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BULLETIN 79

PALAEOMAGNETISM OF THE MONTEREGIAN HILLS, SOUTHEASTERN QUEBEC

A. Larochelle

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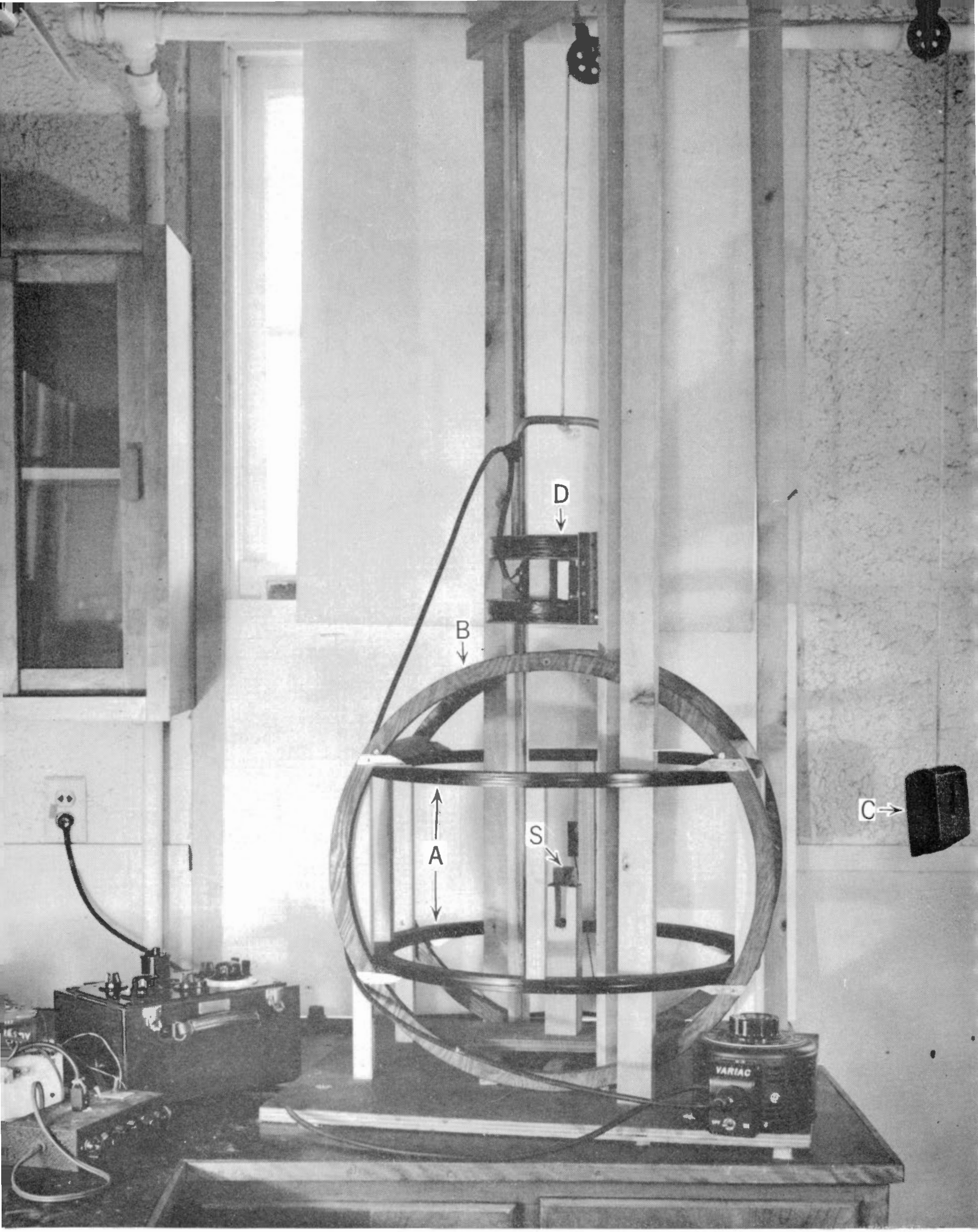

Plate I. *Apparatus for magnetic washing:*
A, B. Helmholtz coils   C. Counterweight   D. Demagnetizing coil   S. Specimen.

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PREFACE

On aeromagnetic maps, most variations expressed by the magnetic contours correspond to gross differences in the underlying rocks. Differences in rock types, however, are not always so apparent, and detailed investigation is necessary to account for the observed phenomena. This is particularly true where reverse polarization has taken place.

In an effort to determine the cause of reverse polarization in parts of the Monteregian intrusions a detailed study, the subject of this report, was made of the remanent magnetism in the rocks concerned.

One of the side results of this study was the tentative conclusion, on geophysical grounds, that the Monteregian intrusions are Jurassic or younger, probably Cretaceous. This age agrees closely with that determined by the potassium-argon method.

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

OTTAWA, September 16, 1960

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PALAEOMAGNETISM OF THE MONTEREGIAN HILLS, SOUTHEASTERN QUEBEC

Abstract

The Monteregian Hills, a series of seven plugs of basic rocks intruding Palæozoic sediments, lie roughly along a curved line extending about 50 miles eastward from Montreal, Quebec. Airborne magnetometer surveys indicate negative anomalies over parts of most of the hills, although strong positive anomalies generally delineate the borders of the intrusive bodies. Attempts to correlate the negative anomalies with the topography of the hills or with petrological boundaries within the igneous masses were fruitless. Remanent magnetization measurements were carried out for a suite of oriented specimens collected from the igneous cores of most of the hills and from the nearby altered sediments. The unstable component of viscous magnetization was removed from the rocks by the slowly decreasing alternating field technique of 'magnetic washing'. After this treatment, the direction of the remanent magnetic moment in the rocks was found to be slightly different from that of the present earth's field or diametrically opposite to it.

The cause of the stable reverse polarization was investigated with the aid of polished sections and Curie point determinations. It was concluded from these results and from the reverse polarization of the altered sediments collected near the igneous contacts that the reverse polarity of parts of the igneous bodies is related to reversals of the former geomagnetic dipole field rather than to a self-reversal mechanism inherent in the rocks. A comparison of the position of the geomagnetic pole for the period during which the rocks were formed with those derived from well-dated sedimentary and volcanic rocks collected elsewhere in North America suggests that the basic rocks of the Monteregian Hills were intruded during the Jurassic or later. This result is in agreement with the K/Ar datings of the Monteregian Hills intrusions.

Résumé

Les collines Montérégiennes forment un groupe de sept coupoles de roches basiques intrusives dans les couches sédimentaires paléozoïques de la partie sud-est de la province de Québec. Elles sont réparties à peu près suivant un arc de courbe à partir de Montréal et qui se prolonge sur une distance d'une cinquantaine de milles vers l'est. Des levés au magnétomètre aéroporté indiquent la présence d'anomalies négatives sur la plupart des collines bien qu'on note des anomalies positives particulièrement prononcées à la bordure des coupoles. C'est en vain qu'on a tenté d'expliquer l'existence des anomalies négatives par le relief à la surface de chaque colline ou par les changements dans la composition pétrographique de chaque masse ignée. On a mesuré le magnétisme rémanent d'une série d'échantillons orientés prélevés, d'une part, du noyau igné de la plupart des collines et, d'autre part, de la bordure des roches sédimentaires altérées, adjacentes aux premières. En utilisant une technique de «lavage magnétique», on a éliminé des échantillons la composante instable que représente l'aimantation visqueuse. Cette technique consiste à exposer l'échantillon aux effets d'un champ magnétique alternatif à amplitude décroissante. Ce traitement a eu pour effet de donner à l'aimantation résiduelle des roches étudiées une orientation un peu différente de celle du champ

géomagnétique actuel, soit dans le même sens que celui-ci ou soit dans le sens diamétralement opposé.

On a cherché à connaître la cause de l'inversion de la composante stable de l'aimantation par l'examen de sections polies et par la mesure des points de Curie de certains échantillons. A partir des résultats de ces études et de la présence d'aimantation inverse dans les échantillons des roches sédimentaires mentionnées plus haut, on a conclu que la polarization inverse de certaines parties des masses ignées est liée à des inversions de l'ancien champ géomagnétique et non à un processus d'inversion spontanée inhérent aux roches étudiées. On a comparé la position du pôle géomagnétique, pour la période de formation de ces roches, avec les positions déduites du paléomagnétisme de roches sédimentaires et volcaniques d'âges bien connus et de provenances différentes en Amérique du Nord. Cette comparaison porte à croire que les roches basiques des collines Montérégiennes ont été injectées au cours du Jurassique ou plus récemment. Des radiodatations par la méthode du rapport K/Ar faites sur des échantillons de roches ignées provenant de ces Collines ont donné des résultats concordants.

Introduction

About 100 years ago it was reported in the literature (Melloni, 1853)[1] that certain rocks possess remanent magnetization. Only during the last few decades however has palaeomagnetism been widely recognized as a potentially useful tool in the hands of the geoscientist. At first, the primary object of this discipline was to reconstruct the intensity and attitude of the earth's magnetic field in the different geological ages. Since then, magnetization data have been used to plot the course of polar wandering and to estimate the direction of continental drift (Runcorn, 1955), and they have been tentatively used to solve problems in structural geology (Blundell and Read, 1958) and correlation (DuBois, 1959a), and to estimate the age of rocks (Armstrong, 1957).

The record at the disposal of the palaeomagnetist is the stable component of residual magnetism in rocks. The main basis for believing in the reliability of this record is the remarkable and consistent discrepancies observed between the magnetization directions of certain formations and the present attitude of the earth's field in the same place. In particular, the natural reverse polarization[2] observed in certain rocks is largely responsible for the growth of interest in palaeomagnetism. A subject of great controversy when first reported (Brunhes, 1906), reverse polarization is now mostly considered to be the result of dipole field reversals in the geological past. It must be recognized, however, that certain rocks are reversely polarized on account of a self-reversal mechanism that is inherent in their component minerals assemblage.

In this study, the magnetization of a suite of oriented specimens collected from the Monteregian Hills basic intrusive series was analyzed and the cause of the reverse polarization observed in some of the specimens investigated. The geomagnetic pole position for the period during which the rocks cooled through their Curie point was determined from the magnetization data. By comparing this pole position with those computed from well-dated rocks spanning the geological column in North America, the age of the intrusions is tentatively determined. Finally, this age estimate is compared with that obtained for the same rocks by means of radiogenic methods.

C. E. Anderson, a student with the Geological Survey of Canada during the field season of 1958, assisted the writer with much of the laboratory and field work.

General Geology[3]

The rocks discussed here belong to a group of consanguineous basic intrusive bodies that lie along a curved line extending about 50 miles eastward from Montreal, Quebec (Fig. 1). The topographic expressions of these bodies are known as the Monteregian Hills, which rise abruptly above the surrounding flat surface of the St. Lawrence Lowlands.

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[1] Names and/or dates in parentheses are those of references cited at the end of this report.

[2] A reversely polarized rock is one whose direction of polarization 'in situ' is exactly or nearly opposite to that of the present earth's field at the collecting site.

[3] The reader is referred to Dresser and Denis (1944) for a more complete discussion of this topic.

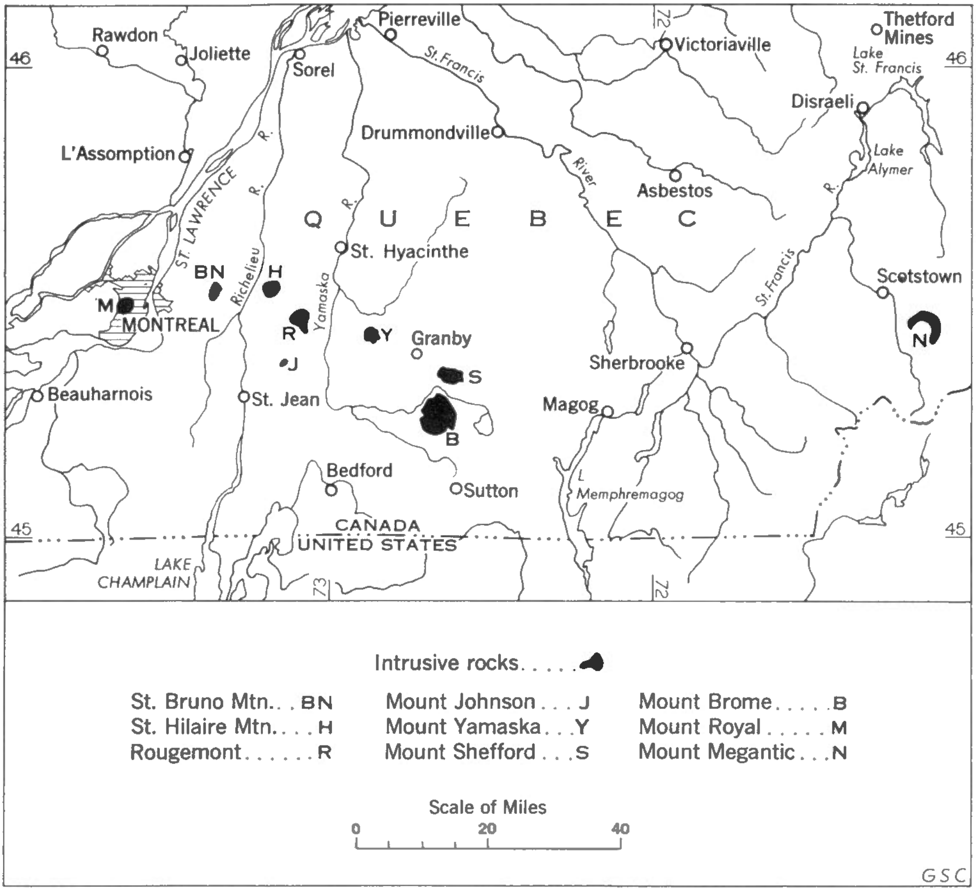


Figure 1. Regional map of the Monteregian Hills.

The igneous cores of the Monteregian Hills consist mostly of alkali (commonly nepheline-bearing) syenites and many varieties of essexites to which various local names have been given. They are generally medium- to coarse-grained rocks with a granitic texture.

The intruded rocks are sediments of Ordovician and Cambrian age. In the eastern part of the region, these were tilted and folded during the Upper Ordovician and Middle Devonian orogenies, but in the western part of the region west of the Champlain fault, which is believed to pass through or within a few miles west of Yamaska Mountain, they are almost undisturbed. Within a few feet of the igneous rocks the sedimentary rocks have generally been altered to hornfels.

The intrusive bodies are generally considered to be either volcanic necks or laccoliths, and breccias in some of them seem to indicate near-surface volcanic activity. The chemical and mineralogical consanguinity of these intrusive bodies, together with their wide distribution, suggest that their parent magma was differentiated at great depth. There is good evidence however to suggest that, for at least some of the hills, the fractionation of the parent magma into the rock types now visible is the product of multiple intrusion. The contacts between certain other rock types are so gradual that there is little doubt that some fractionation also took place near the surface.

It is apparent that most of the hills have experienced some minor faulting, but tilting of the series as a whole or a disturbance involving an entire hill is improbable.

Attempts to establish the age of the Monteregian Hills from field evidence have only succeeded in determining that they could have been emplaced as early as Late Ordovician or as late as Tertiary (Osborne *in* McGerrigle, 1934).

Geomagnetic Features

Aeromagnetic total intensity maps (GSC Geophysics Papers 171 and 183) were published in 1954 for Brome, Yamaska, and Shefford Mountains. The magnetic expression of these three bodies is very conspicuous as the overall intensity of the geomagnetic field and its relief are considerably greater over these bodies than over the surrounding areas. Comparable geomagnetic field contrasts also exist over the other Monteregian Hills, according to an unpublished aeromagnetic map made available to the writer (Paul Riverain, Univ. Montreal, personal communication).

A peculiarity of the geomagnetic field over Yamaska Mountain (*see* Fig. 2) is that at 500 feet above ground the total intensity in some places is as much as 3,000 gammas below the regional magnetic level, whereas elsewhere it is about 3,000 gammas above that level. These differences were traced on the ground by the writer using an Askania type vertical force magnetometer. Maximum intensities on the ground were found to be of the order of 15,000 gammas below and above the regional magnetic field intensity as observed away from the mountain. This kind of feature is not nearly so apparent on the Brome Mountain aeromagnetic map, but a magnetic depression does occur in the southeastern corner of the mountain. There also, ground profiles confirmed a negative anomaly of 12,000 gammas below the regional magnetic level. Its horizontal spread is so small—about 15,000 square feet—that it could not be completely resolved by the airborne magnetometer.

At first glance it might be concluded that the strong positive and negative magnetic anomalies were due to marked differences in elevation of different parts of the mountain. Careful examination, however, shows that high and low areas do not correspond respectively to areas of high and low magnetic intensity (*compare* Fig. 2 with Fig. 8Y).

