A STUDY OF THE REMNANT MAGNETISM OF GRANITE MOUNTAIN, IRON SPRINGS DISTRICT, UTAH

by

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ABSTRACT

Granite Mountain is a laccolithic intrusion of quartz monzonite in the Iron Springs district of southwestern Utah. The intrusion is associated with peripheral replacement deposits of iron ore.

The orientation of the remnant magnetism of 50 samples from Granite Mountain was determined using a specially constructed astatic magnetometer. The magnetometer is capable of detecting fields of the order of 10^{-7} oersteds.

The orientation of the remnant magnetism vectors show two important features. First, vectors with similar orientations exist in geographic domains and secondly, a majority of the vectors are close to the modal azimuth of N 6°W. The present azimuth of the earth's magnetic field at Granite Mountain is N 16°E.

The author believes that the magnetic domains were caused by strong, local magnetic fields. These fields were due to ore bodies that exist or that may have existed in the vicinity of each domain.

The modal azimuth of the remnant magnetic vectors is interpreted as being due to the earth's magnetic field

at the time the remnant magnetism was acquired. Some workers have plotted the path of migration of the earth's magnetic pole throughout geologic history. The intersection of this path and the modal azimuth presumably represents the point in time at which the Granite Mountain intrusion was formed. The age of the intrusion, determined by this method, is early Tertiary and this agrees closely with the age determined by geological methods.

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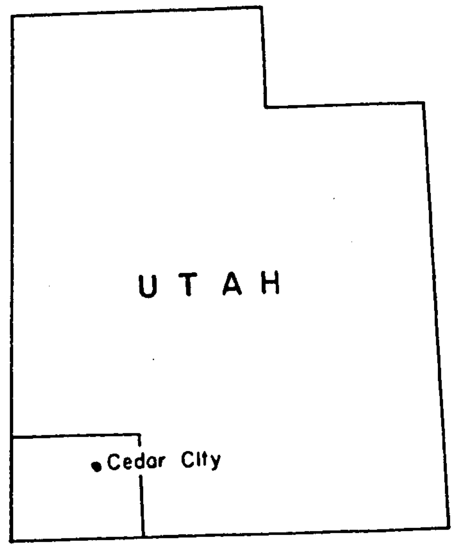
INTRODUCTION

Granite Mountain is one of three laccolithic intrusions in the Iron Springs district thirteen miles west of Cedar City in southwestern Utah (Plate 1). All three intrusions are associated with peripheral iron ore deposits that have been mined extensively for more than half a century.

The purpose of this investigation was to determine the dipole orientation of the remnant magnetism of the intrusive rocks of Granite Mountain, with a view to establishing a pattern. It was thought that such a pattern of dipole orientation might have been affected, to some extent, by the proximity of iron ore bodies. If this were the case, such a pattern might provide a means for locating hidden ore bodies. The second possibility was that knowledge of the orientation of the remnant magnetism dipoles might throw some light on the age of the intrusion. Some workers maintain that the earth's magnetic pole has migrated throughout geologic history. Assuming this to be true, the orientation of the remnant magnetism of Granite Mountain, provided it was unaffected by other causes, should be the same as the earth's magnetic

PLATE 1

Index map of Iron Springs district showing location of Granite Mountain.


UTAH
Cedar City

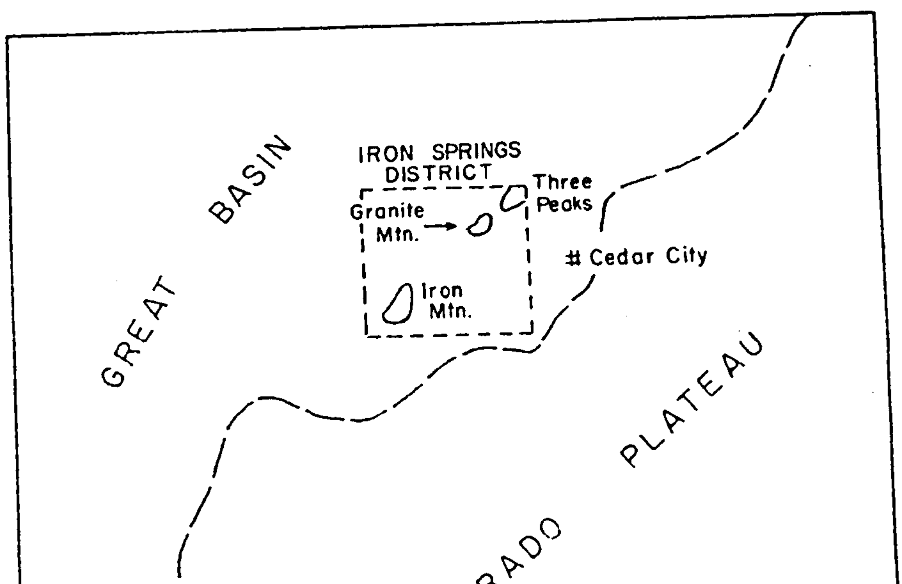

GREAT BASIN
IRON SPRINGS DISTRICT
Three Peaks
Granite Mtn.
Iron Mtn.
Cedar City
COLORADO PLATEAU

PLATE I.

field at the time that the igneous mass cooled through the Curie temperature.

The three intrusions in the Iron Springs district lie along an approximate northeast axis; the northern one is called Three Peaks, the southern one Iron Mountain, while the one in the middle is Granite Mountain. Granite Mountain is the smallest of the three intrusions; its exposure is roughly oval in plan, with the long axis, about 2.5 miles in length trending NE, and the short axis about 1.5 miles long oriented NW.

The highest peak on Granite Mountain has an elevation of 6700 feet above mean sea level, while the surrounding valley floor is between 5500 and 5800 feet in elevation.

All the known iron ore deposits associated with Granite Mountain lie on its northern and eastern periphery. There are numerous small veins of magnetite associated with joints within the igneous mass itself but none of these is being mined.

Fifty eight samples of rock were collected from Granite Mountain between August 21st and September 4th, 1958. The field orientation of each of these samples was known. Cubes, 1 7/8" on a side, were cut from each of the samples in a manner such that the orientation of the rock cubes in space was known. A specially constructed, very sensitive astatic magnetometer was used to determine the orientation of the magnetic dipole of each cube. From this, a plot showing the overall orientation of the remnant magnetism of Granite Mountain was made.

The work described in this thesis was undertaken as part of a research project being carried out under the direction of Dr. Robert L. Dubois. The project is being conducted by the Department of Geology for the Columbia-Geneva Steel Division, United States Steel Corporation.

The author is greatly indebted to Dr. Dubois for his guidance and help throughout this work. He is also indebted to Prof. J. W. Anthony who gave so much of his time and consideration to tackling a number of technical problems and for reviewing and editing this manuscript. Much of the basic construction of the magnetometer unit was done by Dr. Dubois and Prof. Anthony and the author is very appreciative of this. The author acknowledges the help of all his colleagues who worked on the "Anomalous Magnetism" project and who, in one way or another, contributed to this work.

Mr. Max Galbraith, Mr. Robert Rowley, Mr. Charles Ratte and other staff members of the Columbia-Geneva Division of the U.S. Steel Corp. in Cedar City, Utah deserve a special word of thanks for making available maps, considerable information and a means of transportation during the author's visit to Cedar City.

The author is most grateful to Mr. William N. Hackenbracht for his help in collecting specimens in the field; to Mr. Earl C. Flint for cutting many of the specimens; to Miss Suzanne B. Hanella for making some of the statistical calculations, checking the data and helping to edit this paper; to Dr. J. Treat, of the Physics Department of the University of Arizona, for checking the calculations connected with instrumentation problems; and to Dr. M. A. Melton for advice on statistical problems.

Finally, the author is most grateful to Dr. W. C. Lacy, the director of this thesis for his interest, encouragement and advice connected with this project.

INSTRUMENTS AND METHOD FOR DETERMINING MAGNETIC DIPOLE ORIENTATION

INTRODUCTION

In order to determine the magnetic dipole orientation of the rock cubes, a suitable instrument had to be built. The intensity of the remnant magnetism of most rocks is rather low, since, in most cases, this magnetism is imparted by the earth's magnetic field which has a strength of about 0.5 oersted.

Of the various instruments used for determining dipole orientation the astatic magnetometer was chosen as being most suitable for the present study, because of the relative simplicity of construction and because of its relatively high sensitivity. The instrument built was modeled after one constructed by P. M. S. Blackett (1952).

The magnetometer is situated at the Geochronology laboratories of the University of Arizona, at Toumamoc Hill, three miles west of Tucson, Arizona. Toumamoc Hill is composed of dark volcanic rock and the building housing the magnetometer is, itself, constructed of this same rock which has a relatively high magnitude of remnant magnetism. This does not, however, affect the results significantly though it is certain that for experiments requiring much greater precision, a more suitable location would be essential.

The orientation of the dipole of the rock cubes was determined using the magnetometer. This orientation was then related to the original rock sample from which the orientation of the remnant magnetism of the rock *in situ* was determined.

An approximate measurement of the intensity of magnetization of each of the rock cubes was also made using the magnetometer. The instrument is, however, capable of measuring the intensity of magnetization of a specimen with accuracy.

CONSTRUCTION OF THE ASTATIC MAGNETOMETER

In principle, the astatic magnetometer consists essentially of two equal and oppositely directed horizontal magnets affixed to a vertical rod at a distance, z, apart. The rod is suspended by a fine fibre from a rigid support. A perfectly astatic system, that is, one in which the resultant magnetic moment of the suspension is exactly zero, is unaffected by a uniform magnetic field such as the earth's field. In a non-uniform field, on the other hand, such a system undergoes a deflection which is proportional to the difference in horizontal field strength at the top and bottom magnets; the deflection, therefore, measures the vertical gradient dH/dz of the horizontal component of the magnetic field.

