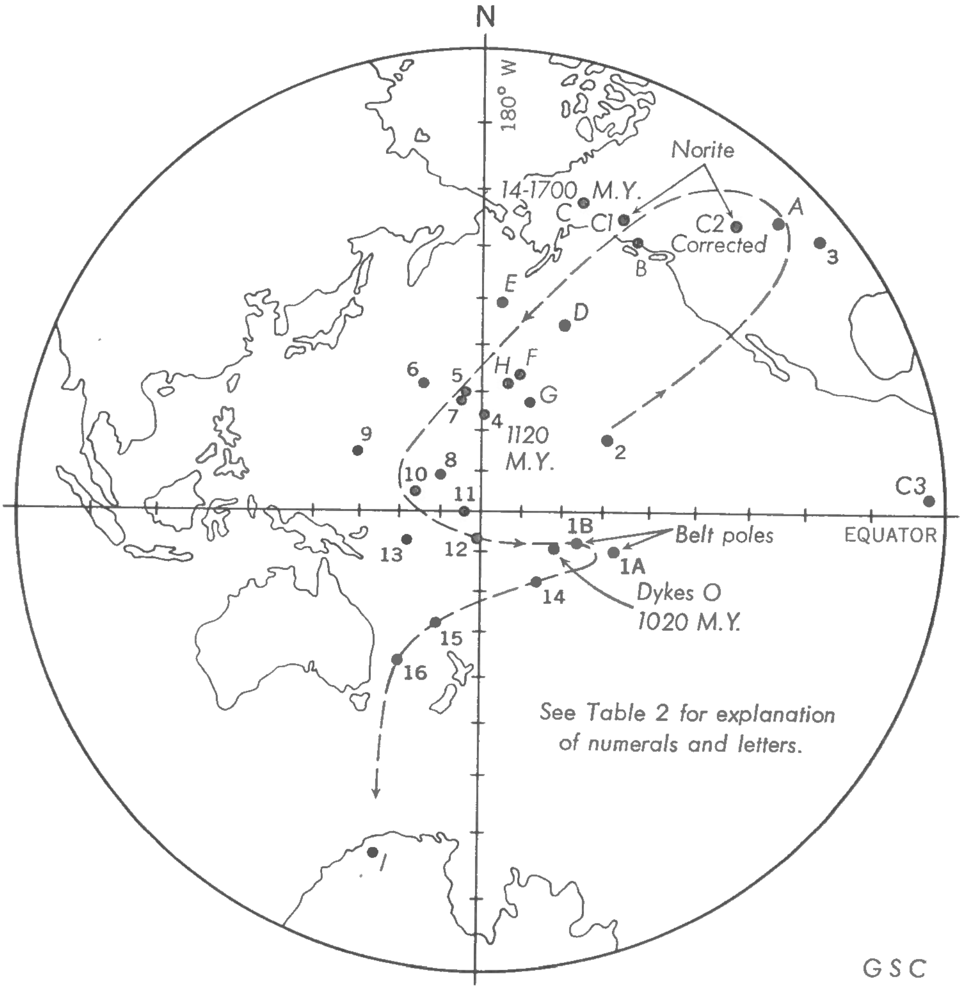


FIGURE 7. Generalized polar wandering curve for Proterozoic rocks of North America (*after* Black, 1963).

The coordinates for the palaeo-geomagnetic pole positions were found to be 130°W and 58°N for the 'uncorrected', and 107°W and 47°N for the 'corrected' models, respectively.

As shown in Figure 7, these two pole positions do not differ appreciably.

The 'north' pole position for the post-irruptive diabase dykes has coordinates 162°W and 8°S.

Correlations with pole positions of other Precambrian formations in North America are illustrated on Figure 7, and listed on Table II.

The 'uncorrected' pole position for the north range of the irruptive agrees well with Hood's (1958) results and falls along the polar wandering curve after DuBois (1962) for rocks of Keweenawan age. However, recent radioactive dating indicates that the norite was intruded between 1,400 to 1,700 million years ago (Fairbairn, *et al.,* 1960). If this dating is reliable, it would suggest either that the polar wandering path in pre-Keweenawan times intersected the path traced approximately 400 to 700 million years later, or that the pole position remained fairly stable in pre-Keweenawan (Huronian) times but started to wander in the late Keweenawan. There is also the possibility that the age determination of the rocks on which DuBois' polar wandering curve is based may be in error.