As the topographic effect seems to be negligible, the presence of anomalies of opposite polarity over the same bodies must have some other explanation. Either the residual magnetism of parts of the bodies is oriented in a direction opposite to that of the present earth's field, or the magnetic susceptibility in parts of the bodies is negligible as compared with the extremely high susceptibility of the rocks in adjacent parts of the bodies. If the second of these hypotheses is true, similar rocks should underlie areas showing similar magnetic anomalies and they should differ from rocks underlying areas showing different magnetic anomalies. This is so because it has been shown that the degree of magnetic susceptibility is a function of the composition

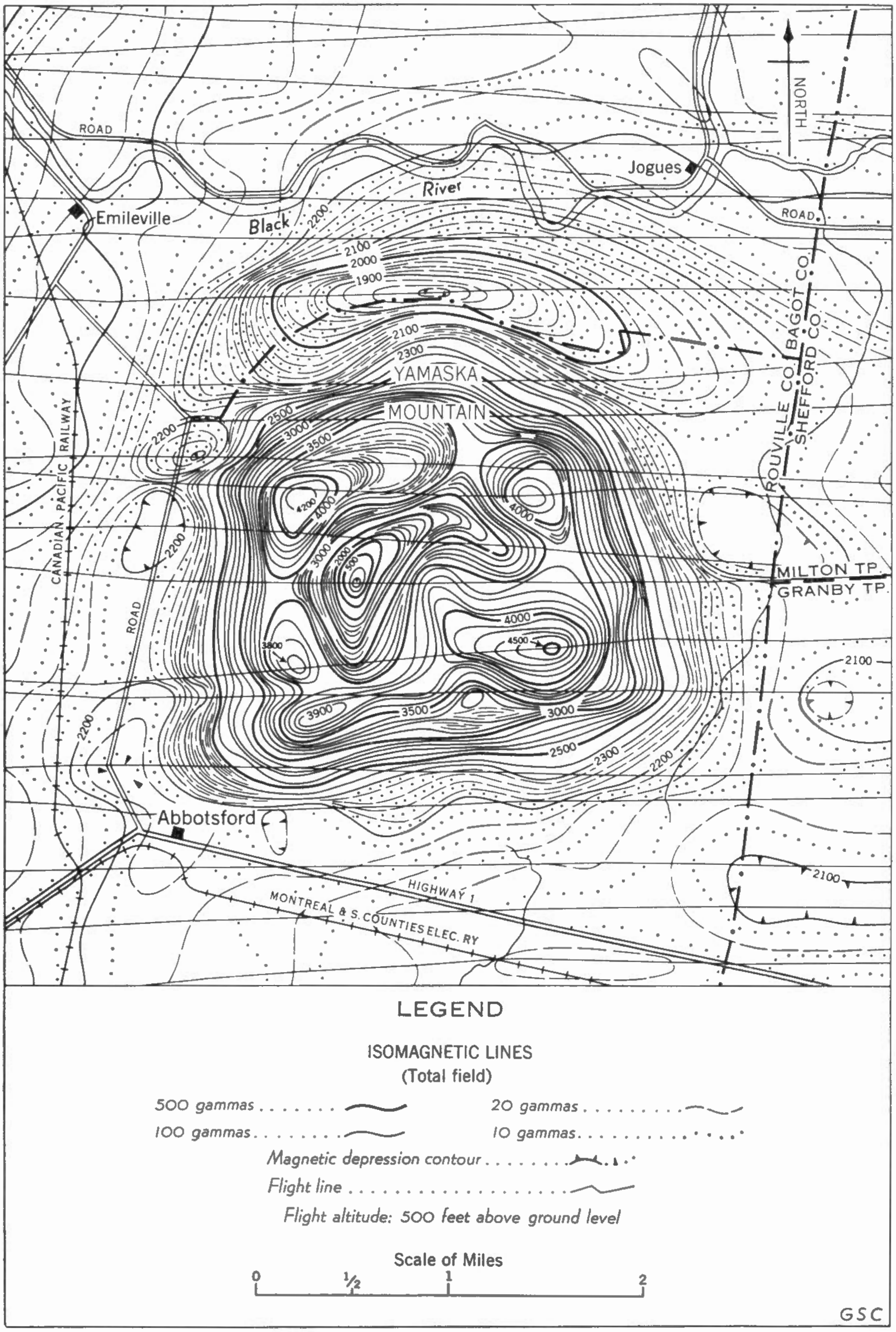


Figure 2. **Aeromagnetic map of Yamaska Mountain.**

and texture of a rock. The Monteregian Hills have not been mapped geologically in sufficient detail to permit a direct comparison of the geological map with the aeromagnetic map. In an effort to solve this problem samples were taken and the measurement of their residual magnetization is the basis of this report.

Collection and Preparation of Specimens

In collecting the oriented specimens the following technique was followed. A flat surface, say a joint plane, was selected on the outcrop and on it a horizontal arrow was drawn. The direction of dip of the surface was also marked by a line perpendicular to the arrow. Before the specimen was broken away from the outcrop the azimuth of the arrow was determined with a Brunton compass, held a few feet above the outcrop, and the slope of the dip line measured with a clinometer. These measurements were made with an estimated accuracy of ±1 degree. In order to eliminate errors from local magnetic effects, the compass readings were corrected by adding the angular difference between the apparent azimuth of the sun and its true azimuth as given in the ephemeris tables. In the collection of about half of the specimens, if sun conditions permitted, the possible error occasioned by local magnetic attraction was eliminated by the use of a solar compass.

In the laboratory the specimens were first embedded in plaster of Paris in such a way that their original attitude in the field was reproduced. A 2-inch-diameter vertical core was then drilled from the specimen and the core cut into two or three 1-inch cubes, precaution being taken to faithfully preserve the field orientation.

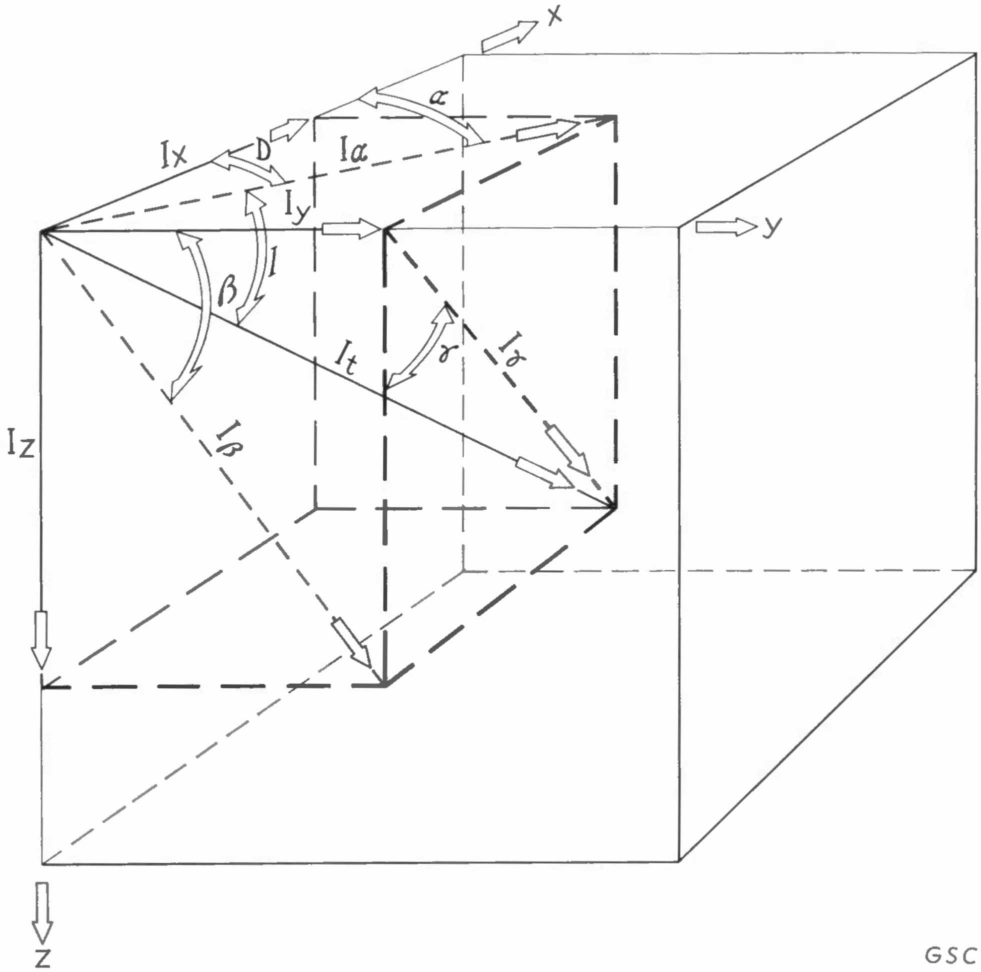
Measuring Techniques

Two types of instruments were used, depending upon the intensity of magnetization of the rocks dealt with: an astatic type magnetometer and a rock generator or spinner-type magnetometer. The former is a very sensitive apparatus, well suited for rocks having low intensities of magnetization. Measurements with this type of instrument are, however, slow and tedious. The rock generator type of instrument is not so sensitive but is much faster to use, and stereographic projections can be used to resolve the magnetometer readings in terms of inclination and declination.

The astatic magnetometer used in the present study was kindly put at the disposal of the writer by the Geomagnetic Division of the Dominion Observatory. An instrument of this type has already been described by Collinson, *et al.* (1957).

The components of the remanent magnetization along the X, Y, and Z axes are measured (*see* Fig. 3). From the moduli of I_x and I_y, it is possible to determine the orientation of I_α in the horizontal plane. The angle (I_α, X) corresponds to the declination D of the total intensity magnetic vector I_t. The inclination I of I_t may be calculated by using the relation: $\tan(I) = I_z/I_\alpha$.

The rock generator type magnetometer used was a modification of those described in the literature by Bruckshaw and Robertson (1948), Johnson (1938), and Johnson, Murphy, and Michelsen (1949). The unit is schematically represented in Figure 4, and was designed and built under the direction of L. S. Collett of the Geological Survey of Canada.



GSC

Figure 3. Sketch showing terms used, X direction corresponds to astronomic north of specimen in situ.

An ordinary A.C. electric motor is used to spin the rock cube at the rate of about 1,800 rpm. The rotation of the cube (of magnetic moment I_t) in the vicinity of coil L_2 generates a voltage across the end terminals of the coil. Coil L_3, which is well separated from the spinning cube, is wound in series opposition with coil L_2. Transient fluctuations in the magnetic field surrounding the instrument will generate a voltage across each of the coils. As the coils are wound in series opposition the two voltages will cancel each other. The voltage generated in coil L_3 by the spinning cube is negligible compared with its counterpart across L_2, due to the geometrical configuration of the coil system. A small Alnico magnet towards the motor end of the shaft is used to generate a reference voltage across coil L_1, at the same frequency as the voltage generated by the spinning cube. The phase angle between this voltage and voltage across L_2 may be made zero by rotating coil L_1 about the spinning axis. This provides

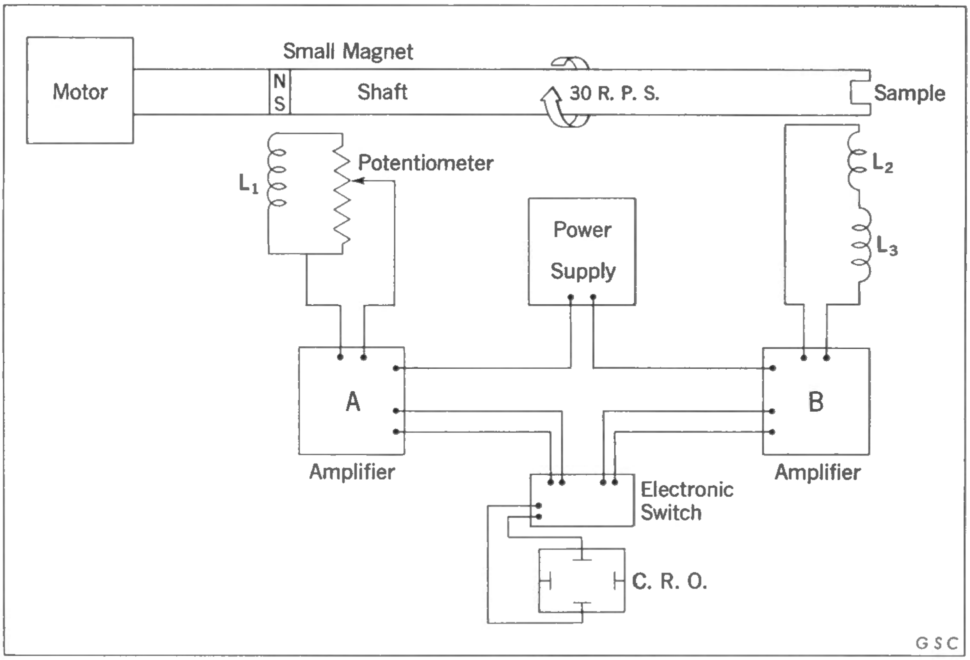


Figure 4. Schematic diagram of rock generator.

a means of measuring angles α, β, and γ (*see* Fig. 3). Similarly, the amplitude of the two voltages may be made equal by means of the potentiometer across coil L_1, this providing a means of measuring the intensity of magnetization of the components I_α, I_β, and I_γ. The two voltages are amplified through separate channels which feed into an electronic switch and their respective traces may be observed on the screen of a cathode ray oscilloscope. When the two traces blend into one on the screen, the graduation of the potentiometer and the position of coil L_1 are recorded. The former being a measurement of I_α, I_β, and I_γ and the latter of α, β, and γ. The limit of resolution of the instrument is of the order of 10^{-5} emu/cu. in. and angles may be determined with an accuracy of 5 degrees.

Theoretically, only two of the three sets of parameters (I_α, α), (I_β, β) and (I_γ, γ) are necessary to determine the angles of declination D and inclination I of the magnetization of a cube. In practice, however, it was found that by doing so considerable error might be introduced. A simple example will illustrate this. Assuming a possible error of 5 degrees in the angle measurements, let us assume a magnetization vector whose true declination is 130 degrees and whose true inclination is 44 degrees. If this vector were measured with a perfect instrument, the angles α, β, and γ, would be 130, 52, and 327 degrees respectively. With an instrument yielding results accurate to the nearest 5 degrees, the angular readings could be, say, 125, 56, and 322 degrees respectively. It is shown in Figure 5 that the great circles corresponding to these angles do not intersect at a single point but that the intersection of any two of them forms the corner of a spherical triangle ABC projected on the horizontal plane.

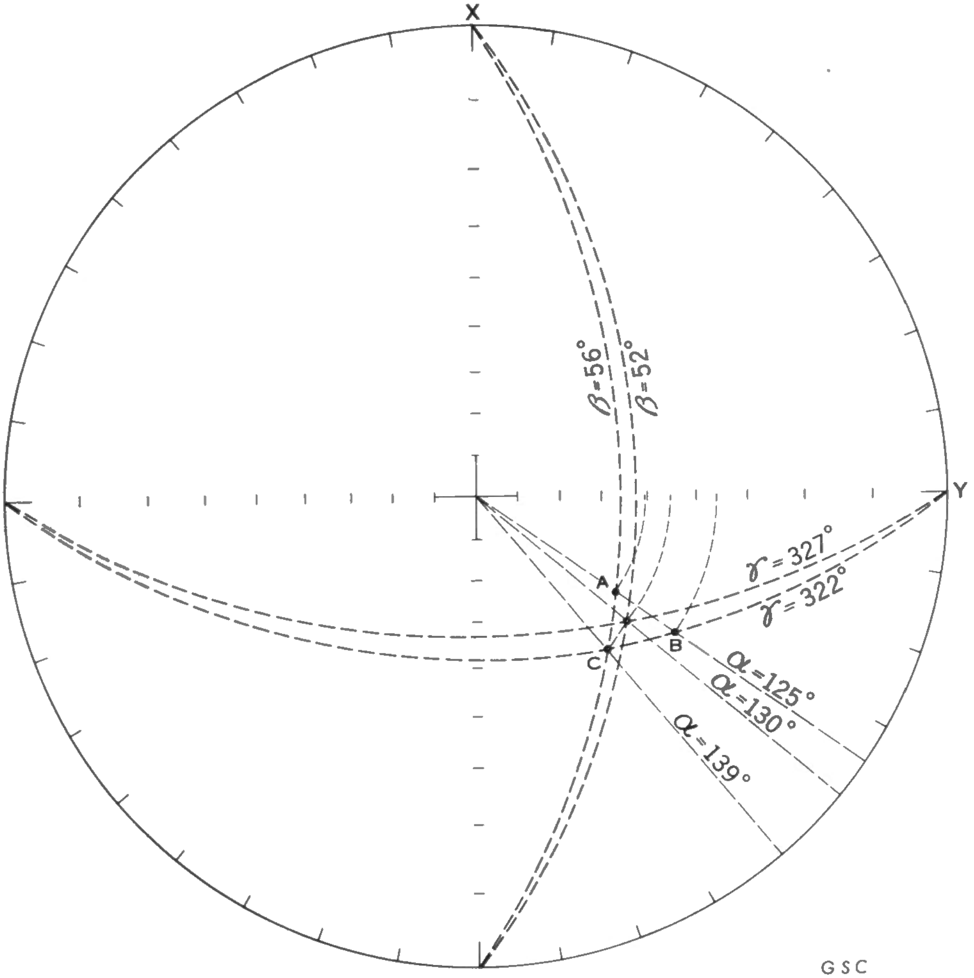


Figure 5. Method of determining 'I' and 'D'.