In our instrument, the rod with the two magnets, (hereafter referred to as the "magnetometer suspension" or simply, the "suspension") is housed in a closed plexiglass chamber to protect it from air currents, etc. The suspension consists of an aluminum rod, 3/32" in diameter, by means of which two small Alinco magnets are held 15 cms. apart (Plate 2). The top magnet is attached rigidly to the rod, whereas the lower magnet is glued to the rod with rubber cement, in the same plane as the upper magnet. This is done to allow a slight adjustment of the lower magnet after the suspension is in its place in the instrument. The magnets have dimensions of 0.376" x 0.065" x 0.065" and each has a moment of 6.504 pole cms.

Midway between the two magnets and exactly at right angles to the plane in which they lie is a small axis about which a very small trimming magnet can be rotated in a vertical plane. The trimming magnet is a very weak magnet made by grinding down a larger magnet to a narrow, geometrically accurate prism. This was done to be sure that the magnetic dipole of the trimming magnet

PLATE 2

Magnetometer suspension. Front and side views, (actual size).

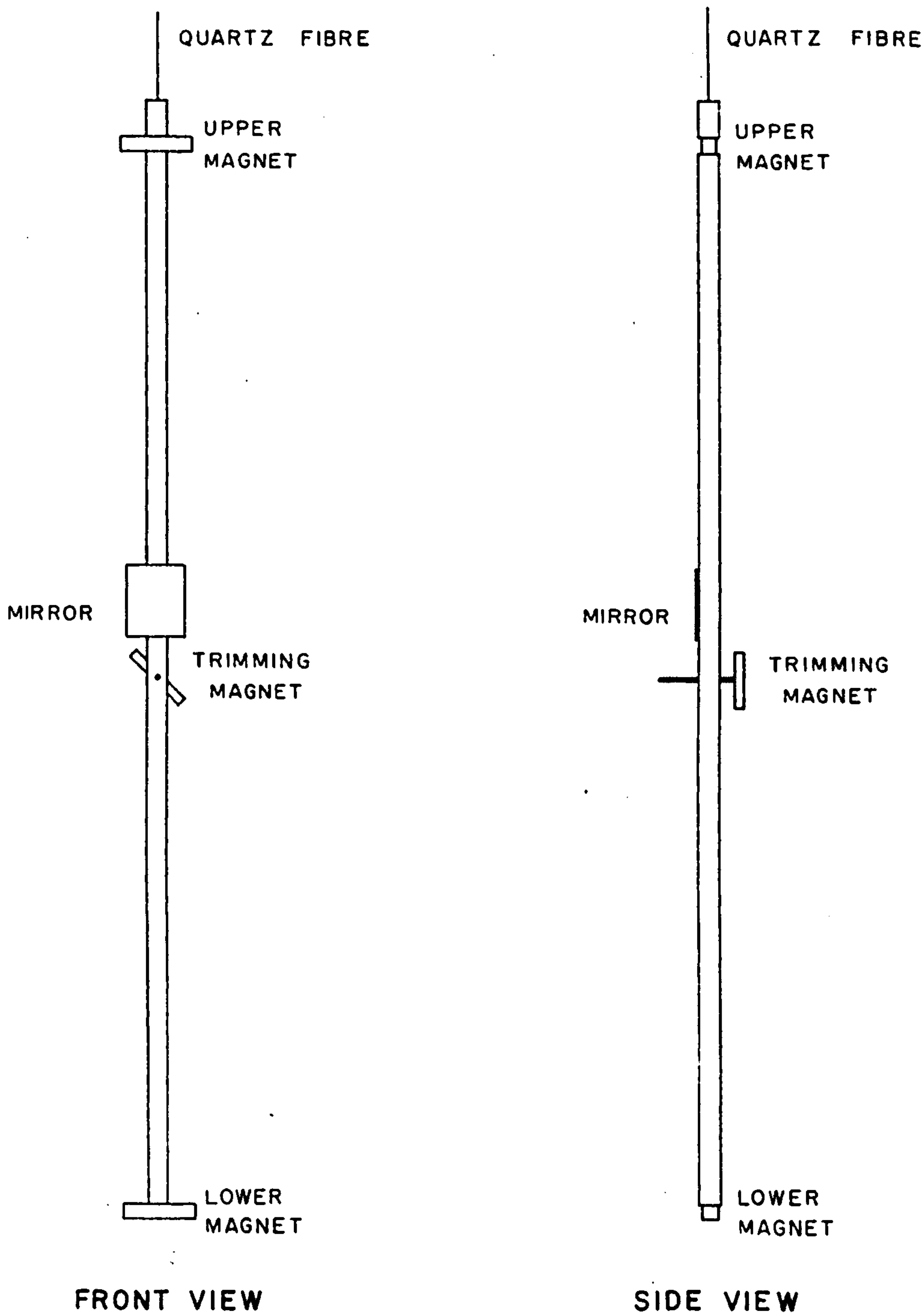

QUARTZ FIBRE
UPPER MAGNET
MIRROR
TRIMMING MAGNET
LOWER MAGNET
FRONT VIEW
QUARTZ FIBRE
UPPER MAGNET
MIRROR
TRIMMING MAGNET
LOWER MAGNET
SIDE VIEW

PLATE 2.

corresponds exactly with its long axis. The prism was then magnetized by a small solenoid and then demagnetized to an experimentally determined optimum value.

Just above the trimming magnet a very thin mirror (1.0 x 0.7 cms.) is attached to the aluminum rod, approximately parallel to the plane of the two main magnets. The mirror reflects a collimated beam of light from a lamp to a scale; this measures the angular deflection of the magnetometer.

The magnetometer suspension weighs 2.4 grams and is suspended by a fine quartz fibre from a brass rod held in the plexiglass housing (Plate 3). The quartz fibre is 7.8 cms. long and has a diameter of 9 microns.

The housing for the suspension consists of a plexiglass cylinder of 2" I.D., with a small glass window just opposite the mirror on the suspension. The housing is fitted with leveling screws which rest on a three legged platform.

The sensitivity and accuracy of the instrument is increased by reducing external magnetic fields to a minimum because the suspension always has a minute magnetic moment which would be affected by an ambient field and also because an ambient field tends to induce some magnetism in a specimen during measurement. The earth's field is nullified by imposing an exactly equal and opposite

PLATE 3

Magnetometer housing and specimen carriage. The photograph shows a rock cube in position for measurement.

PLATE 3

field by means of three pairs of Helmholtz coils. These coils are arranged with their centers on three axes, one vertical and two horizontal, at right angles to each other. The coils in each pair are placed parallel to one another at a distance apart, equal to their radii (Plate 4, Fig. 1). The Helmholtz coils are supported by aluminum braces, within a wooden frame that rests on the floor. The frame is 6'7" on a side and is built of vertical posts and cross pieces held together by wooden dowels and glue. The coil frames are constructed of plywood and glue and each carries two concentric windings of 100 turns of No. 18 gauge enamelled copper wire. The ends of each coil are connected to a terminal block and thence to a 12 volt DC source through a milliammeter, rheostat and switch. The two coils forming a pair are connected in series to one switch and rheostat. The inner coil winding on each coil-frame is used to nullify the earth's magnetic field. The outer winding is present so that secondary fields may be imposed on the system if desired.

Each pair of coil frames is referred to by that component of the earth's field which it opposes. Thus, the pair of horizontally placed coil-frames opposes the vertical component of the earth's field and are termed the "vertical coils". The other two pairs are referred to as the N-S and E-W coils respectively. The radii of the coils are as follows: N-S 78 cms., E-W 89 cms., and vertical 84 cms.. The disparity in radii permits the coil frames to fit one within another.

The Helmholtz coils are oriented along an azimuth 12° west of magnetic north in order that a significant component of the earth's field is opposed by the E-W coils. If the coils are oriented on magnetic north there is always a very small component in the E-W direction that is too small to be counteracted by the available rheostats. The switches, rheostats and milliammeters are assembled for convenience at a control panel (Plate 4, Fig. 2).

At the intersection of the axes of the Helmholtz coils, there is a space of approximately 2 cu. ft. that is essentially astatic. The magnetometer housing and stand are arranged within the frame holding the coils so that the suspension lies within this astatic space. The entire housing containing the suspension can be withdrawn upwards out of the main frame by means of an overhead pulley arrangement.

Below the suspension housing is the specimen carriage. This is mounted on the top of a thick, vertical plastic rod that can rotate freely within a plastic tube. The specimen carriage can be raised or lowered by means of a string and pulley arrangement and is supported by a stand, independent of the magnetometer suspension. A

PLATE 4

Figure 1. Helmholtz coils. The photograph shows the three pairs of Helmholtz coils. The magnetometer suspension is in the housing in the center.

Figure 2. Control panel.

PLATE 4

Figure 1.

Figure 2.

vertical scale shows the distance between the lower magnet and the upper surface of a cube on the specimen carriage. The carriage is machined to hold a 1 7/8" cube of material. It can be rotated freely in a horizontal plane by means of a pulley arrangement. The angle through which the carriage is rotated is measured with a full-circle protractor fixed to the base of the specimen carriage; a fiducial pointer is fixed to an independent support.

The apparatus is completed by a collimating lamp and a frosted glass scale placed at a distance of 1 meter from the suspended magnetometer. The light beam is directed at the mirror of the magnetometer suspension and the light is focused to show a fine vertical line on the glass scale which is calibrated in millimeters. The arrangement can detect a rotational movement of the magnetometer of 1.275 minutes of arc.

The entire apparatus is constructed of wood, aluminum, brass, plastic or some other non-ferromagnetic material. In addition, ferromagnetic materials are kept at a minimum in the area near the apparatus. This is done to keep the inhomogeniety of the ambient magnetic field to a minimum.

No special effort is made to reduce disturbances due to vibration. For measurements involving greater precision than those made, some extra care would have to be given to eliminating this source of error.

PRELIMINARY ADJUSTMENTS OF THE MAGNETOMETER APPARATUS

Nullifying the earth's magnetic field.