It is interesting to note that pole positions for the Purcell System (Collinson and Runcorn, 1960; Black, 1963) lie within the oval of error for the position obtained for the diabase dykes. From a review of the geological evidence, Black has tentatively dated the Purcell System as 1,000 million years. This agrees very well with the radiogenic age of 1,020 million years for the diabase dykes. Black found it necessary to modify DuBois' curve so as to embody this new pole position for the Purcell System. From the coincidence of pole positions, it appears that the present results agree well with the polar wandering curve modified by Black (*see* Fig. 7).

PALAEOMAGNETISM AND THE ORIGIN OF THE SUDBURY IRRUPTIVE

Palaeomagnetic data alone cannot be used to indicate which of the five hypotheses of origin of the Sudbury irruptive outlined earlier in this report is the most acceptable. Additional geological and geophysical evidences must be considered as well; some of these are enumerated below.

(1) Shearing, foliation, and schistosity are pronounced in the south range and are virtually absent in the north range.

(2) In the north range the irruptive is underlain by the strongly metamorphosed Levack complex. Most geologists, including Collins (1935), Thomson (1956), and Langford (1960), have inferred that this northern buttress has not been disturbed to any appreciable extent by post-irruptive deformation. If it can be assumed that the norite-micropegmatite intrusion has been protected by the Levack complex from strong shearing and foliation, it follows that the attitude of the north range in turn has not been displaced markedly from its original position.

(3) Gravity data (Miller and Innes, 1955) favour the hypothesis that the irruptive has an asymmetric basin shape and that there was no large single plug or neck in the centre to serve as a feeder. If, however, a large single feeder did exist, the gravity measurements would suggest its location along the southern boundary of the irruptive.

(4) The proportion of acidic to basic rock, especially in the north range, is far greater than can be explained by magmatic differentiation. One explanation is that the micropegmatite forms a more or less horizontal crust over the norite and has therefore been exaggerated by erosion. Double intrusion has also been suggested to explain this phenomenon (Phemister, 1925).

(5) Although the sequence of development of the intra- and extra-basinal accumulations is still an enigma, the local origin of the volcanic debris via glowing avalanches and fissures around the rim of the irruptive (Williams, 1956) seems to be well established.

(6) The irruptive rocks are younger than the overlying volcanics and sediments.

The value for the relative rotation between the sectors of the irruptive was obtained by allowing their mean directions of magnetization plotted stereographically to lie on a great circle. The angular distances between these points would then represent the degree of folding.

Assuming that both rims of the irruptive were intruded simultaneously, the present study has indicated that the amount of relative rotation between the calculated mean directions of magnetization for the north and south ranges is approximately 40 degrees. The horizontal axis of rotation lies in the direction

N67°E and agrees very well with the axis of folding determined by Collins (1935) for the intra-basinal Whitewater Series. The east and northeast parts of the irruptive have been folded as well towards the inside of the basin. If it is assumed, from foregoing considerations (1) and (2), that only a small amount of folding took place in the north range, that is, about 5 to 10 degrees, then the south range has been rotated through the remaining 30 degrees. These figures are for the proportional movements of the north and south ranges with respect to an hypothetical fixed axis placed between them, not for the absolute rotations of the irruptive. By the same considerations, the 'east' range has been rotated towards the inside of the basin about 30 degrees.

The significance of this new data to the hypothesis of emplacement of the Sudbury irruptive should now be apparent. The palaeomagnetic data indicate that folding subsequent to intrusion of the irruptive did take place but that it was not severe enough to produce the present attitudes around the Sudbury Basin. It also indicates that the north range has not been displaced markedly from its original position, that the irruptive was not initially a more or less horizontal sill, and that the extent of folding in the south range subsequent to intrusion was 30 to 40 degrees. Present and probable original attitudes of the norite are shown on Figure 1. The original attitude of the irruptive in the south range varied from close to vertical in the southwest to about 50 degrees in the east. Rotation of the original magnetization direction in specimens from the Falconbridge area (sector 6, Fig. 1) appears to have been greater than average and is calculated to be approximately 45 to 50 degrees. Data from this locality are based on scanty sampling, however, as indicated by the large circle of confidence on Figure 3. Nowhere was the original attitude of the irruptive in the south range less than 10 to 15 degrees inclined towards the basin, an average original dip for the central part of the south range being approximately 30 to 35 degrees in a northwesterly direction. Data from specimens collected underground indicate the same directions of magnetization as those collected from the surface.