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 would be 125, 51; 125, 36; and 139, 44 degrees for corners A, B, and C respectively. If one of these three pairs of values were right it is clear that each of the others is very much in error. It is also evident from Figure 5 that any point inside the triangle ABC will be closer to the true value than any of the points, A, B, or C. Unfortunately, in practice the extent of error in the readings for α, β, and γ is unknown, or whether it is too high or too low. For these reasons it is advisable to distribute the possible error equally over each reading. On the stereographic projection this is done by revolving about its main diameter by an equal angle each of the great circles representing α, β, and γ, in such a way that they intersect at a point. This operation is represented in Figure 5, and in this example, a 4 degree rotation in the clockwise direction for the α and γ

circles and in the counterclockwise direction for the β circle yielded a one point intersection for the three circles. By using any one of the corners A, B, or C, the possible error in pole position would be 14 degrees but, if the method described above is used, the possible error is reduced to 7 degrees. In the hypothetical case being considered, the actual error is 8 degrees if corner B is taken as representative of the magnetization vector but would be reduced to zero if the revolving method is used. This ideal condition is, however, only present if the error is of the same order of magnitude for each of the three angles.

That the great circles representing the three angles α, β, and γ, commonly fail to intersect at a point is due partly to errors in measurement occasioned by the low resolution power of the instrument, partly to a systematic error inherent in the instrument, and partly to inhomogeneities in the distribution of the ferromagnetic mineral through the rock cube. The last two factors may be almost completely eliminated if the cube is spun in a direction both clockwise and counterclockwise about the X, Y, and Z axes. As the motor driving the cube in the present instrument could not easily be reversed, the same result was reached by spinning the cube in the six positions shown in Figure 6. Angles α, β, and γ were first obtained by spinning the cube in positions I, II, and III respectively. The cube was then rotated into positions IV, V, and VI and angles α', β', and γ' measured. If the cube is homogeneous, that

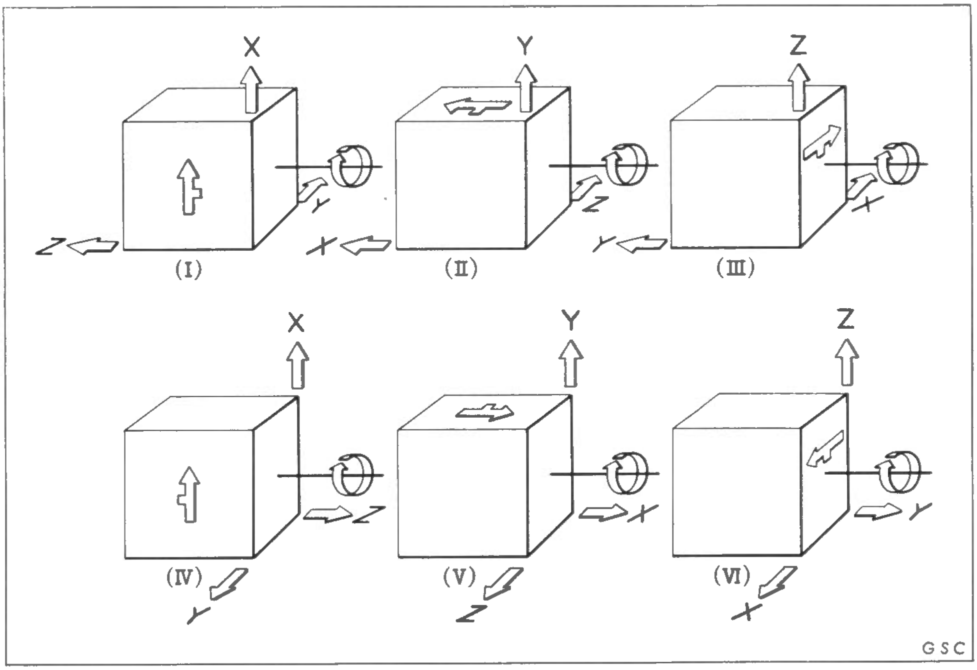


Figure 6. *The six positions in which the cube was spun.*

is that no systematic error is inherent in the instrument and that no error is made in the measurements, the following relationship should hold true:

$$\alpha' = (360° - \alpha); \qquad \beta' = (360° - \beta); \qquad \gamma' = (360° - \gamma).$$

Furthermore, the values $\bar{\alpha}$, $\bar{\beta}$, and $\bar{\gamma}$ derived from the expressions:

$$\bar{\alpha} = \frac{(\alpha + 360° - \alpha')}{2}; \quad \bar{\beta} = \frac{(\beta + 360° - \beta')}{2}; \quad \bar{\gamma} = \frac{(\gamma + 360° - \gamma')}{2}$$

are free from any error in the position of the instrument's zero. Similarly, if the magnetization in a cube is not homogeneous, the lack of homogeneity is at least partly eliminated in the values of $\bar{\alpha}$, $\bar{\beta}$, and $\bar{\gamma}$, as illustrated by the following example. Values of α, β, and γ and α', β', and γ' were read directly on the instrument's dial, and the corresponding values of $\bar{\alpha}$, $\bar{\beta}$, and $\bar{\gamma}$ were computed.

$$\begin{array}{lll} \alpha = 009° & \alpha' = 308° & \bar{\alpha} = 030.5° \\ \beta = 004° & \beta' = 329° & \bar{\beta} = 017.5° \\ \gamma = 057° & \gamma' = 270° & \bar{\gamma} = 073.5° \end{array}$$

In Figure 7, the circles representing the angles given in the first column intersect points A, B, and C, and the probable position of the corresponding vector, as derived by the method described earlier, is indicated at point O. The D and I of this pole are 29 degrees and 13 degrees respectively, and the possible error in using it to represent the magnetization vector in the cube is of the order of 60 degrees. Similarly, angles $(360° - \alpha')$, $(360° - \beta')$, and $(360° - \gamma')$ are plotted and the corresponding points A′, B′, and C′ are obtained. The corresponding point O′ has a D of 37 degrees, and an I of 11 degrees, with a possible error of 35 degrees. Finally, the circles representing $\bar{\alpha}$, $\bar{\beta}$, and $\bar{\gamma}$ are plotted and the corresponding points $\bar{A}$, $\bar{B}$, $\bar{C}$, and $\bar{O}$ indicate a mean D of 32 degrees, a mean I of 12 degrees, with a possible error of only 8 degrees.

Distribution and Measurement of Specimens

Sixty-three oriented samples were collected from the Monteregian Hills, most being from the igneous cores of Yamaska[1] and Brome Mountains (*see* Fig. 8). Some were also collected from the intruded sedimentary rocks at different distances from the intrusive contacts. It will be recalled that the near-contact sediments were metamorphosed into hornfels during the intrusions, whereas the rocks as little as a quarter of a mile away from the contacts did not undergo such metamorphism. It seemed likely that either new ferromagnetic minerals were formed at low temperature as a result of the metamorphism or primary ferromagnetic minerals were temporarily heated above their Curie points. In either case, the rocks would then be magnetized in a direction parallel with that of the ambient earth's field at the time of the intrusions. The magnetization of the rocks remote from the intrusions would naturally have remained unaffected.

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[1] Most samples from Mount Yamaska were collected by R. Mitra.

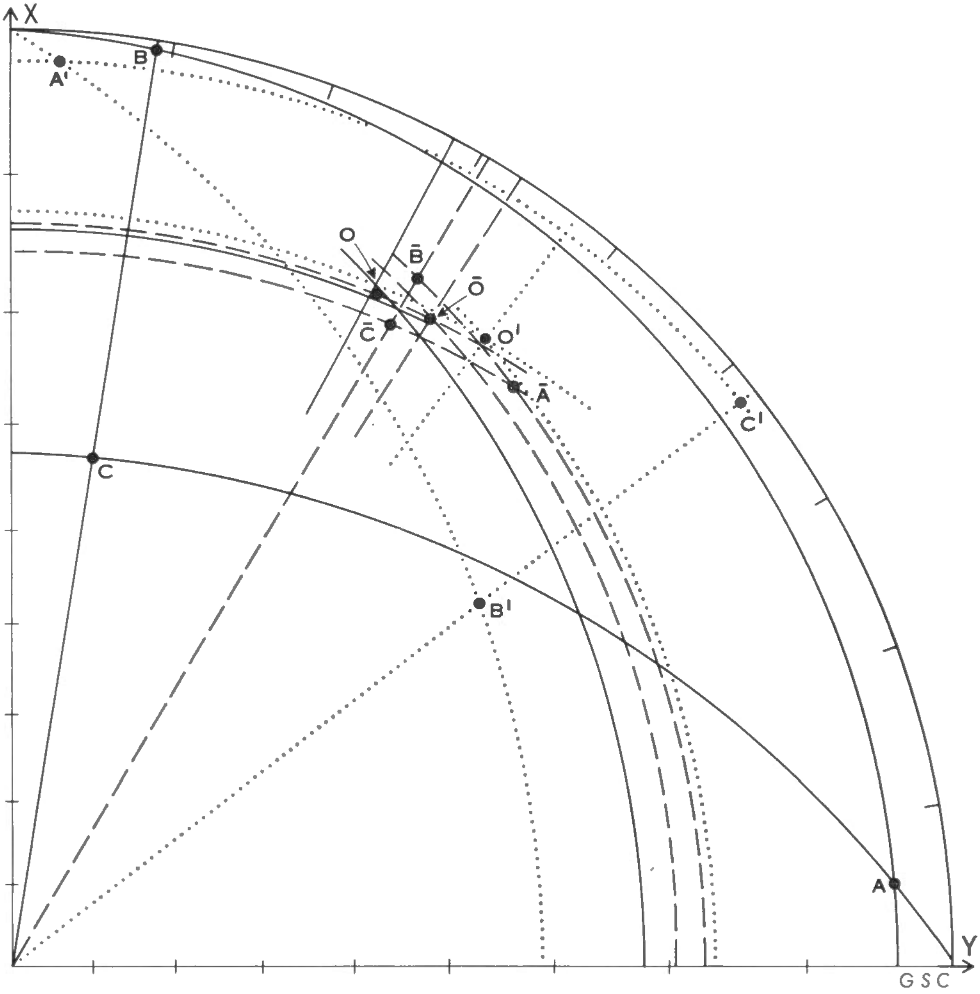

Figure 7. *Reduction in possible error by spinning of cube No. 18-1 in clockwise and counterclockwise directions.*

Some of the specimens collected, both from the intrusive bodies and from the adjacent sedimentary rocks, were not used in the present study, either because of their considerable magnetic inhomogeneity or instability, or because evidence was found that they had been polarized by lightning since the time of their original magnetization. Typical examples of these are discussed on page 21.

The measurements of the usable specimens are given in Table I and the directions of magnetization are represented on a stereographic projection (Fig. 9). Only the arithmetic mean of the directions and intensities obtained from two or three cubes from each sample are given. In no case did the direction for cubes from a single specimen differ by more than 20 degrees. The mean orientations were computed graphically on a stereonet. Intensities are not reported for the specimens measured

Table I

Direction of Residual Magnetism of Specimens from Monteregian Hills

			Before Magnetic Washing			After Magnetic Washing		
Specimen No.	Collecting Site **	Number of Cubes	Declination	Inclination	Intensity emu/cu. in. × 10^{-5}	Declination	Inclination	Intensity emu/cu. in. × 10^{-5}
3*	Y	2	265	−40	....	159	−30	....
5	B	2	353	+50	270	012	+28	....
6*	B	2	103	−16	....	048	−71	....
7	S	3	018	+05	56,033	003	+41	2,710
9*	B	2	173	+27	....	283	−26	....
10	S	3	118	−63	448	134	−62	294
12	S	2	114	+16	557	150	−38	796
13	R	2	333	+44	631	314	+53	434
14	R	3	223	−03	1,617	166	−38	576
15*	R	2	077	+36	....	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	....
30	J	2	333	+57	5,960	340	+57	3,430
32	J	2	332	+59	9,180	343	+57	6,107
36	B	2	145	+05	3,880	122	−40	2,670
37	B	2	160	−24	14,675	119	−51	6,550
37-b	B	2	123	−15	14,300	118	−42	7,215
38	B	2	142	−22	8,485	113	−45	4,045
38-b	B	2	115	−24	10,645	098	−45	4,480
39	B	2	134	−16	35,050	109	−41	5,155
40	B	2	001	+38	37,650	136	−63	683
41	B	2	014	+42	2,720	111	−60	885
42	B	2	043	−19	97,800	139	−38	7,075
43	B	3	147	−28	51,030	136	−35	13,923
44	B	3	142	−28	9,080	087	−40	2,360
53	Y	2	085	−14	756	169	−59	1,336
55	Y	2	258	−35	1,895	170	−61	190
67	Y	3	144	−43	40,400	162	−67	56,733
71	Y	2	219	−56	33,900	171	−61	15,600
72	Y	2	208	−67	72,400	160	−53	18,550
74	Y	2	111	−46	26,900	128	−70	20,600
87	Y	3	036	+51	4,373	025	−65	1,555
103	Y	3	242	+40	59,766	225	−18	2,593
104	Y	2	018	−16	56,500	341	−57	1,924
105	Y	3	174	−69	2,340	148	−66	1,973
111	Y	3	319	+38	4,586	022	−70	2,303
113	Y	3	265	+15	22,600	315	−60	3,156
120	Y	3	228	−63	29,200	204	−66	40,950
121	Y	3	230	−57	25,166	198	−71	27,533
138	Y	2	073	+46	1.660	304	−65	1,435

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

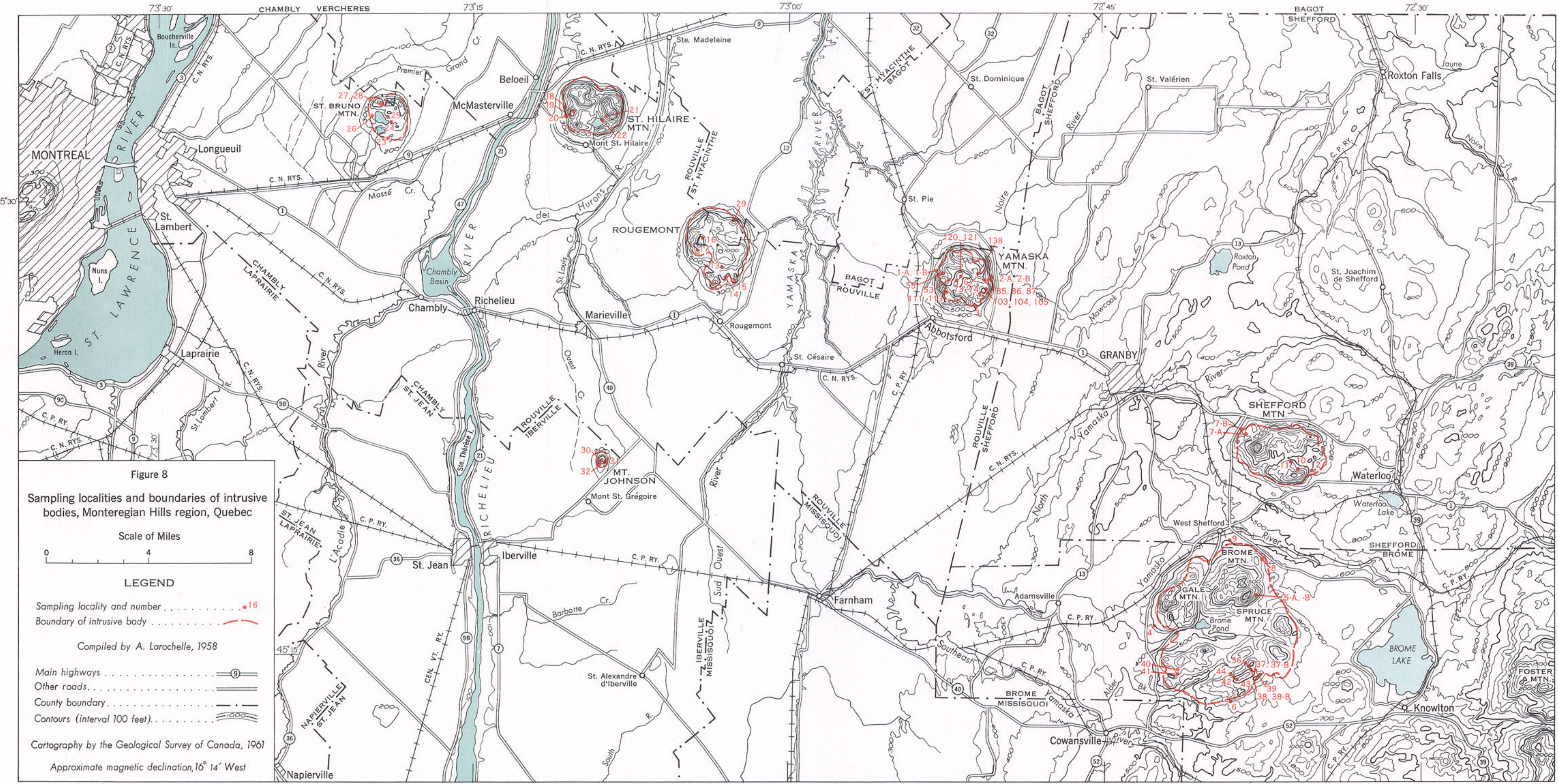

Figure 8

Sampling localities and boundaries of intrusive bodies, Monteregian Hills region, Quebec