Before each series of measurements is begun, the earth's field must be nullified as completely as possible. This is done by raising the suspension housing upward, out of the sphere of the Helmholtz coils. A sensitive compass is placed at the intersection of the exes of the Helmholtz coils and a current is passed through the N-S and E-W coils until the compass needle shows no preferred orientation. The current is allowed to pass for about 15 minutes and if no change in the behavior of the compass needle is observed the horizontal component of the earth's field is considered to be just balanced. The currents that are passed through the N-S and E-W coils are approximately 0.22 amps and 0.053 amps, respectively. The current passed through the vertical coils is 0.41 amps. This last figure is obtained by calculation, knowing the vertical component of the earth's field at Tucson and the radii of the vertical coils. The field, H_x, generated by a pair of Helmholtz coils which are a distance apart equal to their radii, is given by

$$H_x = \frac{4\pi nI}{10R} \times \sin^3 A$$

where,

n = number of turns in each coil
I = current strength in amps.
A = 63°26'
R = radius of each coil in cms.

Therefore,

$$I = \frac{10R \times H_X}{4\pi n \times \sin^3 A}$$

Hence, for the vertical coils,

$$I = \frac{10 \times 84 \times 0.4391}{4\pi \times 100 \times 0.7153}$$

$$= 0.4104 \text{ amps.}$$

Experiment has shown that the value of the current flowing in the vertical coils is not significant. Changing the value from 0 amp. to 0.75 amp. does not produce any significant change in the results obtained.

The apparatus has no mechanism to compensate for rapid fluctuations in the earth's field. It would be possible to attach a flux gate arrangement to the secondary windings of each pair of coils to automatically compensate for fluctuations in the earth's field. Repeated checks during the experiments have shown that the fluctuation of the earth's field, during the time of measurement per specimen, is usually insignificant provided the zero position of the magnetometer is checked before and after the measurement of each specimen. For this reason a flux gate arrangement was not used.

It may be well to point out that the presence of a uniform field, such as the earth's field, does not effect the values of the measurements obtained. The only effect that such a uniform field has on the measurements is to reduce sensitivity.

Astaticizing the magnetometer suspension.

When the current in the Helmholtz coils is turned on, the magnetometer is deflected through an arc that is inversely proportional to the degree of asticism of the suspension. The deflection can be brought to a minimum value by turning the trimming magnet to an experimentally determined optimum position. The amount of deflection can be decreased still further by rigidly clamping the aluminum rod of the suspension and then rotating the lower magnet through a minute arc in a horizontal plane. The optimum position of the lower magnet is determined by the method of trial and error. Because of the very delicate nature of this adjustment, there is a definite limit to which the astaticism of the suspension can be refined.

After these adjustments are made the suspension still retains a very small horizontal moment which is approximately normal to the plane of the two main magnets. In our apparatus, this moment is approximately normal to the axis of the E-W Helmholtz coils. This provides an approximate method of determining the magnitude of the residual magnetic moment, hence, the degree of astaticism of the suspension. The position of the light beam on the scale is noted keeping the earth's field uncompensated. The position is then determined with the earth's field just balanced. The deflection, ΔD, is then approximately proportional to the magnetic torque due to the E-W coils.

Now, torque, U, on the quartz fibre is given by

$$U = \frac{\Delta D \times Z \pi r^4}{4dl} \qquad (1)$$

where

ΔD = deflection on scale
= 19.3 cms.
d = distance from suspension mirror to light-scale
= 135 cms.
Z = modulus of rigidity of quartz
= 4.97×10^{11} cgs units
r = radius of quartz fibre
= 4.5×10^{-4} cms.
l = length of quartz fibre
= 7.8 cms.

Field, H_{ew}, due to E-W coils = 5.396×10^{-2} oersteds.

But torque, U, due to H_{ew} is given by

$$U = H_{ew} M_s, \qquad (2)$$

where

M_s = the residual moment of the suspension.

Combining (1) and (2), we get

$$H_{ew}\ M_s = \frac{\Delta D \times Z\pi r^4}{4dl}$$

Therefore,

$$M_s = \frac{\Delta DZ\pi r^4}{4dl \times H_{ew}}$$

$$= \frac{19.3 \times 4.97 \times 10^{11} \times \pi \times 4.5^4 \times 10^{-16}}{4 \times 135 \times 7.8 \times 5.396 \times 10^{-2}}$$

$$= 5.437 \times 10^{-3} \text{ pole cms.}$$

The degree of astaticism, S, is defined as the ratio of the moment, M, of one of the main magnets to that of the whole suspension. That is,

$$S = \frac{M}{M_s} = \frac{6.504}{5.437 \times 10^{-3}} = 1196.$$

It is interesting to compare this value with the value of S = 5000 which Blackett obtained for his extremely sensitive instrument.

Measurement of angle ϕ

After the magnetometer suspension has been adjusted, the horizontal angle, ϕ, between the plane of the magnets and the fiducial pointer is measured. This is done 10 times using a plumb-bob and the average is taken. The angle, ϕ, remains constant so long as the suspension is not tampered with after adjustment.

Temperature control.

A definite relationship exists between temperature and the zero position of the magnetometer. It has been found that, other things being constant, the magnetometer wanders at the approximate rate of 3 scale divisions per degree change of temperature. The cause of this wandering is not completely understood. During the time of measurement of a single specimen the temperature must be kept constant within 0.5°C, otherwise errors occur, especially in the measuring of weakly magnetized samples.

Static electricity.

When adjustments are made on the magnetometer suspension the housing picks up a static charge which causes the magnetometer to behave erratically. For this reason the apparatus is allowed to stand, for 12 to 18 hours after any major adjustment before measurements of specimens are commenced.

As would be expected, this cause of error is more prevalent in dry than in moist weather.

SENSITIVITY OF THE MAGNETOMETER

In order to obtain a quantitative idea of the sensitivity of the magnetometer a small solenoid was built. The solenoid was placed 72cms. below the lower magnet of the suspension, with its axis horizontal and at right angles to the plane of the magnet. A small current, I, was passed through the solenoid and the deflection on the scale was noted. Using the following data, the sensitivity of the magnetometer was calculated:

Number of turns in the solenoid, N = 89

Length of solenoid, l_s = 3.3 cms.

Radius of coils, a = 0.381 cms.

Distance to lower magnet, L_1 = 72 cms.

Distance to upper magnet, L_2 = 87 cms.

Current passed through solenoid, I = 0.5 amps.

Deflection produced, ΔD = 2.0 cms.

The value of the field, H, perpendicular to the axis of a solenoid is given by

$$H = \frac{2 \quad NIa^2 l_s}{3L^3 \left(4a^2 + l_s^2 \right)^{\frac{1}{2}}} \times 10^{-1} \text{ oersteds} \quad (3)$$

Therefore, at the lower magnet the field, H_1, due to the solenoid is given by

$$H_1 = \frac{2 \times 89 \times 0.5 \times 0.381^2 \times 3.3 \times 10^{-1}}{3 \times 72^2 \times \left(4 \times 0.381^2 + 3.3^2 \right)^{\frac{1}{2}}} \text{ oersteds}$$

$$= 3.532 \times 10^{-6} \text{ oersteds.}$$

Similarly, at the upper magnet, the field, H_2, due to the solenoid is given by

$$H_2 = \frac{2\pi \times 89 \times 0.5 \times 0.381^2 \times 3.3 \times 10^{-1}}{3 \times 87^3 \times (4 \times 0.381^2 + 3.3^2)^{\frac{1}{2}}} \text{ oersteds}$$

$$= 2.002 \times 10^{-6} \text{ oersteds.}$$

$$\therefore \quad \Delta H = H_1 - H_2 = 1.530 \times 10^{-6} \text{ oersteds.}$$

Sensitivity, g, is given by

$$g = \frac{\Delta H}{\Delta D} \qquad (4)$$

$$= \frac{1.530 \times 10^{-6}}{20} \text{ oersteds per mm. of deflection}$$

$$= 7.65 \times 10^{-8} \text{ oersteds / mm.}$$

$$= 7.65 \times 10^{-7} \text{ oersteds / cm.}$$

This value for the sensitivity may be considered the limit of detection. In order that the orientations of the magnetic dipoles of the rock cubes be determined with accuracy the field difference, ΔH, due to the cube, should be about 10^{-6} oersted.

In order to check the order of magnitude of ΔH, the modulus of rigidity of the quartz fibre can be calculated and compared with the standard value.

The torque, U, on the suspension is given by

$$U = \Delta HM \qquad (5)$$

Combining equations (1) and (5) we get

$$Z = \frac{4 \times Mld \times \Delta H}{\pi \times r^4 \times \Delta D}$$

$$= \frac{4 \times 6.504 \times 7.8 \times 135 \times 7.65 \times 10^{-7}}{\pi \times 4.5^4 \times 10^{-16}} \text{ cgs units}$$

$$= 1.628 \times 10^{11} \text{ cgs units}$$

Standard value of Z is 4.97×10^{11} cgs units (Strong, 1938). This compares very well with the calculated value of Z, considering the approximations made during the calculation.

METHOD OF DETERMINING THE MAGNETIC DIPOLE ORIENTATION OF THE ROCK CUBES

After the current in the Helmholtz coils has been switched on, the light spot on the lamp-scale is adjusted to the zero mark. After a period of 10 minutes if there is no shift in the position of the light-spot, the apparatus is ready for use.

On each rock cube a corner is chosen and the faces around it are named A, B, and C in a clockwise direction, such that, the A face is the upper, horizontal face of the cube and the AB edge is roughly N-S in respect to the orientation <u>in situ</u>. The other three faces are named D, E and F, with D opposite A, E opposite B and F opposite C. The corners where these faces are indicated are marked with black. The cube is placed on the specimen carriage in such a way that the corners ABC and DEF always have a similar orientation with respect to a mark on the carriage. This is done to facilitate later plotting of observations. The cube is first placed with face A up and carefully co-centered with the suspended magnetometer. The carriage is slowly rotated until the magnetometer, after being deflected to one side at the beginning of the test, returns to the zero point. At this point, the magnets and the dipole of the cube lie in the same vertical plane.