These data, therefore, disprove Collins' (1935) folded flat sill hypothesis and Hamilton's (1960) extrusive origin hypothesis. Workable hypotheses for the origin of the Sudbury irruptive are thus limited to those of Knight (1917), Thomson (1956), and Wilson (1956).

Although there is no unequivocal evidence to substantiate any one of the three workable hypotheses, the writer favours a modification of Wilson's funnel-shaped intrusion hypothesis. The intrusion is believed to have been emplaced initially with an asymmetric form, from a source somewhere below the south range of the irruptive. Post-irruptive slumping and folding towards the interior of the basin resulted in the present attitudes.

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APPENDIX

Table I. Directions of Magnetization

Table II. Precambrian Pole Positions

Table I

Directions of Magnetization

	Initial		Final (after 'washing')		
Sample No.	Declination	Inclination	Declination	Inclination	Circle of Confidence
Norite Influenced by Olivine Diabase Dyke Intrusion					
16S	245	22	246	18	
16K	246	1	246	1	
17S	297	−8	270	−3	
17K	264	−5	264	−5	
24S	254	−4	251	−6	
24K	256	−3	258	−5	
Mean			256	0	11°
Olivine Diabase Dykes					
15S	292	50	—	—	
15K	266	52	267	5	
34S	267	7	266	−2	
34K	266	30	280	9	
119S	245	−25	246	−15	
119K	174	2	247	−2	
120S	78	61	253	−8	
120K	242	44	263	0	
Mean			260	−2	11°
Sectors Nos. 1 and 2					
92S	358	−39	284	74	
92K	64	−45	—	—	
93S	208	−87	208	−87	
93K	86	−78	72	−86	
94S	351	72	351	72	
94K	7	69	7	69	
101S	290	72	290	72	
101K	113	−31	—	—	
103S	—	—	—	—	
103K	324	63	324	63	
8S	287	9	306	23	
8K	294	65	260	72	
51S	150	−34	307	73	
51K	202	66	221	69	
52S	170	69	205	85	
52K	270	72	325	75	
95S	340	72	323	74	
95K	316	54	0	63	
99S	296	55	269	57	
104K	318	71	308	69	
91S	291	30	270	16	
91K	347	9	334	9	
99K	217	37	216	36	
100S	174	26	178	29	
100K	145	−20	197	11	
104S	289	33	285	24	
Mean			308	76	8°

Table I (*Cont'd.*)

	Initial		Final (after 'washing')		
Sample No.	Declination	Inclination	Declination	Inclination	Circle of Confidence
Sector No. 3					
107S	—	—	—	—	
107K	—	—	—	—	
102S	—	—	—	—	
102K	196	−60	12	59	
108K	321	33	315	54	
108S	274	15	269	24	
Mean					
Sector No. 4					
54S	349	54	316	71	
54K	204	29	—	—	
55S	176	2	—	—	
55K	—	—	—	—	
56S	11	−30	43	72	
56K	266	72	44	77	
53S	21	83	357	79	
53K	308	78	308	78	
Mean			2	79	11°
Sector No. 5					
33S	67	48	65	49	
33K	78	40	75	38	
35S	9	79	5	69	
35K	333	61	331	57	
59S	81	46	75	34	
59K	76	41	76	41	
97S	78	88	78	88	
97K	16	57	18	59	
98S	128	67	128	67	
98K	84	79	84	79	
37S	172	−46	352	47	
37K	—	—	—	—	
36S	40	70	62	39	
36K	75	48	77	46	
57S	95	58	84	61	
57K	48	70	50	77	
96S	72	62	65	64	
96K	—	—	35	77	
47S	281	33	278	21	
47K	—	—	—	—	
48S	124	−51	111	−45	
48K	294	30	—	—	
Mean			63	62	11°
Sector No. 6					
29S	202	14	198	21	
29K	181	31	181	27	
30S	117	63	176	40	
30K	158	0	181	44	
31S	227	30	179	55	
31K	133	39	140	30	
Mean			176	38	17°