Printed by the Surveys and Mapping Branch

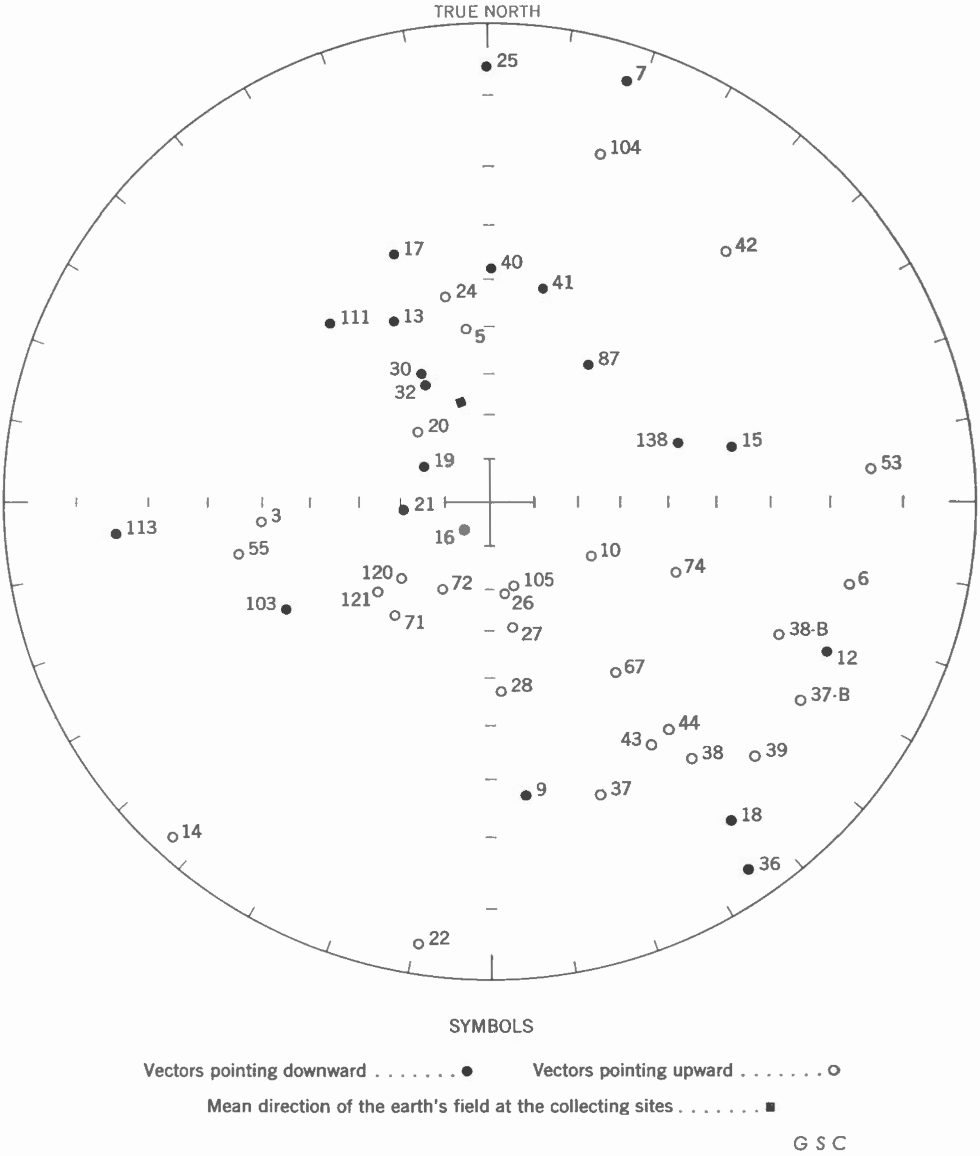

Figure 9. *Stereographic projection of natural remanent magnetism of fifty specimens collected from the Monteregian Hills.*

with the astatic magnetometer, as they are not of sufficient interest for the present to justify the amount of work required to compute them.

The scatter in the magnetization direction in the rocks of the Monteregian Hills (*see* Fig. 9) is so great that it is hardly possible to assign them to distinct groups. It can be noted, however, that most upward-pointing vectors are in the 3rd and 4th quadrants whereas the downward-pointing ones are in the 1st and 2nd quadrants.

In many specimens (including some of sedimentary origin) the direction of magnetization points steeply upward, which elucidates the cause of the negative anomalies mentioned earlier. By comparing Figures 8 and 2 it can be seen that, on Yamaska Mountain at least, normally polarized rocks were not found below negative anomalies, although in a few instances (e.g., specimens Nos. 53 and 55) reversely polarized rocks were collected in zones of positive anomalies. The latter phenomenon may be explained by the fact that the in situ induced polarization of these rocks due to the present earth's field, which is necessarily normal, may sometimes be stronger than the reverse remanent polarization. Another feature of the upward-pointing polarization of some of the rocks is that they are relatively stable magnetically, despite the tendency of the present geomagnetic field to magnetize them in the normal direction. This does not mean that the normally polarized rocks are necessarily magnetically unstable, although most are probably as complex magnetically as the reversely polarized rocks. A complete analysis of the above data scarcely seems justified because of the high degree of scatter: it is perhaps important to investigate the various possible causes of this scatter.

Although every practical precaution was taken to determine the orientation of the specimens in situ, an error of a few degrees could nonetheless be introduced in this operation. Similarly, a further slight error in orientation could be introduced in the process of cutting the specimens into cubes. Other factors of purely local nature, such as slight local displacements of bedrock at the collecting sites, could account for other slight errors. All these would show as scattering in the final diagram. On the other hand, errors due to lack of precision in the measurements or to slight inhomogeneities in the rocks would to some extent be eliminated by averaging the measurements of several cubes cut from a single sample.

On the whole, these factors are considered to be relatively unimportant, and it is unlikely that they are the only causes of the scattering. Probably more important is the fact that the rocks of the Monteregian Hills series were magnetized over a period lasting several thousand years, during which time the direction of the earth's field probably varied considerably, thus causing marked differences in the direction of the remanent polarization.

It does not seem possible to apply a systematic correction to the observed data to eliminate the scattering introduced by the factors enumerated above, and, for the present, some degree of scattering due to these causes must be accepted. There remains, however, the complex nature of the remanent polarization of the rocks in situ, which may be responsible for most of the observed scatter, and this can to some extent be eliminated.

Components of Remanent Magnetism

If an igneous rock is susceptible of being permanently polarized magnetically, it may reach that state in one of four ways. These have been termed *thermomagnetization, isothermal* magnetization, *anhysteritic* magnetization, and *chemical* magnetization. The same rock may bear simultaneously components of magnetization resulting from two or more of these processes, these components not necessarily being parallel with one another. The resultant magnetization in such cases corresponds to the vectorial sum of the components involved.

It is a well-established fact that if a rock is heated above a critical temperature (known as its Curie point), it loses all of its remanent magnetism. If the rock is then allowed to cool in a constant magnetic field, such as the earth's field, it will acquire a component of magnetic polarization which is directed along the ambient field. This process is known as thermomagnetization.

If a rock is placed in a constant magnetic field for a relatively short time at a temperature below its Curie point, it may acquire a component of remanent magnetization directed along the ambient field. The rock is then said to be isothermally magnetized. The intensity of this component depends upon the intensity of the ambient field, the length[1] of exposure to the magnetic field, the size, distribution and nature of the ferromagnetic minerals in the rock, and other factors.

When an alternating field is applied to a ferromagnetic body, its magnetic moment changes continuously. As this change is not a reversible process, energy must be delivered by the alternating field generator and a correspondent quantity of energy is dissipated by the ferromagnetic substance in the form of heat. As this energy loss is particularly obnoxious to the efficiency of certain industrial devices (such as transformers) several techniques have been suggested (Ewing, 1886; Maurain, 1904) for reducing it to a minimum. One of these techniques consists of submitting the ferromagnetic material to the action of an alternating field of slowly decreasing amplitude and at the same time to that of a constant field. This treatment produces in the ferromagnetic material a strong magnetic component that is appropriately called 'anhysteritic'. Some rocks have apparently been magnetized in situ by this process upon being struck by lightning. In this case, the alternating field results from the high-amperage alternating currents accompanying the electrostatic discharge and the constant field is the ambient earth's field.

Chemical magnetization, so far, is the least studied process of rock magnetization. It is impressed on rocks as they undergo chemical alteration and is acquired by newly formed ferromagnetic minerals. Like isothermal and anhysteritic magnetization, this process may be effected at temperatures considerably below the Curie point of the minerals being formed and it is directed along the ambient earth's field.

Significance

The geological significance of each magnetic component depends on its ability to record the attitude of the earth's magnetic field at a particular time in the past.

Isothermal magnetization is introduced into rocks over long periods of time during which the orientation and intensity of the earth's field must have varied considerably. Thus the total isothermal magnetism in a rock is the resultant of several components, each produced over a relatively short interval during which the attitude of the earth's field did not change appreciably. This picture is further complicated if isothermal magnetization has a 'viscous' nature, that is if it deteriorates with time

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[1] A distinction is made by some workers (viz., Thellier, 1937) between 'isothermal' and 'viscous' magnetization, the latter referring to the magnetic polarization acquired by substances exposed to a constant field for periods longer than one minute.

when it and the ambient field are no longer aligned. It can thus be seen that this magnetic component not only fails to reflect the attitude of the earth's field at any particular time in the past history of the rock that bears it, but also marks those components that do.

Anhysteritic magnetization in rocks was first identified as the effect of lightning by Folgheraiter (1894) who gave the name of 'punti distinti' to sites where this phenomenon was observed. Pockels (1901) and Toepler (1901) further studied the magnetization of rocks due to lightning, and observed that its direction assumes a radial pattern on the earth's surface about a central point where the intensity is at a maximum. This observation and the fact that lightning may strike a rock at any time throughout its history make it obvious that anhysteritic magnetization in rocks is objectionable in palaeomagnetic studies.

Chemical magnetization may reflect the attitude of the earth's field at the time the rock was metamorphosed. The complex mechanism of chemical magnetization is still, however, obscure (Haigh, 1958), and for this reason few palaeomagnetic studies have been made of metamorphic rocks.

Thermomagnetization has the combined advantages of not deteriorating with time and of reflecting the attitude of the ambient earth's field at the time the rock cooled. The experiment of heating a rock above its Curie point and letting it cool in the earth's field has been carried out many times by many workers and on different rock types. Always it has been found that the resultant thermomagnetism is in perfect accordance with the ambient field. Furthermore, the rate at which thermomagnetization takes place depends not merely upon the general cooling of the rock, but more precisely upon the cooling rate at temperatures in the vicinity of the Curie point of its ferromagnetic constituents. It has been shown by Grabovsky, Petrova, and Isakova (1956) that 90 per cent of the thermomagnetic component is fixed during the interval it takes the rock to cool from its Curie point to a temperature about 50° C below it. Thermomagnetization then reflects the attitude of the earth's field for a precise interval of time in the history of igneous rocks and is therefore a very satisfactory component for palaeomagnetic studies.

Recognition of Specific Components

The presence in a rock of some of the magnetic components described above may readily be deduced by considering the conditions under which the rock was formed or to which it has been exposed. For instance, all igneous rocks bear a component due to thermomagnetization because all cooled from temperatures above the Curie point to temperatures far below it. Isothermal magnetization may be found in various degrees of intensity in any rock type because of the ubiquity and constant action of the earth's magnetic field.

Anhysteritic magnetization in rocks may be detected by its radial distribution and by its limited coverage of rarely more than a few tens of square metres. Another criterion for its recognition is the extremely high intensities near the centre of the radial patterns. Thus, if the magnetization directions of two samples collected close together are radically different, or if the intensity of magnetization of one sample is much stronger than that of a nearby sample of similar petrographic composition, anhysteritic magnetization may be suspected. Finally, chemical magnetization is almost inevitable in rocks that show signs of metamorphism, especially if the ferromagnetic part of the rocks appears to be secondary. Chemical magnetization is also probably the main component in red beds, although these beds are not generally classified as metamorphic rocks.

A few field and laboratory tests may also be used to recognize an isothermal component in rocks. The two classical field tests suggested by Graham (1949) consist essentially of evaluating the resistance of a rock to acquiring an isothermal component under the action of the earth's field. In the first, the direction of magnetization of specimens collected from flat and folded parts of a formation are compared. If the in situ magnetization is consistently oriented along the present earth's field instead of, in sediments, being consistently related to the bedding plane regardless of its position, it is probable that an isothermal component is masking other components that are more significant. The second test suggested by Graham consists of comparing the in situ magnetization direction of pebbles of a given petrographic composition in a conglomerate. There again, if the magnetization in the pebbles is consistently oriented along the present earth's field, it is probable that the formation from which the pebbles were derived readily acquired an isothermal component and probably carries it.

Thellier (1937) has described a laboratory test whereby it is possible to measure the susceptibility of a rock to acquire an isothermal component. The test consists of orienting the specimen in the laboratory in such a position that it occupies a fixed attitude with respect to the earth's field. The specimen is held in this position for two weeks and its remanent magnetization determined. It is then rotated 180 degrees about a horizontal axis perpendicular to the meridian. After another two weeks the specimen's magnetization is again measured. The amount of the discrepancy between the two sets of measurements is considered to be a measure of the susceptibility of the rock to acquire an isothermal component.

An isothermal component in a rock can be recognized by the fact that it is rather easily removed if the specimen carrying it is placed in a space free of any magnetic field except of that produced by an alternating current of slowly decreasing amplitude. Specimens carrying anhysteritic, chemical, or thermoremanent magnetization components are considerably less affected by this treatment. A simple experiment was carried out to demonstrate the relative difference in hardness between thermomagnetization and isothermal magnetization. A cube of essexite was exposed to a constant field of 115 Oersteds for five minutes. The remanent magnetization of the cube consisted then of an isothermal component introduced by this process and a thermoremanent component originally in the cube. The order of magnitude of the total magnetization was $276{,}000 \times 10^{-5}$ emu/cu. in. An alternating field was generated with an amplitude of 66 Oersteds. The specimen was placed in a space free of any magnetic field and the source of alternating field was slowly brought around the specimen and then removed. The magnetic moment of the cube was then measured and found to be reduced to $175{,}000 \times 10^{-5}$ emu (*see* Fig. 10). This treatment was repeated with amplitudes of the alternating fields set at 90, 125, 160, 195, 260, 320, and 390 Oersteds.