Two such null points are obtained in each complete revolution of the specimen. One, in which the N pole of the lower magnet is near the S pole of the cube, is called the NS null point; the other, in which the N poles of both the cube and the lower magnet are adjacent, is called the NN null point. Readings of the position of the carriage are taken at both null points. The procedure is repeated until concurrent readings are obtained. After measuring side A, the procedure is repeated with each of the other faces lying uppermost. A total of twelve readings is obtained for each specimen.

Ideally, for each face, the NS and NN null points should differ by exactly 180°. Often this is not the case. The deviation from ideal behavior may be due to one or more of the following reasons:

1) The axis of rotation of the suspension and of the carriage may not be absolutely coincidental. This is the most common cause of error.

2) The cube may not be centered properly on the specimen carriage.

3) The cube of rock may be geometrically imperfect or unsymmetrical.

The error due to the first two causes can be almost completely eliminated by plotting the mean position of the dipole as derived from the NN and NS null points. The polarity of the azimuths are noted i.e. whether the azimuth measured is for the north or the south pole of the rock cube.

METHOD OF DETERMINING THE APPROXIMATE INTENSITY OF MAGNETISM OF THE ROCK CUBES -

The rock cube is rotated to the NS null point. The carriage is now rotated again through an angle, E, exactly 90° from the null point and the deflection, Δ D, of the light spot on the scale, is noted. This deflection is a functionof the intensity of magnetization of the rock.

The difference in field strength, Δ H, at the two magnets of the magnetometer, due to a rock cube having a magnetic moment, M_c, at a mean distance, L, from the lower magnet of the suspension, is given approximately by

$$\Delta H = M_c \left[\frac{1}{L^3} - \frac{1}{(L + z)^3} \right]$$

But from equation (4),

$$\Delta H = g \Delta D.$$

Therefore,

$$M_c = g \Delta D \times \frac{L^3 (L + z)^3}{[(L + z)^3 - L^3]} \qquad (7)$$

The intensity of magnetization, I_m, of any material is given by

$$I_m = \frac{M_c}{V} \qquad (8)$$

where V is the volume of the material.

Combining (7) and (8) we have

$$I_m = \frac{g \Delta D}{V} \times \frac{L^3 (L + z)^3}{[(L + z)^3 - L^3]} \qquad (9)$$

In our experiments, the rock cubes are held at a mean distance of 5 inches from the lower magnet, so that

L = 5 inches = 12.7 cms.
(L + z) = 27.7 cms. (z is the distance between the two magnets = 15 cms.)
V = 108 cu. cms.
$g = 7.65 \times 10^{-7}$ oersteds/cm. of deflection.

Inserting these values in equation (9), we have

$I_m = 1.6 \Delta D \times 10^{-5}$ cgs units/cc

In this study an arbitrary scale of intensity of magnetization from 1 to 5 has been used. The values of ΔD and I_m on this arbitrary scale are given in Table 1. below.

TABLE 1.

Scale Value	Strength	Deflection, ΔD, in cms.	Intensity of magnetism, I_m, in 1×10^{-5} cgs units/cc
1	very weak	0 to 1.0	0 to 1.6
2	weak	1.0 to 3.0	1.6 to 4.8
3	moderate	3.0 to 10.0	4.8 to 16.0
4	strong	10.0 to 20.0	16.0 to 32.0
5	very strong	more than 20.0	more than 32.0

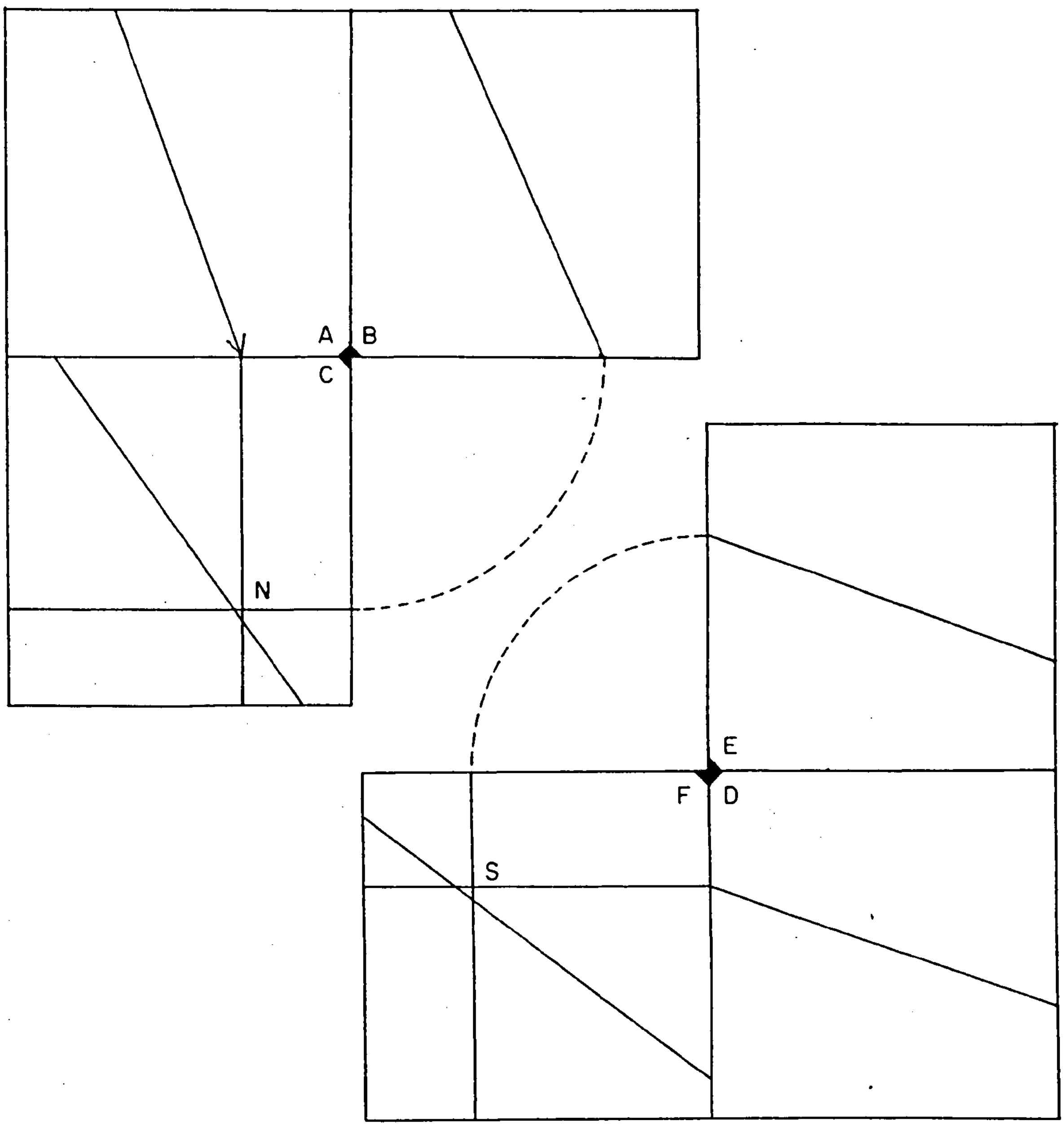
It should be pointed out, once more, that the values for I_m given in Table 1. are only approximately correct. The value of this arbitrary scale of strength lies in the fact that it provides a rapid means of comparing the magnetic intensities of individual samples in a single set of measurements.

PLOTTING THE OBSERVATIONS

From each zero point reading obtained, the angle ϕ is subtracted and the results plotted on paper layouts, representing each face, as shown in (Plate 5). The plot

PLATE 5

Example of pole positions plotted on paper layout. The azimuth is drawn on each face and then extrapolated if necessary to cut the others near a point which is one of the two poles. Knowing that face A is always horizontal, the azimuth and plunge of the dipole vector is measured. Note the small triangle of error at each pole position.



SPECIMEN NUMBER: ZGM-3-58

PLUNGE OF DIPOLE = 23° DOWN

AZIMUTH OF DIPOLE FROM EDGE AB = 342°

TRUE AZIMUTH OF DIPOLE = N 18° W

PLATE 5.

appears as lines which, when extrapolated, intersect at two points, one on each of two opposite faces. These points represent the magnetic dipole passing through the center of the cube. Therefore, the points should be symmetrical about the center of symmetry of the cube.

In practice, it is found that the lines do not always intersect at a point but that they form a small triangle of error. Generally, the intersection of the bisector of the triangle of error is taken to be the pole position. By superimposing the plans of the two opposite faces on each other, over a light table, the mean position of the poles is determined. By simple solid geometry, the field orientation of the dipole is then found.

In a few cubes the dipole is almost normal to one set of faces. Consequently, the magnetic component parallel to these faces may be extremely small. Because of this, the readings obtained from such a pair of faces may be in considerable error, and a large triangle of error may result. In these special cases, the poles are considered to be at the intersections of the extrapolated lines from the other faces of the cube.

GEOLOGY

GENERAL STATEMENT

The geology of Iron Springs district in Iron County, Utah, was first studied in detail by Leith, and Harder (1908) who established the general stratigraphic column, the relationship of the iron ores to the igneous intrusions and some of the ore controls. The area was later studied by Butler (1920) and Gregory (1950). Mackin (1947) and (1954) conducted a very detailed study of the Iron Springs district. He modified the original stratigraphic column proposed by Leith and Harder and has advanced detailed theories of ore control. Most of the geology described in this paper is taken directly from Mackin and the geologic maps are also after Mackin (1954).

The most important geological features of the Iron Springs district are the three large quartz andesite laccoliths, lying along a northeast-southwest line across the district. The Granite Mountain laccolith is exposed only in its upper portions, as are the other two laccoliths. At no place has the laccolith been bottomed either by erosion or by drill holes. The rock of the

Granite Mountain intrusion is extremely uniform in composition and corresponds to a quartz andesite or quartz monzonite (Williams, S.A., personal communication).