Table I (*Cont'd.*)

	INITIAL		FINAL (after 'washing')		
Sample No.	Declination	Inclination	Declination	Inclination	Circle of Confidence
Sector No. 7					
18S	172	74	180	70	
18K	186	65	186	65	
19S	156	68	152	67	
19K	134	14	151	61	
20S	147	44	148	38	
20K	154	36	154	36	
23S	185	67	191	65	
23K	184	77	174	76	
26S	151	62	151	58	
26K	160	75	161	71	
22S	341	83	345	84	
22K	306	78	306	78	
114K	77	85	2	77	
Mean			170	63	10°
Sector No. 8					
14S	179	66	177	66	
14K	171	65	171	65	
25S	160	73	163	69	
25K	101	65	165	67	
27S	174	76	178	76	
27K	101	65	183	70	
40S	181	65	183	66	
40K	32	−50	—	—	
41S	164	64	169	57	
41K	143	54	135	49	
49S	170	70	172	72	
49K	242	76	173	64	
115S	348	58	329	63	
115K	6	51	6	51	
Mean			168	66	6°
Sector No. 9					
42S	183	66	185	60	
42K	220	65	202	62	
45S	155	58	160	57	
45K	175	67	181	70	
46S	191	43	155	56	
46K	155	65	145	56	
116S	198	39	205	63	
116K	202	62	202	62	
117S	183	61	183	61	
117K	193	64	193	64	
43S	345	62	353	60	
43K	—	—	—	—	
Mean			180	64	9°
Sector No. 10					
62S	350	71	1	64	
62K	—	—	—	—	
109S	324	43	16	74	
109K	163	64	179	44	

Table I (*Cont'd.*)

	Initial		Final (after 'washing')		
Sample No.	Declination	Inclination	Declination	Inclination	Circle of Confidence
Sector No. 10—Conc.					
110S	276	78	—	—	
110K	—	—	334	61	
111S	243	66	246	67	
111K	244	66	244	68	
112S	181	62	—	—	
112K	287	21	—	—	
113S	278	54	270	63	
113K	220	82	198	71	
65S	30	74	85	80	
65K	18	49	117	69	
60S	271	−27	277	19	
60K	303	34	271	−23	
61S	33	−17	40	−17	
61K	9	65	—	—	
64S	275	− 7	285	−4	
64K	223	48	—	—	
Mean			261	79	19°
Sector No. 11					
80S	265	73	284	75	
80K	307	65	273	75	
81S	331	75	—	—	
81K	324	45	324	47	
82S	238	−50	—	—	
82K	323	−76	—	—	
83S	229	56	261	56	
83K	266	58	266	58	
84S	255	55	263	54	
84K	258	55	258	55	
85S	268	68	267	65	
85K	259	61	259	61	
78S	245	37	242	38	
78K	263	31	263	31	
79S	70	29	—	—	
79K	99	64	—	—	
Mean			273	62	9°
Sector No. 12					
3S	285	67	282	66	
3K	288	57	288	57	
88S	—	—	—	—	
88K	15	69	15	69	
89S	342	60	342	60	
89K	339	73	339	73	
90S	110	−36	—	—	
90K	274	63	274	63	
2S	332	69	—	—	
2K	351	63	345	55	
86S	104	−50	280	51	
86K	10	64	—	—	
87S	27	1	—	—	
87K	221	−18	222	−13	
Mean			320	71	16°

Table I (*Cont'd.*)