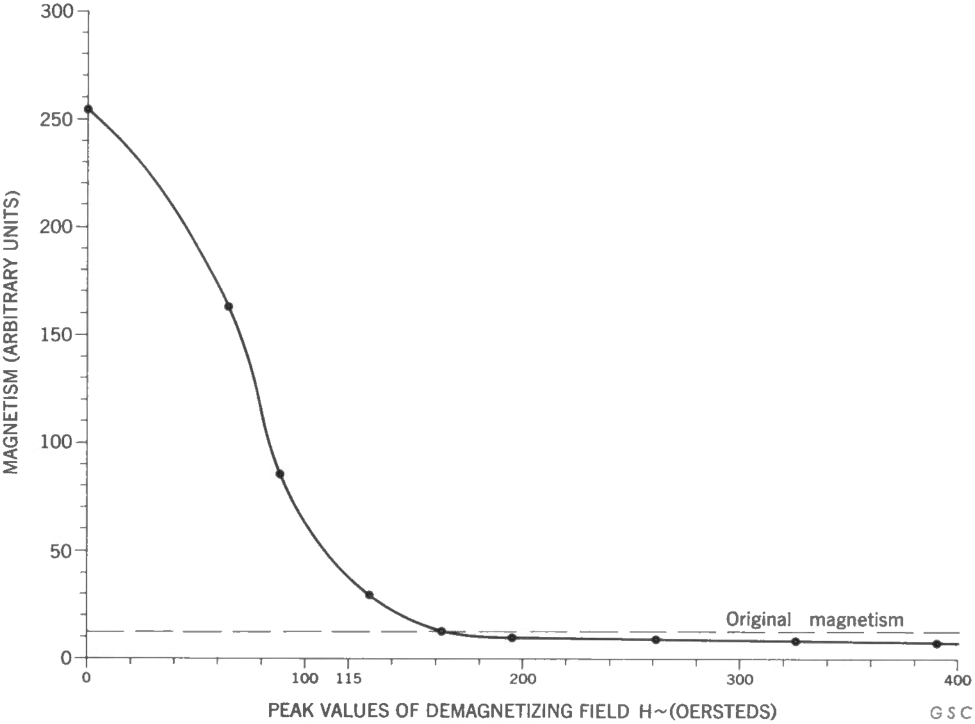

Figure 10. *Graph showing progressive destruction of isothermal component.*

The magnetization of the cube was measured after each exposure and found to decrease rapidly up to the 160 Oersteds setting above which the rate of decrease was considerably less. The magnetism then left in the rock had essentially the same orientation as before the exposure of the cube to the constant field and was interpreted as the original thermoremanent component in the rock. Another cube of the same specimen was heated above 700° C for one hour and then allowed to cool in air in the earth's field. The resulting thermoremanent magnetization was found to be $47{,}000 \times 10^{-5}$ emu/cu. in. After submitting the cube to a series of alternating field demagnetizations as described above, its magnetization was still $23{,}000 \times 10^{-5}$ emu/cu. in. after the 260 Oersteds setting. The orientation of the magnetization did not vary throughout the treatment. Experiments of this type were carried out by Haigh (1958) to show the relative difference in 'hardness' between chemical, isothermal, and thermoremanent magnetism. Independently, Rimbert (1955) studied the relative 'hardness' of anhysteritic, thermoremanent, and isothermal components. The conclusion of these experiments has been that isothermal magnetism may readily be eliminated from a rock but that anhysteritic, chemical, and thermoremanent components resist much longer the action of an alternating field of slowly decreasing amplitude.

Because an isothermal component is apt to be present in some parts of a rock series and absent in others, it could be a major cause of scattering among a group of magnetization measurements. Furthermore, as this component is misleading in an attempt to determine the attitude of the earth's field at a particular time in the past, it must be removed from rocks to be used for this purpose. The slowly decreasing amplitude, alternating field technique was therefore applied to the specimens used in this study to see if an isothermal component was present in some of the rocks of the Monteregian Hills, and by eliminating it, to reduce the scatter displayed by the initial measurements. If successful, it should then be possible to determine the mean orientation of the earth's magnetic field at the time the igneous rocks were intruded or the sediments metamorphosed.

Elimination of Isothermal Component from Rocks of the Monteregian Hills

Instrumentation

Two precautions are necessary in designing an apparatus for 'magnetic washing' by the slowly decreasing amplitude, alternating field technique. First, there must be provision for placing the specimen in a magnetic-field-free space in order to prevent the introduction of an anhysteritic component during the application of the alternating field. This condition was satisfied by placing ~~two~~ the specimen~~s~~ at the centre of symmetry of two mutually perpendicular Helmholtz coils (*see* Pl. I), one horizontal and one vertical but with an axis pointing north. The direct currents in these coils are critically adjusted so that the magnetic field at the centre of symmetry is less than 50 gammas. The intensity of the vertical and horizontal components of this field are measured from time to time by means of a fluxgate magnetometer (Serson, P. H., and Hannaford, W. L. W., 1956) and, if necessary, the currents in the coils adjusted for minimum field. The earth's field being reduced to about one part in a thousand, the component of anhysteritic magnetization that might result is negligible.

The second precaution is that the amplitude of the alternating field must be decreased slowly and gradually. This cannot be done simply by introducing a rheostat in series or a variable transformer[1] in parallel with the 60 cps alternating voltage source because current with these instruments can only be made to vary in discrete intervals. It has been found that slowly removing the alternating field source (in this case the small Helmholtz coil D in Plate I) from the specimen is an efficient way of uniformly reducing the amplitude of the alternating field in the vicinity of the specimen without risk of introducing in it an anhysteritic component.

Results

The specimens whose initial measurements are listed in Table I were subjected successively to slowly decreasing amplitude, alternating fields of 50, 100, 150, and 200 Oersteds maximum amplitude. The magnetization was measured after each run and the operation stopped if the direction of magnetization showed no change after two successive runs. The average of the measurements of the magnetism in the cubes from each specimen after treatment are listed in the last three columns of Table I and the magnetic vectors plotted stereographically in Figure 11.

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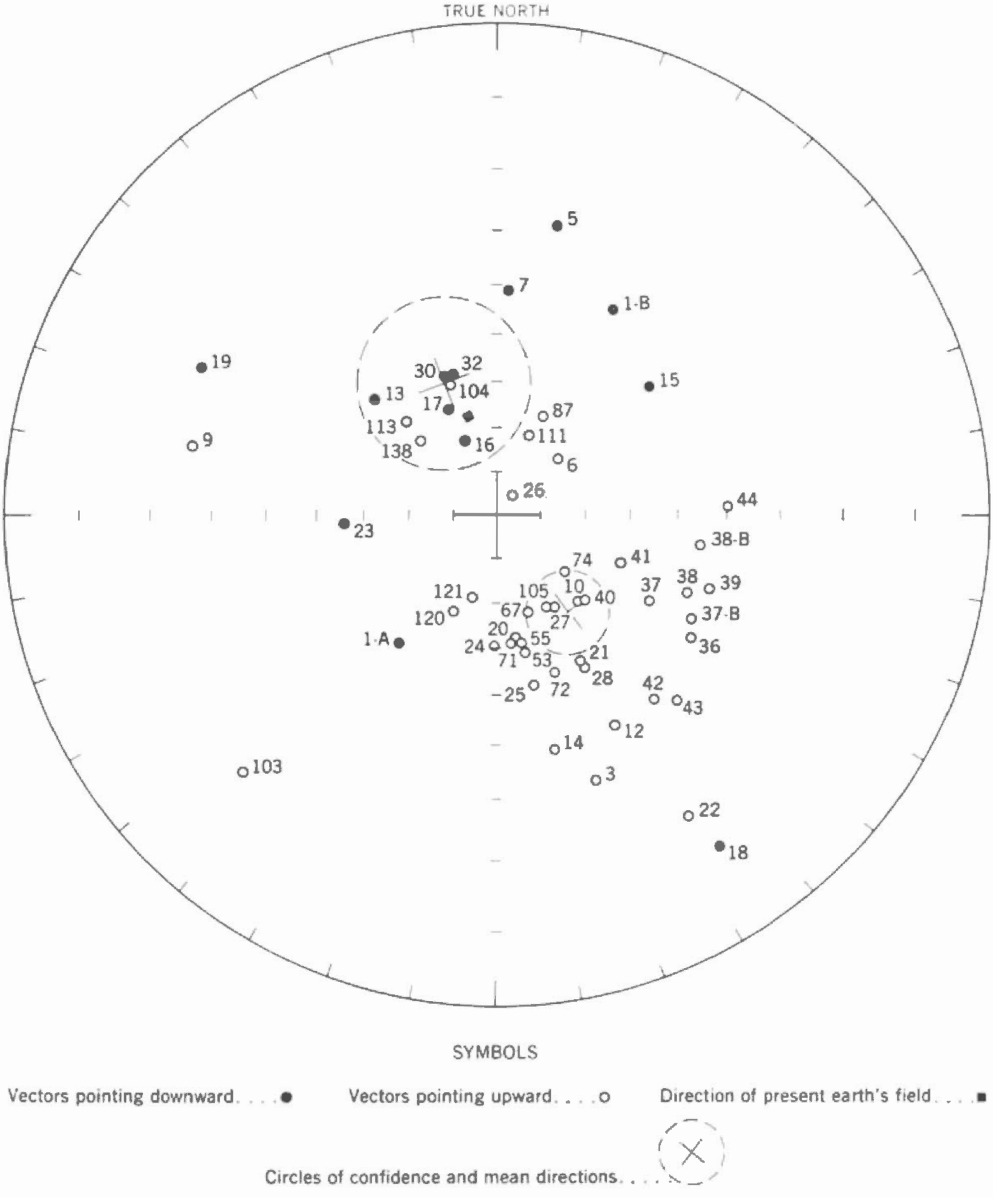
[1] The Variac shown in Pl. I is used only in setting the maximum amplitude of the applied alternating field.



GSC

Figure 11. Stereographic projection of the vectors of the remanent magnetism of fifty-one specimens after magnetic washing.

By comparing Figure 11 with Figure 9 an appreciable decrease in the scatter of the magnetization directions can be seen as a result of the magnetic washing. It will also be noted that many of the specimens that were originally polarized downward are now polarized upward, i.e., reversely. In no case, however, was the polarity of originally reversely polarized rocks changed as a result of magnetic washing. This in itself points to the greater stability of the reverse components, which are therefore of thermoremanent or chemical origins rather than of isothermal origin.

A comparison of the intensities before and after magnetic washing (*see* Table I), shows that in most specimens the intensity of magnetization has decreased; in some the reduction is comparatively small, and in five it has actually increased. This is easily explained if it is assumed that the unstable isothermal component points downward, as it almost certainly does because of the constant orientation of the earth's field in this general direction during at least the past 500 years. In rocks bearing a stable reverse component, this reverse component may have been completely or partly masked during the first set of measurements by the isothermal component, which would account for the reversal of the magnetic polarity in some of the specimens and for the increase in magnetic intensity in others. The more general case, of which the intensity decreases in either normally or reversely polarized rocks, is not incompatible with this explanation because the magnetic stability of the two types of magnetic components is only relative, as indicated in the experiment described on page 17.

One more observation may be made about Figure 11: the plots of the polarization directions are generally distributed in two groups, upward-pointing vectors in the 4th quadrant and downward-pointing vectors in the 2nd quadrant. The downward-pointing vectors are considerably fewer than the upward-pointing ones, perhaps mainly because the sampling density is not uniform throughout the Monteregian Hills. Possible explanations for the mixed polarity is discussed on page 24.

Before attempting to make a statistical analysis of the results, it was necessary to examine individually those specimens whose magnetization direction either conflicts rather drastically from the general grouping given above or is apparently unrelated to the direction of the earth's field at the time of the intrusion. These are specimens 1-A, 1-B, 9 and 18.

Specimens 1-A and 1-B are of hornfels and were collected from spots less than 5 feet apart and within 10 feet of the intrusion on Yamaska Mountain. Their difference in magnetizations of almost 90 degrees in direction suggests that they were erratically magnetized by lightning. Their incorporation with the rest of the specimens would not however change the end results appreciably as their mean direction is not far off the mean obtained for the normally polarized rocks. Nevertheless, because their considerable divergence might only be an expression of a much more important change in the overall magnetization of the rock, they were not used in the statistical analysis of the data.

Specimen 9 was collected at least a quarter of a mile from the nearest intrusive rocks on Mount Brome and its in situ magnetization direction was probably not affected by the intrusion but was mainly governed by many other independent pre- and post-intrusive phenomena. The magnetization data obtained for this specimen were also discarded.

Specimen 18 was made the object of a special study because its original magnetization was particularly intense compared with that of the other specimens collected. Furthermore, this magnetization was found to be extremely persistent, even after the specimen was submitted to a demagnetizing field of 300 Oersteds maximum amplitude. A cube of this specimen was then heated above 700° C and kept at this temperature for one hour after which it was allowed to cool in the ambient earth's field. Its magnetization, then considered as pure thermomagnetization, was found to be only $5{,}560 \times 10^{-5}$ emu/cu. in. as compared with the $228{,}500 \times 10^{-5}$ and $102{,}200 \times 10^{-5}$ emu/cu. in. as obtained for the same cube before and after magnetic washing. A similar treatment was given to other specimens of the series listed in Table I and it was invariably found that the intensities of magnetization after the heating and cooling in the earth's field never exceeded by more than 10 per cent of the intensities prior to the treatment. Furthermore, the value of $5{,}560 \times 10^{-5}$ emu/cu. in. is much closer than $228{,}500 \times 10^{-5}$ to the intensity of the other specimens collected from the Monteregian Hills series. As there is no sign of metamorphism in the specimen, it seems most probable that the extremely strong component of remanent magnetization is made up of a thermoremanent component of average intensity and of a very strong anhysteritic component. The collecting site of this specimen is on the top of Mount St. Hilaire which favours the hypothesis of magnetic polarization by lightning. On account of this possibility, specimen 18 was not considered further in the present study.

Statistical Analysis of the Data

In order to compute the mean direction of a group of vectors of various magnitudes, it is necessary first to assign each of these vectors a uniform statistical weight, namely a standard magnitude. The direction of the vectorial sum 'R' of the standardized vectors corresponds to the mean direction of the original group.

In dealing with the palaeomagnetism of rocks, it is considered that, although the *true* magnetization direction of a *group of specimens* may not correspond exactly with the mean magnetization direction of *the* group, the probable *maximum* angle θ between the two directions may be established statistically.

The true direction of magnetization of a formation would thus be enclosed by a circular cone of half-angle θ and centred about the computed mean direction. It is obvious that the intersection of this cone with a spherical shell forms a circle if the apex of the cone and the centre of the sphere are made to correspond. Furthermore, as all circles on a sphere project stereographically as circles (Penfield, 1901), the stereographic representation of the cone mentioned above is a circle, commonly referred to as the *circle of confidence.* Fisher (1953) has provided the statistical theory for calculating the radius of this circle. His equation is:

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

where P is the probability that the magnetization direction of the formation lies inside the cone of half-angle θ, N is the number of samples involved, and R the magnitude of the resultant of the standardized magnetization vectors, the standard magnitude being chosen as unity. It may be verified by equation (1) that if all the magnetization vectors are parallel for a group of samples, then R is equal to N, implying that $\theta = 0$. In this limiting case the mean direction and the actual direction of magnetization of the formation would be identical.

In order to compare the degree of scatter in different sets of observations, it is useful to establish an index κ that is characteristic for a given group of magnetization vectors. The value of κ is given by the following equation:

$$(2)\ \kappa = \frac{(N-1)}{(N-R)}$$

where N and R have the same meanings as in equation (1). When κ is large, most of the vectors are parallel with their mean direction and vice versa. In the limiting case where all vectors are parallel, R equals N, and κ is infinite. In a case where half of the vectors are antiparallel to the other half, R = 0 and κ is less than unity.

Statistically the two groups of vectors described in the last section were considered separately, and the corresponding values of θ and κ were computed for each group according to equations (1) and (2). The value of P in equation (1) was set at 0.95 in each case. The results are listed in Table II.

Table II

Statistical Data for the Magnetization Directions of Forty-nine Monteregian Hills Specimens

Group	N	R	D	I	θ	κ
Downward pointing	10	8.86	340°	57°	18°	7.9
Upward pointing	39	33.95	142°	−62°	9°	7.5

N: Number of specimens
R: Vectorial sum of the standardized vectors
D: Declination of the mean vectors
I: Inclination of the mean vectors
θ: Radius of the circle of confidence
κ: Index of scatter

The mean directions and corresponding circles of confidence are shown in Figure 11.

The review by Runcorn (1955) of the palaeomagnetic literature was scanned in order to compare the order of magnitude of the computed κ's given above with those obtained for sets of magnetization data considered significant by other workers. Among the published results for twenty-two such sets, κ's as low as 5 and as high as 115 were reported, most being between 10 and 40. The κ's listed in Table II are thus within the range of values accepted by others as suitable for palaeomagnetic data but are admittedly among the most widely scattered groups reported. The accuracy of quantitative conclusions based on these data is therefore open to some question, but the qualitative conclusions, which are independent of the scatter index, may be accepted with confidence. The two are therefore considered separately.