The stratigraphic sequence in the district has a maximum thickness of 6500 feet and crops out in successive rings around the intrusive. The dip of the sedimentary rocks is very steep at the contact with the laccoliths but it decreases farther away from the contact. These general relationships are modified, locally, by faulting.

The youngest rocks in the stratigraphic sequence are a series of latitic lavas and associated pyroclastics probably of Eocene age. These rocks are exposed in the Eight Mile Hills, southeast of Granite Mountain, and elsewhere in the district. They are essentially identical in chemical composition with the intrusive rock. The intrusions were probably emplaced shortly after the volcanic rocks were spread out on the surface and are, therefore, most likely to be early Tertiary, and possibly Eocene in age (Mackin, 1954).

The Homestake limestone is the oldest rock unit found in the district; it is the host rock for the replacement iron ore bodies. At the base of the Homestake limestone there is a siltstone unit that is very resistant to replacement so there is usually a barren zone up to a few tens of feet thick between the ore bodies and the intrusive.

The ore bodies are pods measuring up to 1000 feet along the strike and down the dip and as much as 230 feet in width. The ore is a mixture of hematite and magnetite with the proportion of magnetite varying between 15 and 60 per cent. The iron content ranges from 40 to 60 per cent or more. Accessory minerals include mica, apatite, quartz, chalcedony, jarosite and limonite; lime silicate minerals are rare.

The intrusive body is well jointed. Some of the joints are ordinary tension joints whereas others are selvage joints. Crusts of octahedral magnetite crystals are sometimes seen on the walls of some of the joints. This magnetite is of secondary origin.

PETROGRAPHY OF THE INTRUSIVE

Sixteen randomly chosen samples of the 58 specimens from the Granite Mountain intrusive were studied petrographically by Mr. S. A. Williams of the Geology Department of the University of Arizona. It was found that the rooks had an extremely uniform composition and varied very little from individual to individual.

The rock is a quartz andesite or quartz monzonite porphyry composed of phenocrysts of calcic plagioclase, between 3 and 5 mm. long, set in a fine grained groundmass of quartz, orthoclase and plagioclase more sodic than the phenocrysts. Phenocrysts of augite, hornblende and biotite occur. The biotite is sometimes replaced by sanidine with simultaneous deposition of magnetite. Accessory minerals include sericite, clay, apatite, magnetite, zircon, tourmaline, serpentine, calcite and sphene. Some of the magnetite seems to be of primary origin but most of the magnetite is associated with altered feldspars and mafic minerals and is of secondary origin. It is believed that the alteration is either late magmatic or deuteric.

COLLECTION AND PREPARATION OF SAMPLES

COLLECTION OF SAMPLES

For the purpose of plotting the locations of samples very accurate topographic maps of Granite Mountain were made available to the author by the Columbia-Geneva Division of the U.S. Steel Corp. located at Cedar City. The maps, having a scale of 1 inch equivalent to 400 feet were prepared by photogrammetric methods. The topography of Granite Mountain has considerable relief and variety so that locating a position on the map was easy. However, whenever there was any doubt about the exact location of a point the location was determined by resection.

When a rock suitable for collecting was found, a flat horizontal surface about 1 ½" in diameter was made on the top using a fine rock chisel and hammer. The horizontality of the surface was checked using a small level which is correct to less than 1°. When the surface was perfectly horizontal, a broad band of white tape was fixed securely to it. A Brunton compass was placed on the flat surface and using the compass as an open-sight alidade, a sighting was made on some prominent feature, topographic or otherwise. A line was marked on the tape, parallel to the line of sight. The azimuth of this line was then determined from the map. The azimuth of this line was also determined using the Brunton compass directly. In most cases, there was no observable difference in the azimuth as determined by these two different methods. In a few cases, however, the rock had sufficient magnetic intensity to affect the needle of the compass.

The following guiding rules were adopted during sampling:

1) The specimens collected were rough cubes, 5" on a side. Odd shaped specimens make later laboratory work unnecessarily difficult and inaccurate.

2) As far as possible, the specimens were of fresh and unaltered rock.

3) Care was taken to see that, as far as was determinable, the specimen was collected from bed rock which had not undergone any shift from its original position.

4) The specimens were as free of cracks as possible. Specimens with cracks tend to fall apart during sawing.

CUTTING AND ORIENTATION OF ROCK CUBES

In the laboratory each sample was propped up on a flat, rigid sheet with pieces of broken brick so that the flat surface with the label on it was perfectly horizontal; this was done by using the same level that was used in the field. A wooden mold with perfectly square sides was placed around the specimen and a mixture of plaster of Paris and perlite was poured in to hold the rock rigidly. After the plaster had set, the block was removed from the mold and placed on a flat table top whose surface was marked by azimuth lines from N 90°E to N 90°W. The block was adjusted so that the azimuth line on its label lay parallel to the line having the same azimuth on the table. The side of the block having the closest orientation to true north, was marked with an arrow to show its azimuth. A cube was cut from each block in a diamond rock-saw; the sides of the cube were cut parallel to the sides of the original plaster block. The orientation of the cube was thus ascertained. The top horizontal face of the cube was always called the A face; and the edge between face A and face B was the edge whose azimuth was closest to true north.

EXPERIMENTAL OBSERVATIONS AND RESULTS

INTRODUCTION

Before actual measurements of the orientation of the dipoles of rock cubes was begun, a preliminary set of experiments was carried out to determine the optimum conditions for measurement of the rock cubes. It was necessary to find the optimum distance at which a cube should be placed below the magnetometer suspension, whether the results obtained from the magnetometer readings were correct, how errors could be reduced, etc.

DETERMINING THE OPTIMUM POSITION FOR MEASUREMENT

In the first experiment, the rock cubes were placed as close as possible (1 3/4") to the lower magnet of the suspension. It was found that, as expected, the deflection, ΔD, was large and that the reproducibility of readings was excellent (max. divergence = 2°). However, the triangle of error was found to be extremely large and the positions of the poles on opposite sides of the cube were quite unsymmetrical.

The cubes were then re-run in the apparatus keeping them at a distance (about 11" in most cases) such that the maximum deflection produced by the cube was 1 cm. on the scale. It was found that:

1) reproducibility was poor. The readings showed a maximum divergence of about 10°, consequently, at least 6 readings per null point per face had to be taken to get an acceptable average value.

2) the time required for measurement of each specimen increased enormously. It took about 3 hours per specimen.

3) the triangles of error became much smaller in most cases corresponding to a maximum difference of ± 3° in orientation of the dipole.

4) the poles were symmetrical within the limit of experimental error.

By taking measurements with the cubes at different distances below the lower magnet it was found that the optimum distance was 5". With the center of the cube 5" below the lower magnet, it was found, in most cases, that:

1) the reproducibility was excellent (maximum deviation being about 2°).

2) the time required for measuring one cube was moderate, 1 to 2 hours.

3) the triangles of error were very small. In

fact, they almost became points when the axes of the rotation of the suspension and of the carriage were properly adjusted.

4) the poles were symmetrical, except for a few cases. In these exceptional cases, the asymmetry was presumed to be due to heterogeneous distribution of the ferro-magnetic constituents within the rock.

CHECKING THE MEASURED DIPOLE ORIENTATION

In order to make sure that the measured dipole orientation of a cube was the true orientation a control cube was measured. The control consisted of a plastic cube, 1 7/8" on a side. A 1 inch long piece of wire, very weakly magnetized, was placed within the cube symmetrically with respect to the center. The orientation, that is, the azimuth and plunge, with respect to the faces of the cube was known. A set of readings was taken from the cube and the dipole orientation calculated. The calculated value was found to be identical with the true dipole orientation. The plots did not show any triangles of error; this proved that the value of the measured angle ϕ was correct.

STABILITY OF THE DIPOLE ORIENTATION

There is no way of determining directly how stable the dipole orientations of the rock cubes were. Preliminary tests showed that there was no change in the orientation of cubes placed at random in the earth's magnetic field for 5 to 7 days.

Twenty-three of the samples from Granite Mountain, after initial measurement, were heated to 100°C in an astatic space, in a furnace for 1 hour. The samples were allowed to cool and then remeasured with the astatic magnetometer. A period of about 1 month elapsed between the two sets of measurements. No detectable difference, within the limits of experimental error (2°) was found.

While these tests do not prove that the remnant magnetism of the rocks of Granite Mountain is stable, they do indicate a strong likelihood that this is so.

DEGREE OF ACCURACY OF THE RESULTS

Before any valid conclusions could be drawn, it was necessary to determine the degree of accuracy of the final results. This was done by estimating the maximum possible error and the standard deviation for each of the steps involving error, from field collection to final calculation of the results. For the purpose of this study the standard deviation was considered to be the maximum deviation of two-thirds of the specimens measured.

Of the four major steps considered only in the last was it possible to determine the degree of error with some precision. In all the others the best that the author could hope to do was to make an intelligent guess about the limits of accuracy.

The four major steps involving error are considered below:

1) Field collection: Measurements of azimuth in the field were made using a Brunton compass as an open-sight alidade; a use for which it is not very well suited. The maximum error due to this source was estimated to be $\pm 3°$. By repeating a measurement of azimuth ten times on a single specimen, a maximum deviation of 2° was obtained; this value was taken to be approximately the same as the standard deviation.

The small level used to measure horizontality in the field was correct to $\pm 1°$. Therefore, making allowances for personal error, the maximum error was estimated to be $\pm 2°$ and the standard deviation to be in the neighbourhood of $\pm 1°$.

2) Orientation of the specimen and cutting of cubes: The specimens were oriented using the same level

mentioned above, so that the same error applied for this step as for the previous one.

There were errors, however, that could not be determined in any way, namely error due to the sides of the plaster blocks not being exactly square, error due to sawing the cubes, etc. The author estimated, arbitrarily, that the maximum error due to these causes was $\pm 6°$ and that the standard deviation was about $\pm 3°$.

3) Measurement in the magnetometer: Repeated measurements on the same cubes in the magnetometer showed that the results rarely deviated by more than 2° and almost never by more than 3° so that in this step, the maximum deviation of the dipole orientation was taken to be $\pm 3°$ and the standard deviation $\pm 2°$.