	INITIAL		FINAL (after 'washing')		
Sample No.	Declination	Inclination	Declination	Inclination	Circle of Confidence
Sector No. 13					
4S	288	67	295	64	
4K	304	63	304	63	
5S	299	62	292	59	
5K	342	65	330	57	
6S	345	57	276	64	
6K	—	—	—	—	
9S	286	63	290	61	
9K	284	64	284	64	
50S	290	76	300	71	
50K	189	86	246	88	
11S	15	83	301	63	
11K	2	68	305	67	
1S	302	66	277	35	
1K	213	51	229	47	
7S	318	50	265	25	
7K	263	38	256	4	
10S	281	30	—	—	
10K	295	13	281	22	
Mean			296	67	7°
Sudbury Gabbro					
68S	7	10	—	—	
68K	305	−4	—	—	
69S	305	26	—	—	
69K	225	37	—	—	
70S	202	74	—	—	
71S	50	−12	—	—	
71K	—	—	—	—	
72S	—	—	—	—	
72K	—	—	—	—	
73S	142	67	—	—	
73K	311	45	308	52	
74S	51	69	—	—	
74K	—	—	—	—	
75S	65	79	—	—	
75K	—	—	—	—	
76S	210	55	—	—	
76K	—	—	—	—	
77S	143	22	—	—	
77K	—	—	—		
70K	59	77	—		
Underground *Crean Hill*					
1	89	77	76	51	
2	—	—	—	—	
3	114	63	—	—	
Garson					
4	196	86	—	—	
5	352	70	—	—	
6	140	70	—	—	
7	74	81	—	—	
8	115	65	—	—	
9	242	78	229	66	

Table I (*Conc.*)

	Initial		Final (after 'washing')		
Sample No.	Declination	Inclination	Declination	Inclination	Circle of Confidence
Murray					
10	226	74	255	78	
11	74	76	—	—	
12	151	79	163	81	
13	333	−7	—	—	
14	244	88	—	—	
Levack					
15	293	66	205	65	
16	321	68	320	69	
17	232	89	289	54	
18	299	70	300	68	
19	287	45	285	47	
20	327	62	—	—	
Frood					
21	41	72	—	—	
22	14	78	—	—	
23	355	70	—	—	
Creighton					
24	62	35	—	—	
25	168	50	173	49	
26	157	79	152	75	
27	174	55	176	55	

Specimens 3, 4, 7, 11, 14, 20, 21, 22, 23, 24 are mineralized.

Table II

Precambrian Pole Positions

No. on Figure 7	Formation or Series	Pole Position		Determined by
		Long.	Lat.	
16	Umfraville and Thanet	157.8E	34.2S	Hood
15	Lodore	169.0E	27.0S	Collinson and Runcorn
14	Jacobsville (Keweenaw)	166.0W	17.5S	DuBois
13	Grenville	162.0E	7.0S	DuBois
12	Mean Jacobsville	179.0E	6.5S	DuBois
11	Orienta I	176.0E	0.0	DuBois
10	Jacobsville (Sault)	164.0E	5.0N	DuBois
9	Eileen	150.5E	13.0N	DuBois
8	Freda and Nonesuch	170.0E	9.0N	DuBois
7	Hakatai	175.0E	27.0N	Collinson and Runcorn
6	Sault Freda (?)	164.5E	31.0N	DuBois
5	Copper Harbor	176.5E	29.0N	DuBois
4	Duluth Gabbro	179.5W	23.5N	DuBois
3	Alona Bay Lavas	95.0W	39.0N	DuBois
2	Sibley Series	149.0W	16.0N	DuBois
1B	Belt Series	157.0W	8.0S	Collinson and Runcorn
1A	Purcell System	148.0W	10.0S	Black
0	Diabase dykes	162.0W	8.0S	Sopher
Letter				
I	Chequamegon	131.5E	68.0S	DuBois
H	Mamainse Point Lavas	173.5W	31.5N	DuBois
G	Portage Lake	168.5W	26.5N	DuBois
F	Logan Diabase II	171.5W	33.0N	DuBois
E	Hazel	175.0W	49.0N	Martinez, Howell, Statham
D	Boulter Gabbro	156.8W	42.6N	Hood
C	Levack	140.7W	64.0N	Hood
C3	South Range (Sudbury)	86.0W	2.5N	Sopher
C2	North Range (Sudbury) (after 10° rotation)	107.0W	47.0N	Sopher
C1	North Range (Sudbury)	130.0W	58.0N	Sopher
B	Logan Diabase I	130.0W	53.5N	DuBois
A	Baraga co. dykes	99.5W	45.0N	Graham