Qualitative Conclusions Based on the Palaeomagnetic Data

Reverse Magnetic Polarity

The most interesting aspect of the Monteregian Hills data is that nearly 80 per cent of the specimens bear a remanent polarization that is more or less in the opposite direction to that of the present earth's field; the other 20 per cent roughly conforms to it. Such a mixture in magnetic polarity within a rock unit is not unusual and has been observed by many others and in many different rock types[1]. Two main hypotheses have been presented to explain this phenomenon; one that the dipole field of the earth reversed at least once during the formation of a series, and the other that certain mineral assemblages, irregularly distributed through the series, provide for a self-reversal mechanism where they occur.

The earth's magnetic field has been observed for only the last 500 years—too short a time to allow any definite conclusion to be drawn regarding the physical possibility for reversal of the earth's dipole field. Much data disclosed by recent work in palaeomagnetism, however, seem to support this hypothesis although each case of reverse magnetization must be considered on its own merits.

Review of the Literature

Graham (1949) was the first to dispute the belief that reverse magnetic polarization of rocks in situ is direct evidence of reversal of the earth's field in the past. His main reason for casting doubt on this simple hypothesis was a case group of vectors of mixed polarity that he had observed in a relatively thin but widespread Silurian sedimentary formation in Maryland, U.S.A. He argued that some physico-chemical change had probably taken place in those parts of the formation in which he had observed reverse polarization.

In support of the theoretical possibility of such physico-chemical mechanism, Néel (1951) proposed four mechanisms of self reversal, some of which have since then been used tentatively to explain particular cases of reverse polarization.

In the first of Néel's mechanisms, it is assumed that the rock contains a crystalline substance that has two sublattices, A and B, with the magnetic moments of all the lattice B oppositely directed to those of lattice A. Substances of this nature do exist and are called 'ferrimagnetics'. Supposing the spontaneous magnetization of lattice A (J_A) aligns itself with the ambient field, the resultant magnetization of the two lattices at a given temperature will be ($J_A - J_B$). In particular, Néel suggested that, for some ferrimagnetic substances, the spontaneous magnetization J_A and J_B reacted differently to changes in temperature. It is possible that, in this way, J_B could become larger than J_A above a critical temperature, known as the 'temperature of compensation'. If the temperature of compensation should turn out to be higher than ordinary temperatures at the surface of the earth, the direction of polarization of the ferrimagnetic substance in question would be reversed as the substance cooled from its

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[1] cf. Larochelle, A. (1958): pp. 2 and 3 for an incomplete list of references where mixed polarities are reported.

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 ($Li_{0\cdot5}Cr_{1\cdot25}Fe_{1\cdot25}O_4$) whose temperature of compensation is 100°C. Thus Néel's first mechanism is a physical possibility that may explain reverse polarization in igneous and metamorphic rocks containing certain ferrites of a very definite composition. Such substances have not been identified, however, in any of the reversely polarized rocks found so far.

For his second mechanism, Néel assumed the existence of a ferrimagnetic substance whose composition is such that J_A is always larger than J_B, regardless of the temperature of the substance below its Curie point. Then, if J_A is less stable than J_B under certain physico-chemical reactions, the rock would be reversely polarized in the direction of J_B after this reaction has taken place. The physical possibility of this mechanism has not yet been verified with either natural or synthetic compounds, and, according to Street (1954), it is unlikely to occur.

Néel's third mechanism is based on the interaction between two minerals of different Curie points. The coexistence of two or more ferromagnetic minerals of different Curie points is commonly observed in rocks. For instance, titaniferous hematite-magnetite intergrowths have been reported in many iron ore deposits. If it be assumed 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 that temperature. If certain geometrical conditions are fulfilled, 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 (the spontaneous magnetization of B) is larger than J_A.

Laboratory experiments carried out by Grabovsky and Pushkov (1954) to prove the physical possibility of this mechanism were only partly successful. They aligned alternating plates of magnetite and pyrrhotite in the magnetic meridian and heated them above the Curie point of magnetite (580° C). They then allowed the plates to cool slowly to room temperature, i.e., past the Curie point of pyrrhotite (320° C ±). They found that the pyrrhotite slabs were indeed reversely polarized relative to the ambient field but that the overall polarization of the pyrrhotite-magnetite combination was still along the direction of the ambient field.

However, an observation that establishes 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 it is cooled 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.

An actual case where Néel's third mechanism was proposed 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".

The coexistence of two minerals of different Curie points is also assumed for Néel's fourth mechanism and the polarization of mineral B is also reversed by the demagnetizing field of mineral A, as in the case of the third mechanism. It is further assumed that the polarization of mineral A (whose Curie point is higher) is less stable than that of mineral B. The rock then becomes polarized in the direction of mineral B if mineral A either is destroyed or loses its magnetization.

Variations of this mechanism were suggested by Graham (1953) and by Asami (1956) in attempts to explain the reverse polarization of two specific cases. Graham assumed that the rock he was dealing with originally contained a magnetite-ilmenite intergrowth and was normally polarized. Subsequently, percolating acidic waters were supposed to have partly oxidized the magnetite to form maghemite, which was reversely polarized by the demagnetizing field of the ilmenite (presumed to be ferromagnetic) and unleached magnetite. As magnetite has a much lower coercive force than maghemite, it would eventually lose its original polarization altogether and the rock would then adopt the reversely directed polarization of the maghemite. Asami (1956) interpreted his case of reverse polarization as due to a low temperature exsolution of two phases of titanomagnetite from a solid solution of magnetite-ülvospinel of intermediate composition. Both normal and reverse polarizations are reported among forty-three samples of basalt collected within an area of one square metre. From a thermomagnetic analysis of these rocks, Asami was able to show that the reversely polarized samples contained two different ferromagnetic minerals whose Curie points were 120° C and 500° C, respectively. The normally polarized specimens, however, were found to bear only one ferromagnetic mineral whose Curie point was in the vicinity of 370° C.

Since Néel first formulated the described mechanisms many others have been suggested by different workers and by Néel himself. Néel (1955) suggested possible self-reversals by diffusion involving ionic exchange between the two sublattices in a ferrimagnetic substance or by diffusion with complete change of composition. Gorter (1953) had achieved the diffusion of Al ions from the A sublattice in a ($NiFe_{2-m}Al_{m}O_{4}$) ferrite and he observed a resultant reversal of spontaneous magnetism for this substance. An application of this mechanism to rock magnetism was later suggested by Verhoogen (1956) for substituted magnetites. He also 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, however, to support Verhoogen's hypothesis.

Smelov (1957) recently introduced a new hypothesis to explain the negative polarization of the ore deposits in the Angara-Ilim region of 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 in which state it would lose almost all of its original spontaneous magnetization. Magnetite would remain relatively unaltered and retain its reverse polarization, which is then representative of the rock 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 (1952) on Mount Haruna in Japan. This rock has the extremely rare property[1] of reassuming its reverse polarization after being heated to 700° 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 rocks contain two very different ferromagnetic ingredients, namely a titanomagnetite of Curie point 500° C and a ferromagnetic ilmenite whose Curie point is 200° 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 $(x = 0.5)$ of this series. Conclusive evidence that this member of the hematite-ilmenite series has the inherent property of self-reversal is provided by the fact that reverse polarization is produced in fields as high as 17,000 Oersteds. According to Uyeda (1958), the mineral whose composition is given approximately by $0.5(FeO \cdot TiO_2) \cdot (1-0.5)Fe_2O_3$ is present in the Haruna rocks in two phases which are intimately intergrown. The mechanism finally postulated by Uyeda 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".

The Possibility of Self-Reversal Mechanisms in the Monteregian Rocks

Any attempt by laboratory work to discount the possibility of a self-reversal mechanism in the rocks of the Monteregian Hills should be done with reservations. It is, after all, doubtful if all possible mechanisms have been thought of, and all traces of a mechanism that may once have been active may by now have completely disappeared. Furthermore, conditions required by some of the mechanisms may not be reproducible in the laboratory. Nevertheless, it can be shown that some of the mechanisms listed above are most unlikely to apply to the present case, whereas others may. At best, it is only possible to estimate the probability that the reversely polarized rocks dealt with here were magnetized by a process other than thermomagnetization in a field whose direction was opposite to that of the present earth's field.

It was mentioned earlier that a sample of reversely polarized rock from the Monteregian Hills heated above its Curie point and cooled in the earth's field did

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[1] Balsley and Buddington report similar findings (op. cit).

not resume its reverse polarization. This more or less eliminated the possibility of Néel's first and second mechanisms, as the presence of the unusual ferrimagnetic substances required for these mechanisms would almost necessarily call for the laboratory reproducibility of the reverse polarity.

Néel's third and fourth mechanisms require coexistence in a rock of two ferromagnetic minerals of different Curie points. It can, however, be shown mathematically that this condition is not sufficient to produce a magnetically antiparallel coupling between the two. Uyeda (1955) made a study of some configurations favourable to this type of coupling, and of particular interest is alternating parallel plates of different minerals because this texture is common in natural rocks. Assuming that these plates are evenly distributed along or nearly along the XY, YZ, and ZX planes respectively in a rock mass, it is possible to state the necessary geometrical conditions for the two sets of plates to be magnetized in opposite directions on being cooled below the lower Curie point. According to Uyeda, if L is the height of the plates, d_A and d_B the thickness of the plates formed of mineral A and mineral B respectively, the two sets of plates will have the same or opposite directions of magnetizations as the magnetic meridian, depending whether the point determined by the ratios H_{ex}/J_A[1] and d_B/d_A falls above or below the curves in Figure 12. Thus the presence of two ferromagnetic minerals of different Curie points and their appropriate distribution in a rock must be established before the reverse polarization of the latter may be explained by either the third or fourth of Néel's self-reversal mechanisms.

Néel's mechanism postulating ionic diffusion between the two sublattices of a ferrmagnetic substance is a difficult one to reproduce in the laboratory because the length of time over which it operates is probably far beyond that of a reasonable laboratory experiment. The applicability or not of this mechanism to explain reverse magnetism in the Monteregian Hills cannot therefore be established. This is also true of Verhoogen's hypothesis.

The mechanism suggested by Smelov requires the hypothetic presence of the secondary hematite as one of the ferromagnetic constituents in the rock. A Smelov's type of mechanism could be responsible for the reverse polarity being considered if signs of mineral replacement are present in the rocks dealt with. This condition is discussed on page 29.

Finally, the mechanism suggested by Uyeda to explain the reverse polarization of the Haruna rocks depends on the presence in the rocks of the member of the ilmenite-hematite series whose chemical composition is given by $0.5(FeO\cdot TiO_2)\cdot 0.5(Fe_2O_3.)$ The probability that this particular mineral is present in the rocks of the Monteregian Hills is very small because reversely polarized specimens assumed a normal polarity upon being heated and then cooled in the earth's field. Furthermore, Curie point determinations of some of the Monteregian Hills rocks make Uyeda's mechanism improbable, as is shown later.

In summary, Néel's first and second mechanisms are not likely to have caused the mixed polarity of the Monteregian Hills; Néel's mechanism of ionic diffusion or

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[1] H_{ex} stands here for external field.

the variation proposed by Verhoogen cannot be investigated further; Uyeda's mechanism does not seem probable; and further data are required to judge the applicability of the other mechanisms mentioned. This further data are on the primary or secondary nature of the ferromagnetic minerals in the rocks, and on the coexistence of different magnetic minerals in the same rocks and their geometrical interrelationship. Also, in order to eliminate completely the applicability of Uyeda's mechanism to the present case, it is necessary to establish the absence of the member $0.5(FeO \cdot TiO_2) \cdot 0.5(Fe_2O_3)$ in the rocks dealt with. Two techniques were followed to obtain these data with some certainty; microscopic examinations and Curie point determinations.

Microscopic Examination

Polished sections were made from six specimens—three taken from each of Yamaska and Brome Mountain bodies—and grains which were representative of the ferromagnetic part of these rocks were examined and photographed[1] under a magnification of 400 diameters (*see* Pls. II-IV).

As far as could be detected from microscopic examination, most of the rocks are little metamorphosed and only in specimen 74 (Pl. IV A) was there any sign that hematite has replaced magnetite on the edges of the grains. As all these rocks are reversely polarized, it is improbable that either Graham's or Smelov's mechanisms could explain the reverse polarity.

On the other hand, the regular pattern of dark streaks over the more uniform light grey background consists of a number of plates of a mineral belonging to the ilmenite-hematite series which has been exsolved along the (111) planes of a member of the ülvospinel-magnetite series.[2] It appears further that the ratio d_B/d_A, the thickness of the ilmenite-hematite plates to that of the magnetite-ülvospinel plates, is less than 0.1. By referring this result to Figure 12, it is clear that if both minerals are ferromagnetic they are negatively interrelated. Thus, the possibility that Néel's third and fourth mechanisms could explain the present case of reverse polarization is not yet eliminated, nor is Uyeda's mechanism inasmuch as the chemical composition of the ferromagnetic minerals present has not been established.

Curie Point Determinations

An accurate chemical analysis of the interbanded minerals mentioned above is difficult to make mainly because of the questionable purity of the samples extracted. Chevallier, Bolfa, and Mathieu (1955), and Akimoto (1957) have independently established the relationship between the composition of members of the solid solutions series $x(FeO \cdot TiO_2) \cdot (1\text{-}x)\ Fe_2O_3$ and their Curie points. Their results were based on chemically analyzed synthetic compounds. Pouillard (1950) and Akimoto (1957) have similarly established the relationship for the solid solution series $y(TiO_2 \cdot 2FeO) \cdot (1\text{-}y) Fe_3O_4$. Akimoto's results are represented diagrammatically in Figure 13. Although the accuracy of these data may be questioned, the Curie points can be used to estimate the approximate composition of certain ferromagnetic minerals. As the magnetic

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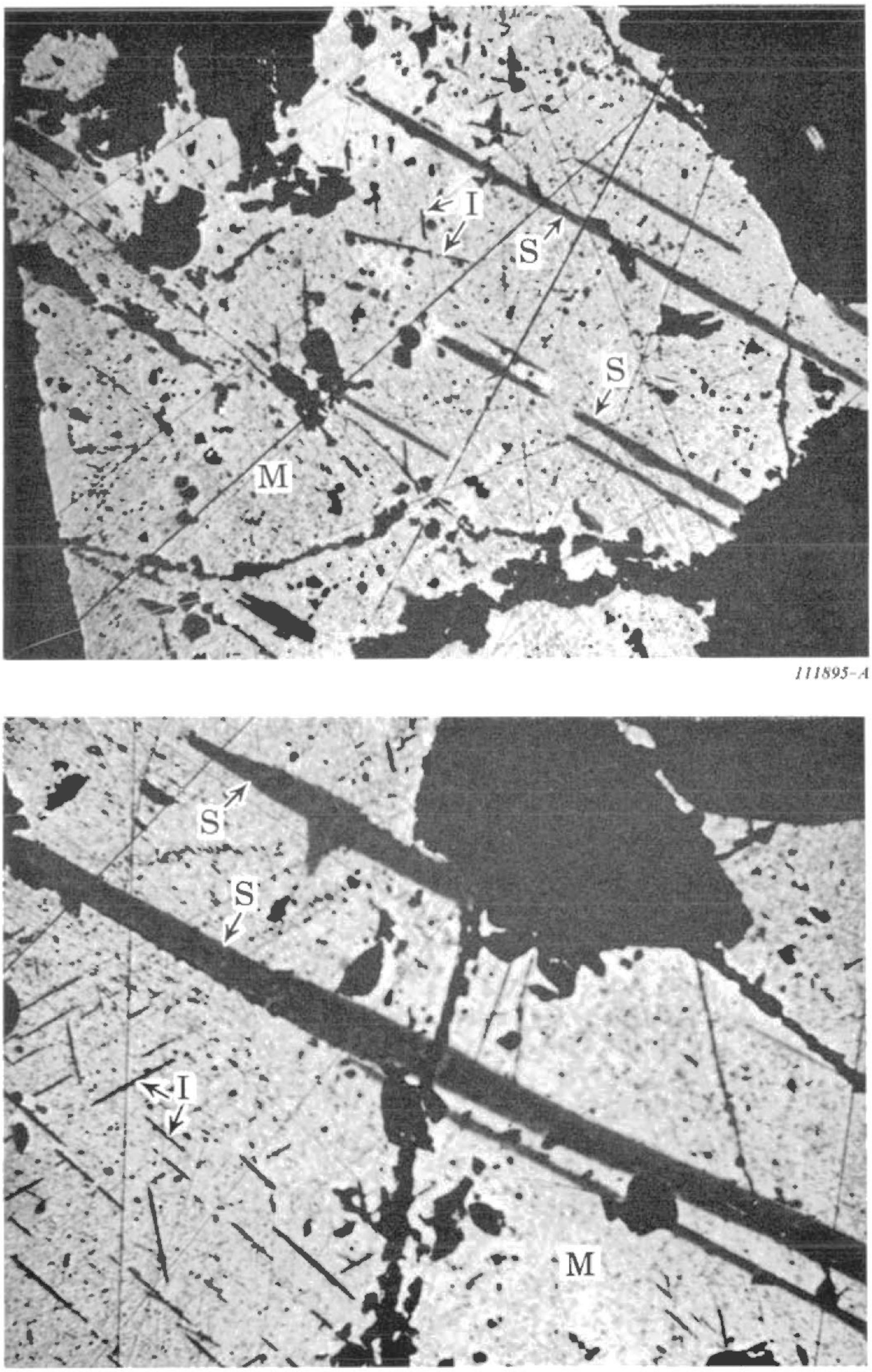
[1] Photomicrography by E. H. Nickel, Mines Branch, Department of Mines and Technical Surveys.