4) Plotting the results: Because the final orientation of the magnetic dipoles was determined graphically, a slight error was probably introduced during plotting. It was considered that the separation, ΔP, of the two poles, when the pole faces of a cube were superimposed on each other, was a function of graphical error, error due to magnetic inhomogeniety, error due to the cube and the suspension not being co-centered, etc.

The error in true orientation of the dipole was measured in terms of the angle, P, at the center of a cube, subtended by the pole separation, Δ P.

Calculation showed that the average value of angle P was 2.02°; and that the maximum value was 6.0°. The standard deviation was ±1.42°.

The standard deviation, σ, for the whole process was obtained by using the following formula:

$$\sigma = \sqrt{\Sigma x^2}$$

where x is the standard deviation for each step. The maximum error is additive. The figures are summarized in the table below:

TABLE 2.

	Step	Maximum Error (°)	Standard Error (°)
1)	Field collection		
	a) due to Brunton compass	±3	±2
	b) due to level	±2	±1
2)	Orientation and cutting of specimen		
	a) due to level	±2	±1
	b) due to sawing, etc.	±6	±3
3)	Measurement in magnetometer	±3	±2
4)	Plotting results	±6	±1.42
	Overall error	±22	±4.58

The maximum error for any single determination was therefore, ±22° and the standard deviation for the whole series about ±5°.

It should be understood that the statistical methods used to determine the overall standard deviation were crude. For the sake of simplicity the individual errors were considered to be strictly additive; this assumption is not true. Consequently, the value obtained for the standard deviation is very approximate.

RESULTS OF MEASUREMENTS

Of the 58 samples collected from Granite Mountain, 50 were measured. The remaining 8 were ruined during sawing, etc. The orientation and the strengths of these specimens are given in Table 3. below.

TABLE 3

Sample	Azimuth of N Pole	Plunge of N Pole (°)	Sense of N Pole	Strength
3	N 18° W	23	Down	3
5	N 63° W	2	Down	4
6	N 7° W	50	Down	3
7	N 12° W	44	Down	3
8	S 17° W	37	Down	4
9	S 31° E	41.5	Down	5
10	N 45° W	64	Down	3
11	N 36° W	17.5	Down	3
12	S 24° E	4	Up	2
13	N 6° E	46	Down	3
14	N 88° E	28.5	Up	5
15	S 0° E	54.5	Up	5

Sample	Azimuth of N Pole	Plunge of N Pole (°)	Sense of N Pole	Strength
16	S 65.5° W	30	Up	3
17	S 11° W	72	Up	2
18	N 19° W	33.5	Down	2
20	N 33° E	1°	Up	3
21	S 21° W	21	Down	2
22	N 82° W	8	Up	5
23	S 51° W	56	Up	3
24	S 45° W	5	Down	5
25	N 83° W	66	Up	5
26	N 32° W	38	Down	3
27	S 89° W	43	Up	4
28	N 6° E	30	Down	2
29	N 43° W	19.5	Down	3
30	N 15° W	39.5	Down	1
31	N 11° E	31	Down	1
32	N 22° W	42	Down	3
33	N 21° W	47	Down	3
34	S 66° E	78	Down	4
35	N 55° W	43	Up	4
36	N 53° W	40	Up	3
37	N 25° W	14.5	Up	5
38	N 33° E	34.5	Up	4
39	S 64° W	3	Up	5
40	S 72° W	44	Down	5
41	N 63° W	22.5	Up	5
42	S 27° W	27	Up	5
44	S 13° E	2.5	Up	5
45	S 41° W	17	Down	5
46	N 36° W	18	Up	5
47	S 59° E	44	Down	2
48	N 32° W	28	Up	3
49	N 30° E	53	Up	5
50	N 65° E	71	Down	5
51	S 64° E	12	Down	3
54	N 10° W	22	Down	3
55	S 55° W	6	Up	5
56	N 5.5° W	12	Down	5
57	S 28° W	49	Down	5

INTERPRETATION OF RESULTS AND CONCLUSIONS

INTRODUCTION

The remnant magnetism of any rock is due to the ferrimagnetic minerals within the rock. Magnetite is the most common ferrimagnetic mineral; others are maghemite, hematite, ilmenite, ulvospinel and pyrrhotite (Nicholls, 1955). The remnant magnetism of the Granite Mountain intrusive is almost exclusively due to magnetite though ilmenite may play a minor role.

An igneous rock such as the Granite Mountain intrusive can acquire its magnetism in one or more of the following ways:

1) Thermo-remnant magnetization: When an igneous rock cools through the Curie temperature in a magnetic field, its ferrimagnetic constituents acquire a permanent magnetic vector. This vector is parallel to the ambient field; its intensity is also proportional to the field provided the field strength is less than a few tens of oersteds (Blackett, 1956). This type of magnetization is called thermo-remnant magnetization or T.R.M..

2) Isothermal remnant magnetization: When a magnetic field acts on a rock at constant temperature, it induces a magnetic vector in the rock. This induced magnetization is called isothermal remnant magnetization or I.R.M.. For a given field the I.R.M. in a rock is proportional to its susceptibility.

The I.R.M. of a rock is usually small; sometimes hundreds of times smaller than the T.R.M. produced by the same field. Also, I.R.M. is much less stable than T.R.M. and requires a much smaller negative field to destroy it. Heating to moderate temperatures destroys the I.R.M. of a rock but it does not affect the T.R.M. (Neel, 1955). Blackett (1956) states that in rocks the I.R.M. due to the earth's field is so small that it can usually be neglected.

3) Partial thermo-remnant magnetization: When a rock below its Curie temperature is cooled from a temperature T_2 to a temperature T_1 in a field H, it acquires a magnetic vector. This vector is parallel to the field H and is called partial thermo-remnant magnetization or P.T.R.M.. The P.T.R.M. of a rock is not affected by temperatures below T_1 but it is destroyed if the rock is heated

to T_2. Further, a P.T.R.M. vector is completely independent of other vectors acquired in temperature changes outside the limits of T_1 and T_2. All P.T.R.M. vectors are added geometrically; nevertheless, each one is independent and preserves an exact "memory" of the temperatures and field which produced it (Thellier, 1946).

4) Chemical magnetization: In an igneous rock some of the ferrimagnetic minerals are produced by secondary processes such as deuteric alteration and hydrothermal action. These processes take place well below the Curie temperature. The newly formed ferrimagnetic minerals assume a magnetic orientation that is parallel to the ambient field. At present little is known about the properties of this type of magnetization (Blackett, 1956).

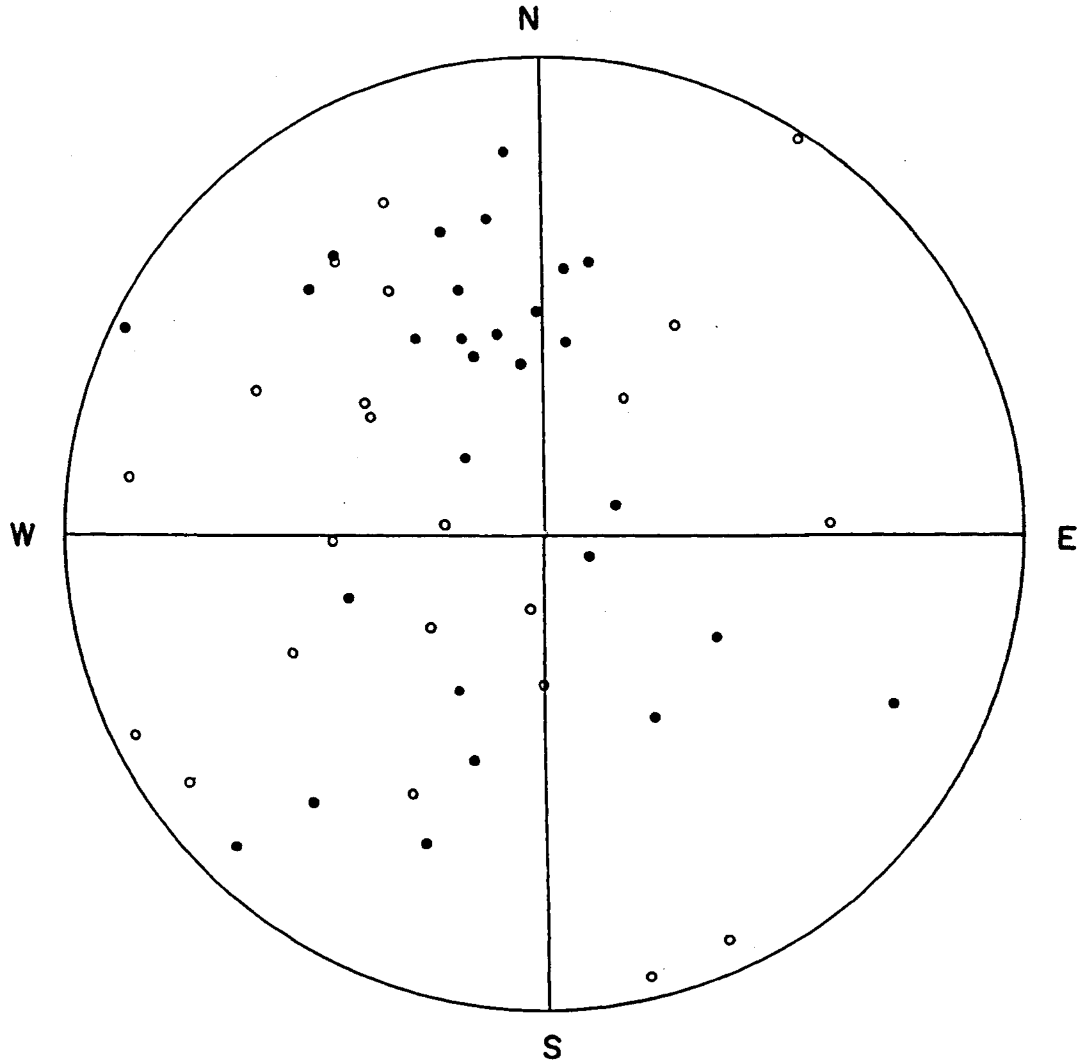
INTERPRETATION OF RESULTS

Plate 6 shows a stereogram of the orientation of the magnetic dipoles of rocks from Granite Mountain. Even a casual study of the stereogram shows certain definite trends:

1) The large majority of dipoles point westward.

PLATE 6

Stereogram of magnetic dipoles of all the specimens from Granite Mountain.



• NORTH POLE DOWN — NORMAL PLUNGE

○ NORTH POLE UP — REVERSED PLUNGE

PLATE 6.

2) The large majority of dipoles, with normal plunge, that is with the north pole pointing downward, have an azimuth lying between N 20°W and N.

Plate 7 shows the location and azimuth of the dipoles on a geologic map of Granite Mountain. This map does not show the effect of plunge of magnetic dipoles, without which an interpretation is difficult. To overcome this difficulty, the author constructed a three dimensional scale modle of Granite Mountain (Plate 8). This model shows (1) the geology of the area, (2) the plunge of the dipoles, (3) the azimuth of the dipoles, (4) the magnetic intensity of the samples, and (5) the topographic elevation of the samples. The magnetic dipoles are represented by correctly oriented pins which are mounted on vertical posts of balsa wood. The height of the wooden posts is equivalent to the elevation of the sample. The magnetic intensities of the samples are indicated by different colors on the pins.

Study of the three dimensional model shows certain definite features:

1) The orientation of the azimuths are in a crude radial pattern. This tendency is most prominent in the northern, north western and western portions of the exposed igneous body.

PLATE 8

Figure 1. Three dimensional model of the orientation of remnant magnetic vectors in Granite Mountain

Figure 2. Another view of the same model.

PLATE 8

Figure 1.

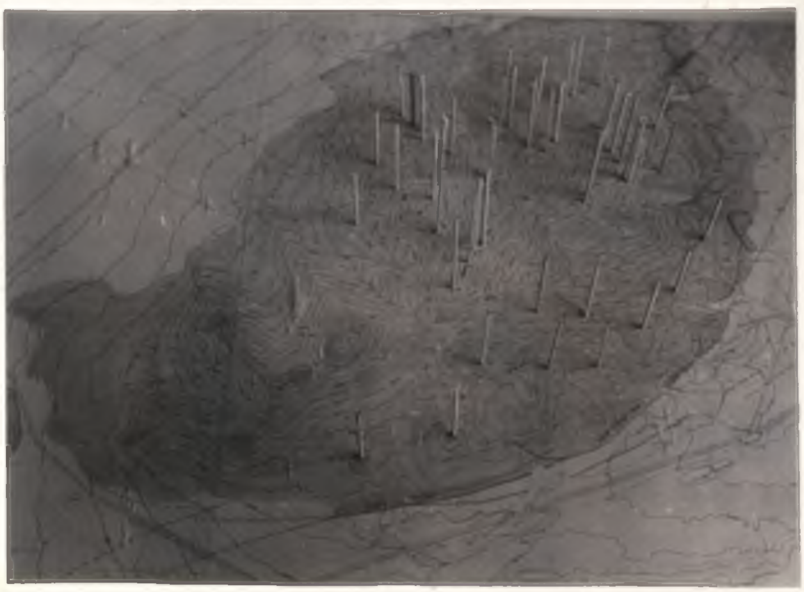


Figure 2.

2) The orientations can be grouped into "domains". Within each domain the dipoles have similar trends which differ from the trend of adjacent domains. The domains seem to differ greatly in size, some being as large as 400 yards across, and others only a few tens of yards.

3) A few specimens have an orientation which is different from the general trend of the domain in which they occur. In many of these cases, the specimen with the anomalous dipole orientation has weak intensity of magnetization.

Plate 9 shows the radial polygon of declinations of all the specimens from Granite Mountain. A pronounced concentration exists between NW and N.

The radial polygon of declinations of only the normally plunging dipoles is shown in Plate 10. It can be seen that the distribution forms a bell-shaped curve with a peak close to N 6°W. Very minor peaks occur at about S 30°W and S 60°E. These two peaks may be considered to be due to statistical variation.

The declinations of the dipoles with reversed plunge are shown in Plate 11. It can be seen that there are no pronounced maxima. The slight variation in distribution can be attributed to statistical error. The

PLATE 9

Radial polygon of the magnetic declination of all the samples from Granite Mountain. Note the preponderance of samples with an azimuth between N and NW.

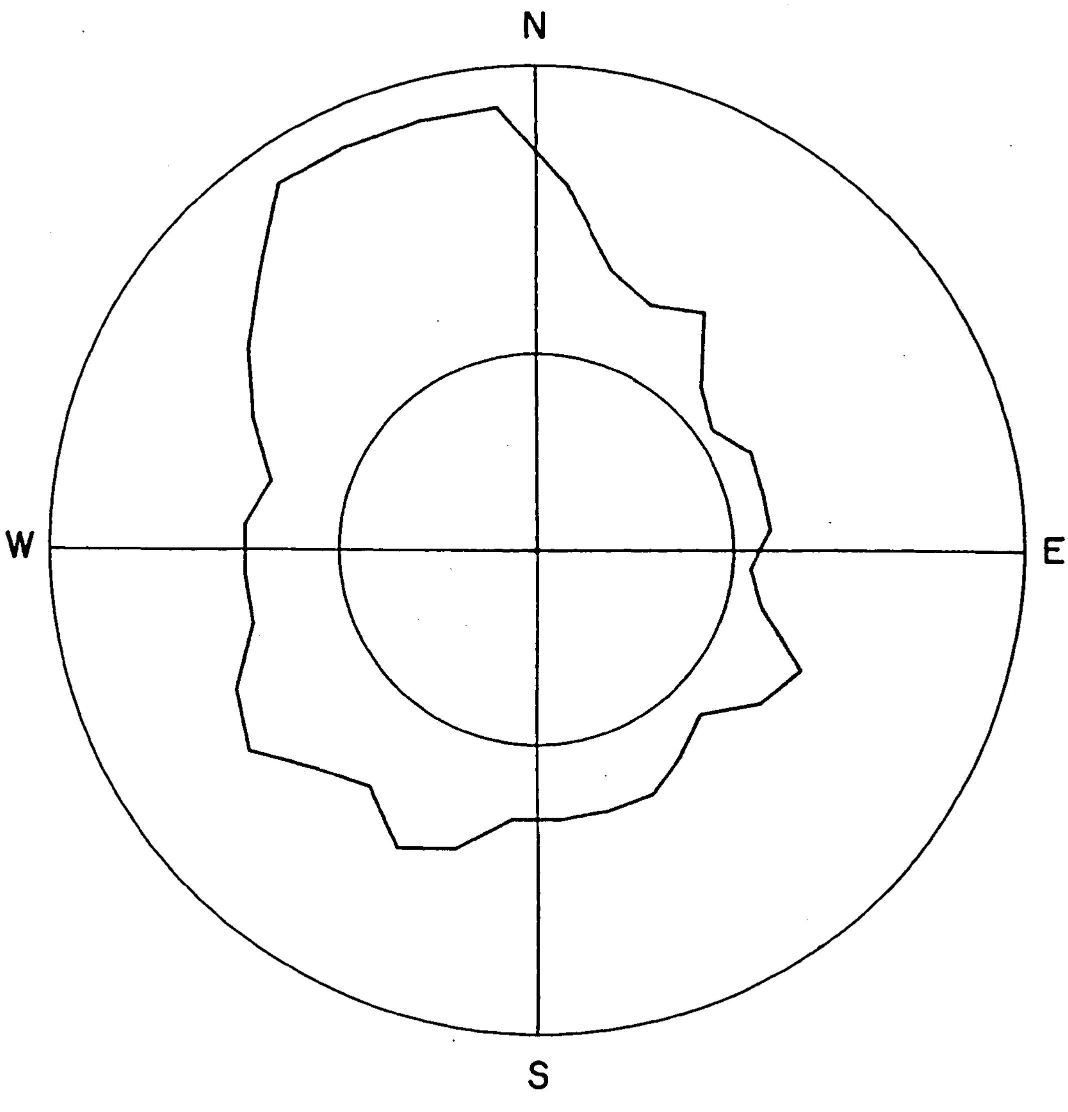


PLATE 9.

PLATE 10

Radial polygon of declinations of only the normally plunging magnetic dipole vectors. Note the pronounced maximum at an azimuth of N 6°W.