[2] In an independent study Nickel (1958) recently reported the existence of an exsolution of magnetite from ülvospinel in specimens from Yamaska Mountain. The scale of this structure is very fine however and its detection was only possible through electronmicroscope observation.



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111895-B

Plate II. Exsolution of ilmenite (I) and Mg-Al spinel (S) from magnetite (M); magnification × 400. Specimens 37-B and 38, both from Brome Mountain.

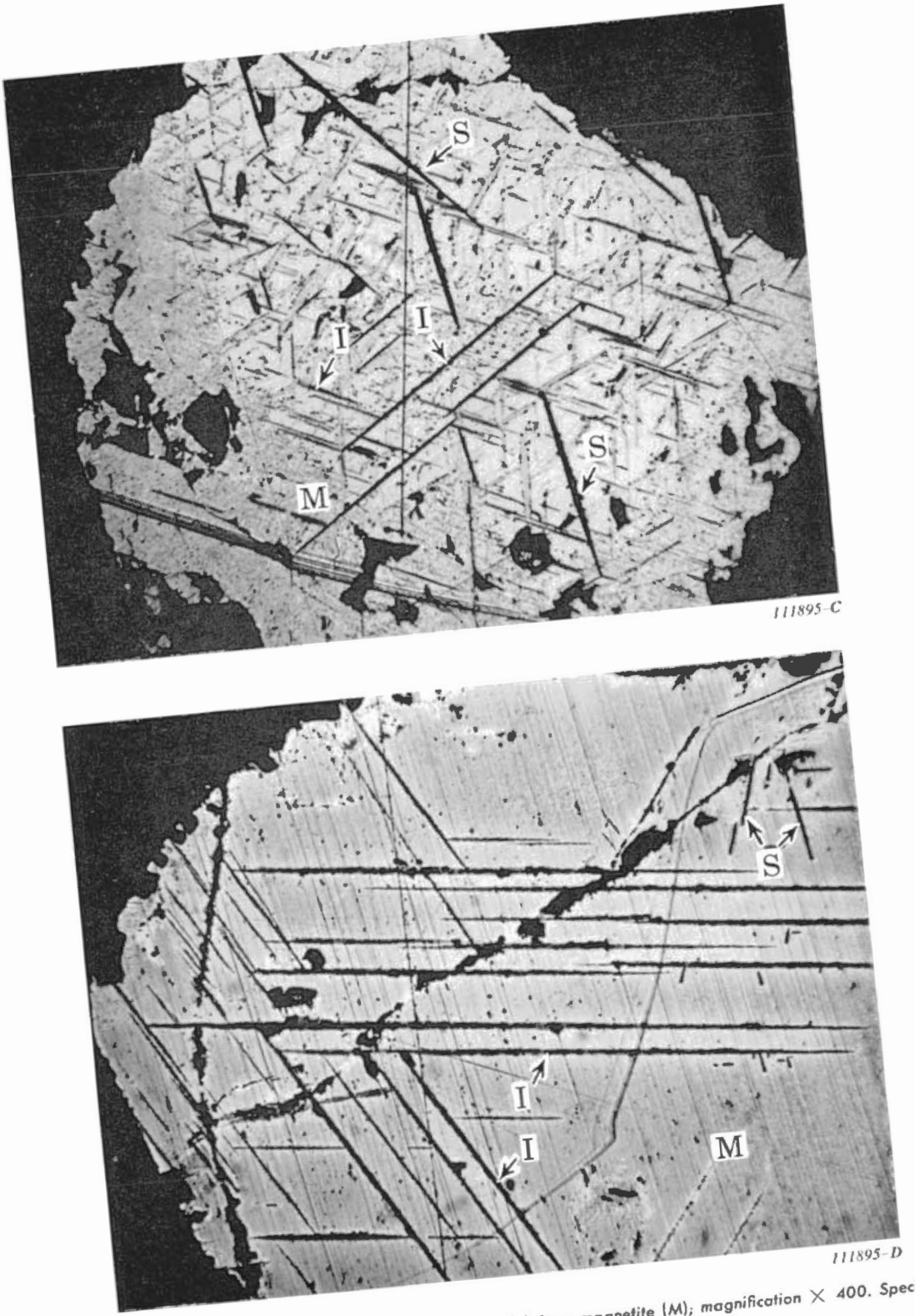
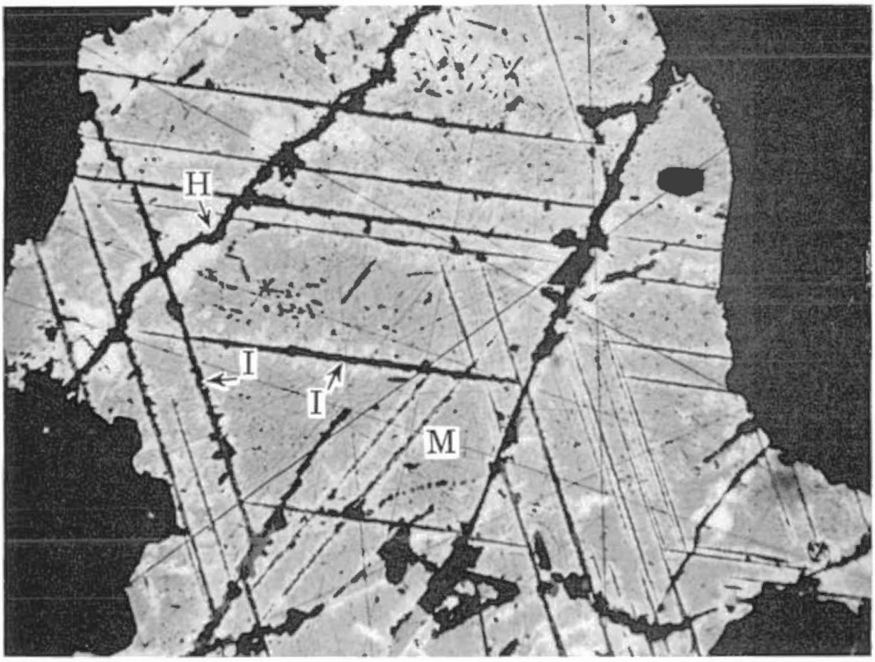


Plate III. Exsolution of ilmenite (I) and Mg-Al spinel (S) from magnetite (M); magnification × 400. Specimen 42 from Brome Mountain; specimen 71 from Yamaska Mountain.



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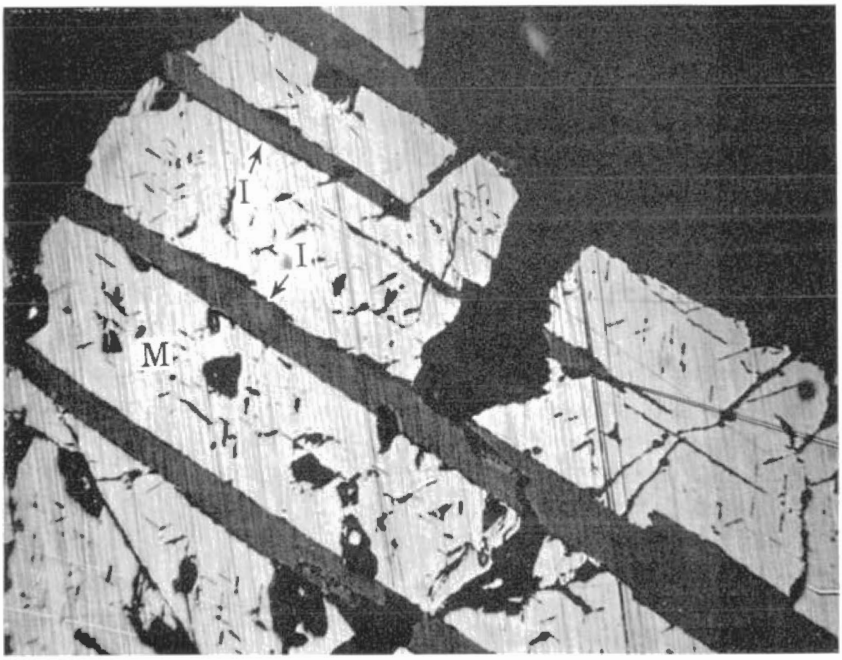

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Plate IV. *Exsolution of ilmenite (I) and Mg-Al spinel (S) from magnetite (M). Replacement hematite (H); magnification × 400. Specimens 74 and 105, both from Yamaska Mountain.*

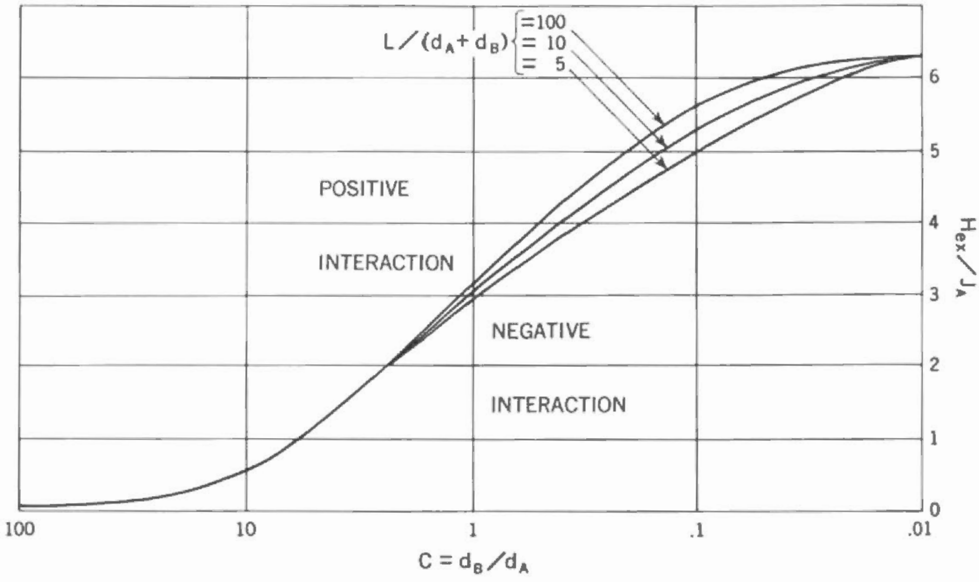

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Figure 12. Magnetic interaction of laminated structures: $L/(d_A + d_B) = 100, 10, 5$ (after Uyeda); L = length of plates; d_A = thickness of plate A; d_B = thickness of plate B; H_{ex} = external field; J_A = magnetization of mineral A.

susceptibility of paramagnetic minerals is negligible compared with that of ferromagnetic minerals, the former may be disregarded in determining the Curie point of the ferromagnetic minerals and no mineral separation or concentration is necessary.

A detailed description of the apparatus used in the present study may be found elsewhere.[1] This instrument is of the torsion balance type and is similar in principle to the instrument described by Pierre Curie (1895), and Chevallier and Pierre (1932).

The Curie points of twenty-one specimens from the Monteregian Hills were determined, including those illustrated in Plates II to IV, and the results are listed in Table III.

It should be noted that most of these specimens appeared to have only one Curie point and thus to contain only one ferromagnetic mineral. It is, of course, possible that two ferromagnetic minerals are present in the rocks whose respective Curie points are so close to one another that they could not be resolved by the instrument. It is also possible that if there are two hypothetical ferromagnetic minerals, one is so scarce with respect to the other that its presence is masked. However, even if these possibilities are so, they would scarcely account for the reverse polarization of the rocks by either the third or the fourth of Néel's self-reversal mechanisms. Furthermore, by comparing Table III and Figure 12, it appears that only specimen 38-B may have the composition $0.5(TiFe_2O_5) \cdot 0.5Fe_2O_3$ postulated in Uyeda's mechanism.

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[1] Larochelle, A. (1961).

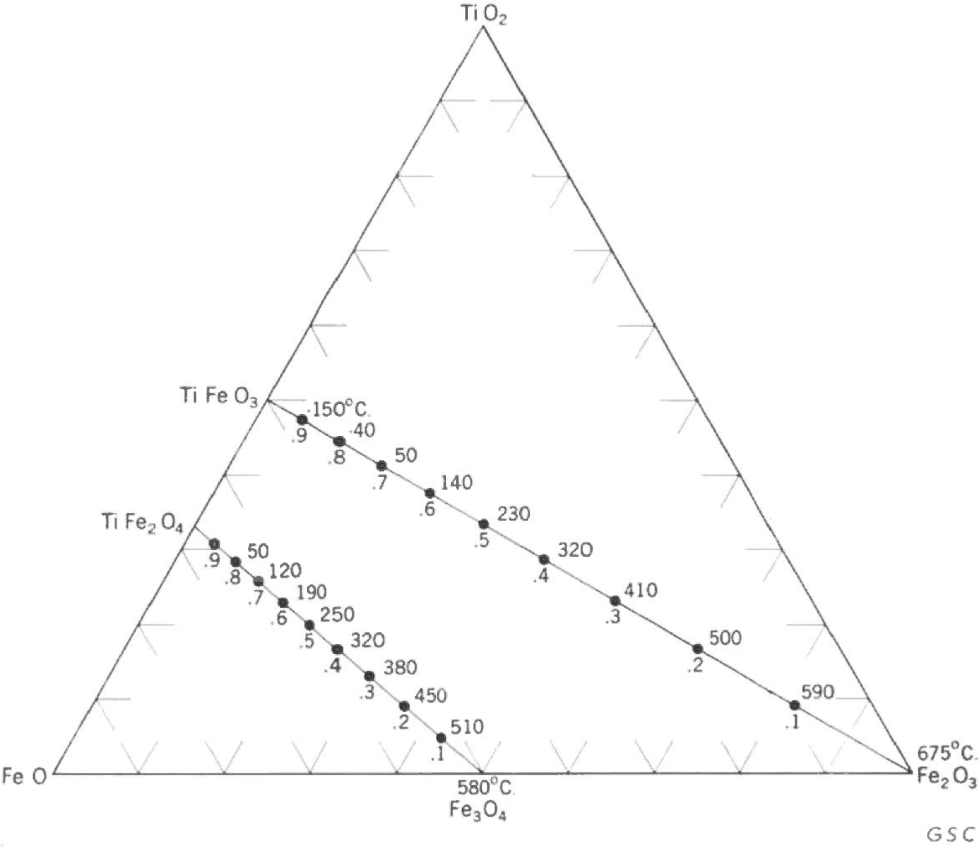

Figure 13. Curie points of the ilmenite-hematite and titanomagnetite series (after Akimoto).

Table III

Curie Points Determinations of Twenty-one Oriented Specimens from the Monteregian Hills

Specimen No.	Location	Curie Points C°	Specimen No.	Location	Curie Points C°
37	Brome Mtn.	492 and 530	71*	Yamaska Mtn.	462 to 535
37-B*	"	565	72	"	542
38*	"	580	74*	"	535
38-B	"	295 and 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 and 565
67	"	538	—	—	—

* Specimens illustrated in Plates II to IV.

The laboratory work described above was conducted to test the likelihood that a self-reversal mechanism caused the partial reverse polarization of the Monteregian Hills. No definite negative evidence was expected from this investigation but positive indications were sought. As it turned out, the evidence secured was conflicting and in part favoured the hypothesis of the earth's dipole field reversal. From the magnetization data, it can be seen that specimens 3, 6, and 20 were reversely polarized in situ although they are hornfels whose composition and texture are very different from those of the adjacent intrusive rocks. It seems probable that these rocks acquired their present polarization at the time of the intrusion either in a process of normal chemical magnetization at low temperatures or by thermomagnetization at higher temperatures. As they are reversely polarized, it is suggested that the ambient field at the time of the intrusion was oriented in a direction opposite to its present one.

Mean Axis of Residual Magnetism

Disregarding the sense of the polarity in the Monteregian Hills, the rocks there appear to be polarized, on the average, along a common axis that is almost parallel with the present earth's field at the site of collection. The attitude of this axis is approximately the mean of the axes of the normally and reversely polarized rocks respectively (*see* Fig. 11). The two last named axes are not exactly opposed to each other but form an angle of about 10 degrees. In order to compute the mean axis of magnetization representative of both groups, all vectors, regardless of direction, were plotted on the lower hemisphere (*see* Fig. 14) and the mean pole position computed.

The mean axis of magnetization thus obtained pierces the lower hemisphere at 325 degrees from the north and 62 degrees below the horizontal plane. A statistical analysis of this data was made according to the method previously described and a resulting κ of 8 and θ of $7\frac{1}{2}$ degrees were obtained.

It is assumed in the following that this mean axis of magnetization is parallel with the lines of force of the ambient earth's field at the time the rocks were polarized. This assumption is based first on the experimental observation that cooling a rock specimen from its Curie point to room temperature has the effect of polarizing the specimen parallel with the ambient field. Furthermore, the polarization direction of recent and contemporaneous rocks is known (Chevallier, 1925; Hospers, 1953; Minakami, 1941) to be parallel with the lines of force of the present earth's field at the collecting sites.

Except for the single case of the Haruna rocks (p. 27), the polarity of the thermomagnetic component in rocks has always been found to be the same as that of the ambient magnetizing field. Nevertheless, as in the Monteregian Hills, the polarity of the ambient magnetizing field cannot be established beyond doubt and the fact that it appears to have been reversed is therefore disregarded. The magnetic axes of the specimens rather than their polarity is considered as the significant feature.

The second assumption made in this interpretation is that the earth's field is equivalent to the sum of a dipole field component coaxial with the earth's axis of rotation and non-dipole components at right angle to it. This interpretation of the geomagnetic picture is justified by the fact that the non-dipole components seem to

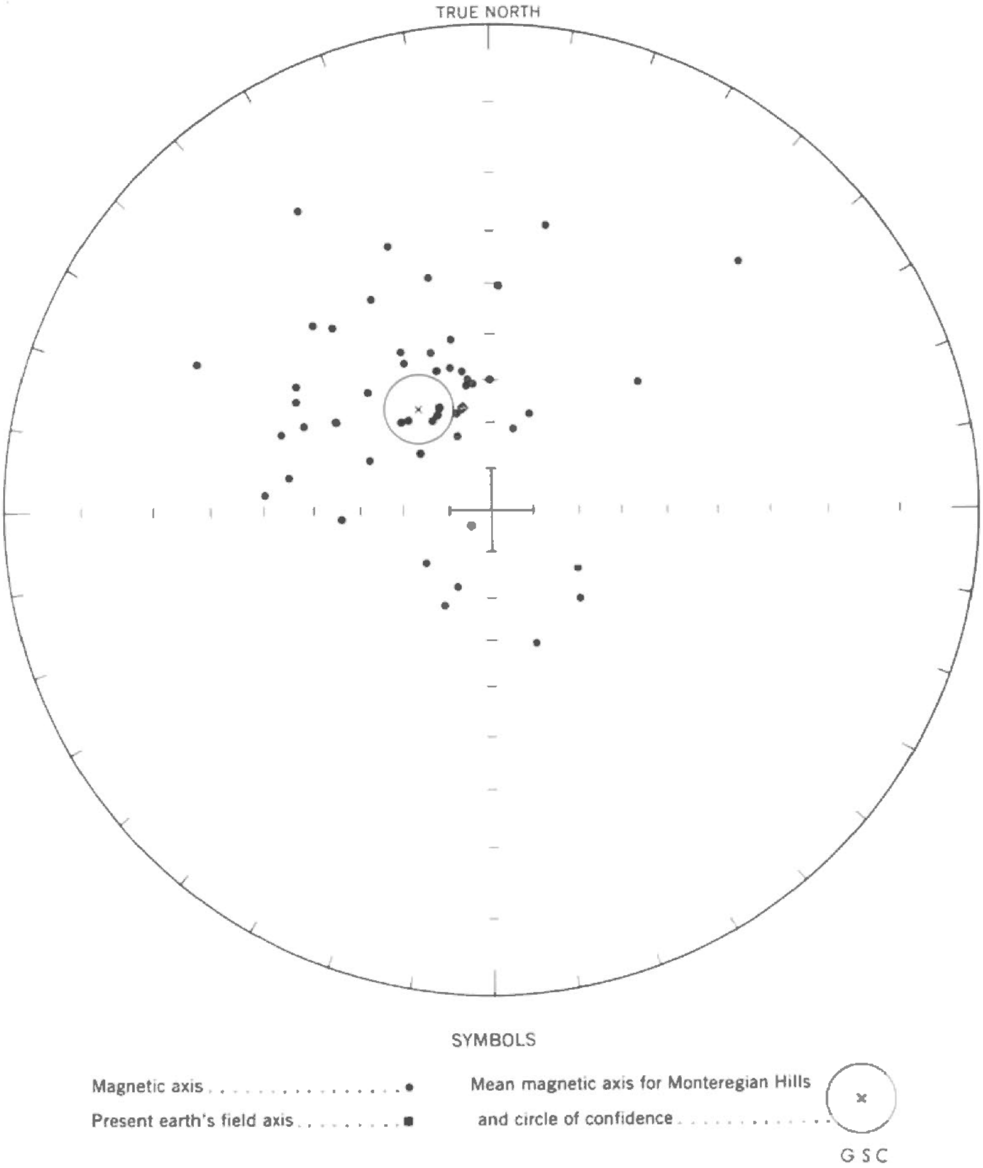

Figure 14. Stereographic projection of magnetic axes for forty-eight specimens shown on Figure 11 plotted on lower hemisphere.

average out over periods of 1,000 to 10,000 years and that over these periods the mean magnetic axis of the earth coincides with the axis of rotation. This is suggested by direct observations of the earth's field over the past 400 years (Chapman, 1951). More convincing still is the fact that the earth's mean magnetic axis as measured in Tertiary and younger rocks corresponds closely to the axis of rotation. Although the origin of the earth's field is not yet completely understood, it is widely believed that it is due to motions of the liquid core. If this is true, as it seems to be, the effect of the earth's rotation must predominate in governing the attitude of the dipole field and in this we find another reason to assume a coincidence over a period of time between the mean geomagnetic axis and the axis of rotation.

Having made these two assumptions, it is possible to derive the colatitude of a point in the past in terms of the present geographic coordinates, knowing the inclination of the magnetic axis at that point. Mathematically this is expressed by the well-known dipole equation:

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

where ψ is the palaeomagnetic colatitude of the point when the magnetic inclination at that point was I. Furthermore, knowing the declination D of the magnetic axis and the present geographic colatitude θ' and longitude ϕ' of the collecting sites it is possible to derive the palaeomagnetic pole position in terms of present day geographic coordinates. This may be done with the use of the two equations*.

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

and

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

where θ and ϕ are the present geographic colatitude and longitude respectively of the palaeomagnetic pole. The values of θ and ϕ may also be obtained graphically using different methods (Graham, 1954; Larochelle, 1958).

The pole position derived from the magnetic data for the Monteregian Hills, according to this method, is given by the coordinates 157° W and 65° N.

Age of the Monteregian Intrusions

As explained earlier, the mean direction and, indirectly, the mean axis of magnetization of a group of specimens do not necessarily correspond to the true direction or axis of the actual magnetizing field, although it is highly probable that the two directions or axes are within a maximum of $\theta°$ from one another—θ referring here to the radius of a circle of confidence. Similarly, the ancient pole position can only be determined to fall within an area of confidence. This area is elliptical, and its axes may either be calculated trigonometrically (*see* Creer, *et al.*, op. cit.) or determined graphically. Pole positions have in this manner been derived from magnetic data obtained from rocks of different types, different ages, and different continents, but only those derived from Palæozoic and younger rocks collected on the North American continent are relevant to the present study (*see* Table IV). In Figure 15 these pole positions and their corresponding ellipses of confidence are represented on a polar stereographic projection of the earth's northern hemisphere.

From an examination of Figure 15 it appears that, in general, the pole continuously shifts northward as the rocks from which its position is derived progress from Cambrian to Tertiary. As others have pointed out (e.g., Armstrong, 1957), this suggests that palaeomagnetic data may be used to determine the age of rocks,

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* *See* Creer, *et al.* (1957).

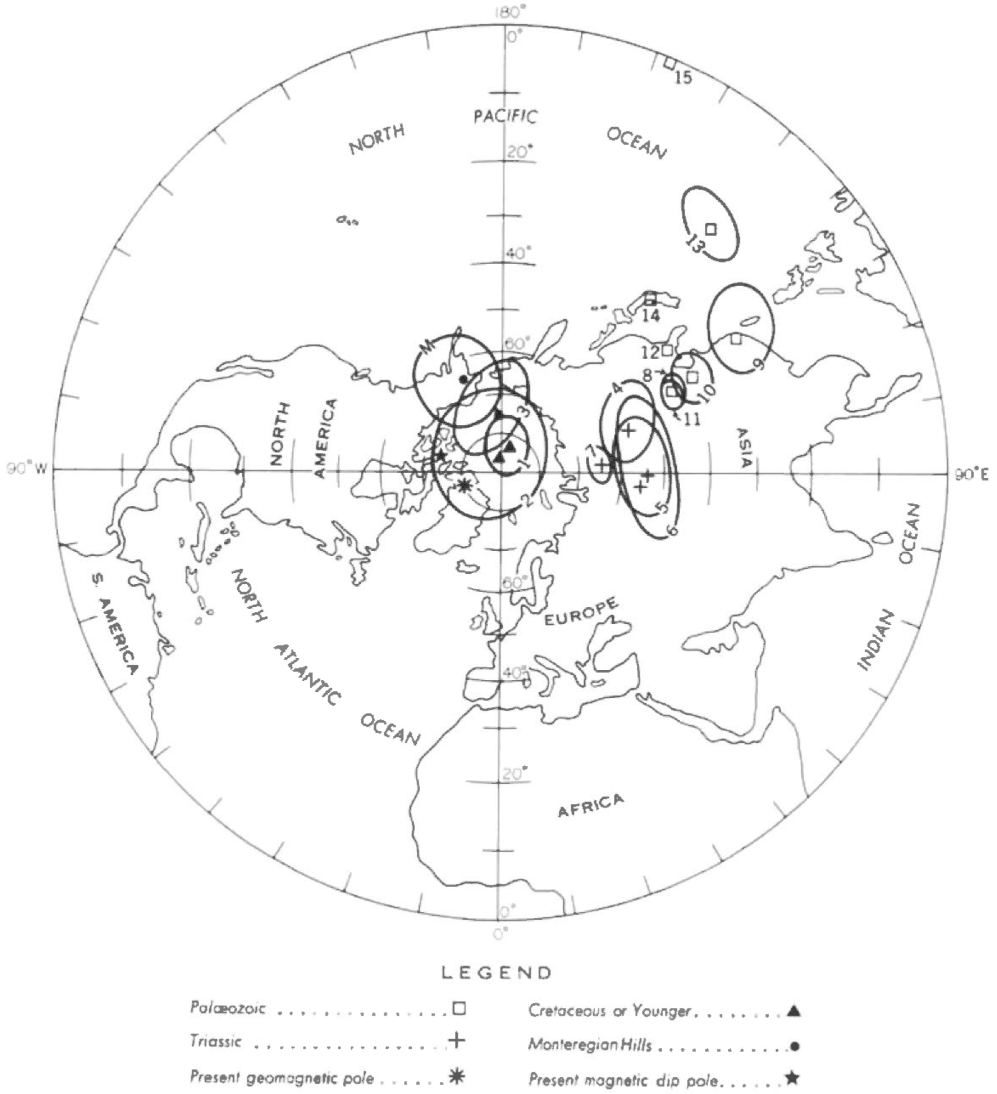
Table IV

Ancient Pole Positions Inferred from North American Rocks

No.	Age	Formation	Mean Magnetization Direction			Collecting Site		Ancient Pole Position		Reference
			D	I	θ	Lat.	Long.	Lat.	Long.	
1	Tertiary	Basalts*	348.5	+75	4.0°	60N	135W	84N	165E	DuBois, P.M. (1959)
2	Pliocene and Miocene	Columbia River Basalts*	357	+66	10.7°	47N	118W	87N	178W	Campbell, C.D., and Runcorn, S.K (1956)
3	Cretaceous	Dakota Sandstones*	342	+62	7°	34N	110W	74N	158W	Runcorn, S.K. (1956)
4	Triassic	Springdale ss	338	+16	9°	36N	113W	55N	107E	Irving, E. (1957)
5	Triassic	Lavas near Holyoke, Mass.	10	+14	11°	42N	73W	54N	90E	DuBois, P.M., *et al.* (1957)
6	Triassic	Lavas and sediments of Connecticut	12	+14	15°	42N	73W	55N	88E	DuBois, P.M., *et al.* (1957)
7	Triassic	Brunswickian, N.J.	6	+28	3°	41N	75W	63N	93E	DuBois, P.M., *et al.* (1957)
8	Permian	Supai Beds (Graham's data)	150	+ 3	5°	36N	113W	43N	113E	Irving, E. (1957)
9	Permian	Supai Beds	133	+23	8°	36N	113W	26N	119E	Runcorn, S.K. (1956)
10	Permian	Supai Beds	146	+ 8	7°	36N	113W	39N	115E	Doell, R.R. (1955)
11	Pennsylvanian	Naco Sandstone*	330	3.4	4°	36N	113W	45N	112E	Runcorn, S.K. (1956)
12	Mississippian	Barnett Shales						41N	128E	Howell, L.G., and Martinez, J.D. (1957)
13	Silurian	Rose Hill Beds	142	+39	5°	40N	78W	19N	138E	Irving, E. (1957)
14	Silurian	Clinton Iron Ore						35N	138E	Howell, L.G., and Martinez, J.D. (1958)
15	Cambrian	Wilburns						0°	158E	Howell, L.G., and Martinez, J.D. (1958)

* Pole positions as computed by the writer from the published directions of magnetism and collecting sites.

θ Radius of the circle of confidence.



The probability that the pole position derived from any group of data lies within the respective oval of confidence is 95%. Numbers refer to Table IV

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Figure 15. Ancient pole positions as inferred from palaeomagnetism.

but it must be stressed that this technique is not yet well established because palaeomagnetic data all through the geological column are still scarce. As far as the present study is concerned, the relatively high scatter of the observed data makes any conclusions more than usually suspect.

Nevertheless, if the pole position of the Monteregian Hills is compared with those derived from other North American Palæozoic or post-Palæozoic rocks, it corresponds closely with post-Triassic poles and, in fact, is closest to the Cretaceous pole (*see* Fig. 15). The overlap of the ellipses of confidence about these two pole positions is also noticeable.

Quite independently of the present study, age determinations by various radiogenic methods of Monteregian Hills rocks and other associated rocks have been made. A summary of the available data on the subject is given in Table V.

According to the world-wide absolute geological time scale reported by J. L. Kulp at the 1959 annual meeting of the Geological Society of America, rocks of Cretaceous age would range from 70 to 135 my, those of Jurassic age from 135 to 180 my and those of Permian age from 220 to 275 my. If these values are compared with the ages reported in Table V, it is apparent that the maximum age of the Monteregian Hills is Permian. On the other hand, Grunenfelder and Silver (1958) have recently shown that the lead-alpha (Larsen's) method is subject to considerable error and that its tendency is to indicate ages that are too great. They base their statement on a comparison of the ages obtained for a given rock by the lead-alpha (450 my), the potassium-argon (250 my) and the rubidium-strontium (290 my) methods. If Grunenfelder and Silver's views are correct, the age of 224 my (Permian) for the Monteregian Hills is too great. Methods using the pleochroic halos, and helium and lead are now widely recognized to give ages that are too young. The two determinations by K/Ar ratios, which are in good agreement, are considered to be the most reliable. It is interesting to note that these two independent determinations agree with that from the palaeomagnetic data and also indicate a Cretaceous or Jurassic age for the Monteregian intrusions.

Table V

Age Determinations of the Monteregian Hills Series by Radiogenic Methods

Collecting Site	Rock Type	Method	Age	Reference
Mount Megantic	Essexite	Pleochroic halos	Tertiary	Osborne (1935)
Mount Royal	Tinguaite	Helium	57 ± 1.5 my	Urry (1938)
" "	"	Lead	60 to 80 my	" "
" "	"	Larsen's method	224 my	Lyons, *et al.* (1957)
Oka	Okaite	K/Ar ratio	145 my	Hurley and Fairbairn (1958)
Brome Mtn.	Essexite	K/Ar ratio	115-140 my	Lowdon, *et al.* (1960)

Whether the accord between the ages obtained from the radiogenic methods and the palaeomagnetic data is purely fortuitous or real is difficult to state with any degree of assurance. It certainly suggests, however, that it may be possible to estimate the age of rocks from their palaeomagnetism and only the accession of more palaeomagnetic data all through the geological column will permit the reliability of the method to be assessed.

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