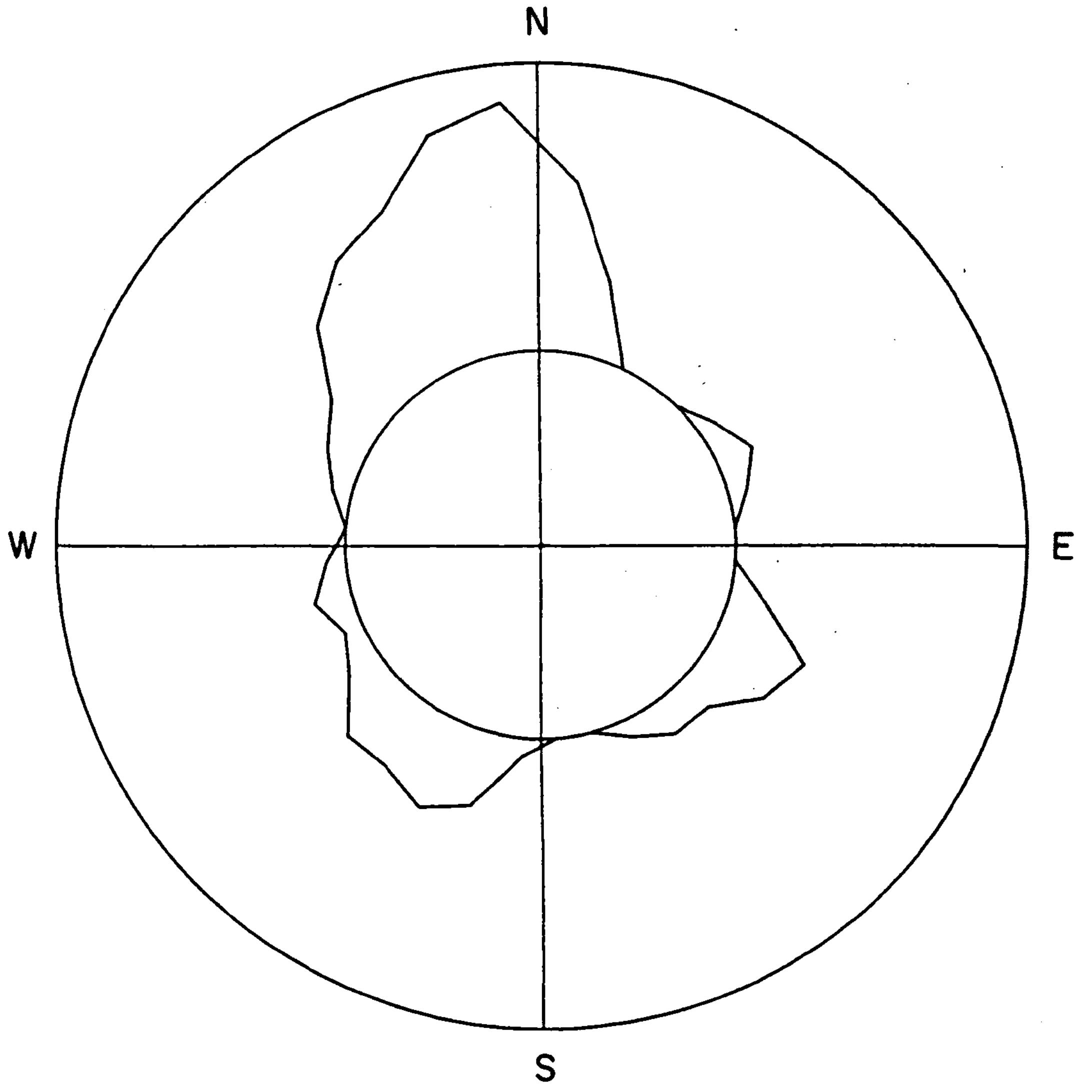


PLATE 10.

PLATE 11

Radial polygon of declinations of reversed magnetic dipole vectors. No pronounced maximum exists but there is a relative preponderance of vectors with a westerly declination.

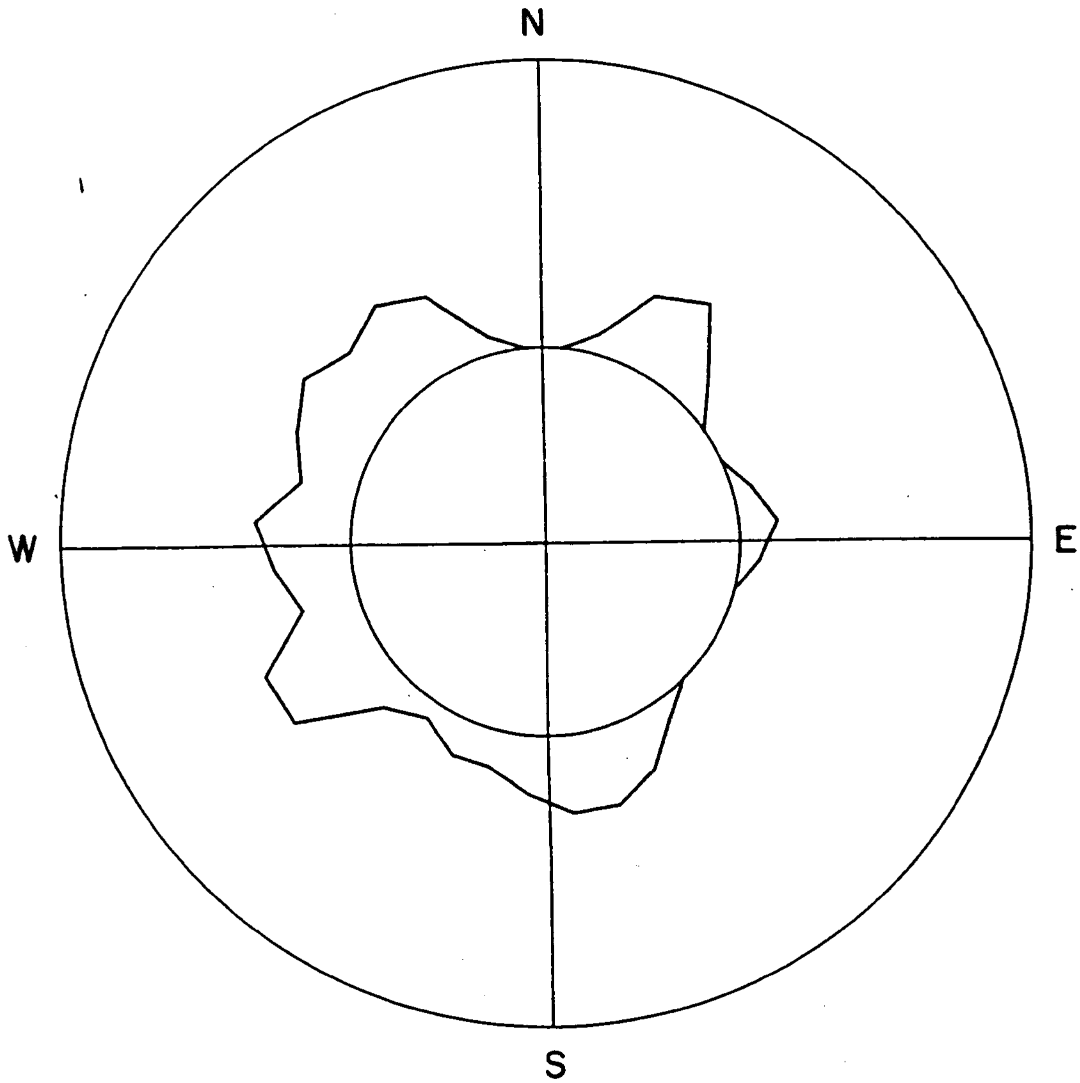


PLATE II.

polygon does, however, show that there is a relative excess of orientations in the western, rather than in the eastern direction.

CONCLUSIONS

The conclusions deduced from the results of the investigation suffer from two important defects. First, there are a number of possible factors relating to rock magnetism that have not been investigated in this project; for example, the mineralogy of the ferromagnetic constituents of the rocks and their relative abundance, which certainly has a bearing on the conclusions. Similarly, studies of alteration patterns and petrography are probably of considerable importance. The second defect is that the number of samples studied (50) is relatively small. Consequently, on this basis the statistical conclusions may be questioned. Even if the conclusions are not completely valid, they do indicate the course along which further thought and experiment should be directed.

EXPLANATION OF THE MAGNETIC DOMAINS

The existence of magnetic domains can be explained by two hypotheses. First, consider the igneous body cooling through the Curie temperature. The ferri-magnetic minerals would assume a T.R.M. parallel to the earth's field at that time; this assumes that no ambient field, other than the earth's field, was present. If some of the igneous body were still fluid below the Curie temperature then large solid blocks might have shifted from their original position. After complete solidific-ation of the igneous mass, these blocks would appear as "disoriented", discreet magnetic domains. If this hypothesis is true, then almost all the remnant magnet-ization in the rock must be T.R.M.. The hypothesis does not seem to be valid for three reasons:

1) Present data on the melting points of igneous rocks make it questionable whether a rock can remain partially fluid below the Curie temperature [Curie temperatures of magnetite, hematite and pyrrhotite are 585°C (?), 680°C and 320°C respectively. (Blackett, 1956)]

2) It is difficult to see what mechanical forces could have moved large solidified blocks within the magma or why such movement would not show

intense stress effects in the fabric of the rock.
3) Petrographic study of the rock shows that much of the magnetite is of secondary origin. The magnetization of this secondary magnetite would have been parallel to the earth's field and different from that of the "disoriented" domains.

The second possible explanation of the domains is that the igneous body solidified and cooled through the Curie temperature, without any major disturbance. The primary magnetite would have assumed a T.R.M. parallel to the earth's field. On further cooling deuteric reactions destroyed the mafic minerals thus releasing free iron oxides. Some of the released iron escaped to the surface to form the iron ore bodies (Mackin, 1954). Mackin believes that ore bodies similar to the ones now exposed on the flanks of Granite Mountain once existed on the roof of the laccolith. While it was being deposited, each body of ore must have been magnetized by the earth's field and by the fields of adjacent ore bodies. Since the ore has a high susceptibility, individual ore bodies must have behaved essentially as dipoles and set up strong, local magnetic fields around themselves. These local fields acting on the adjacent igneous rock must have imposed a vector parallel to the resultant field at that point. This imposed vector was probably P.T.R.M.

The magnetic field due to a dipole is three dimensional and a section through such a field is apt to appear as a magnetic domain. The appearance of magnetic domains on the present erosion surface of Granite Mountain may be merely due to the strong local fields of scattered dipoles that existed while the rock was cooling to its present temperature.

Plate 12 shows that there is a concentration of normally plunging vectors at an azimuth between N and N 10°W and a plunge between 20° and 46°. This concentration, presumably, represents those portions of Granite Mountain that were magnetized by the earth's field only. These portions could not have been close enough to an ore body to have been affected by it. If this hypothesis is true, it might provide a negative tool in the search for hidden ore bodies; that is, if a portion of the intrusion has an orientation very close to the mode, then it indicates the absence of an ore body nearby.

PLATE 12

Contour diagram of normally plunging dipole vectors. The declination of the mode is N 6°W. The inclination of the mode lies between 20° and 46°. Sixty percent of the vectors around the mode lie within the superimposed oval.

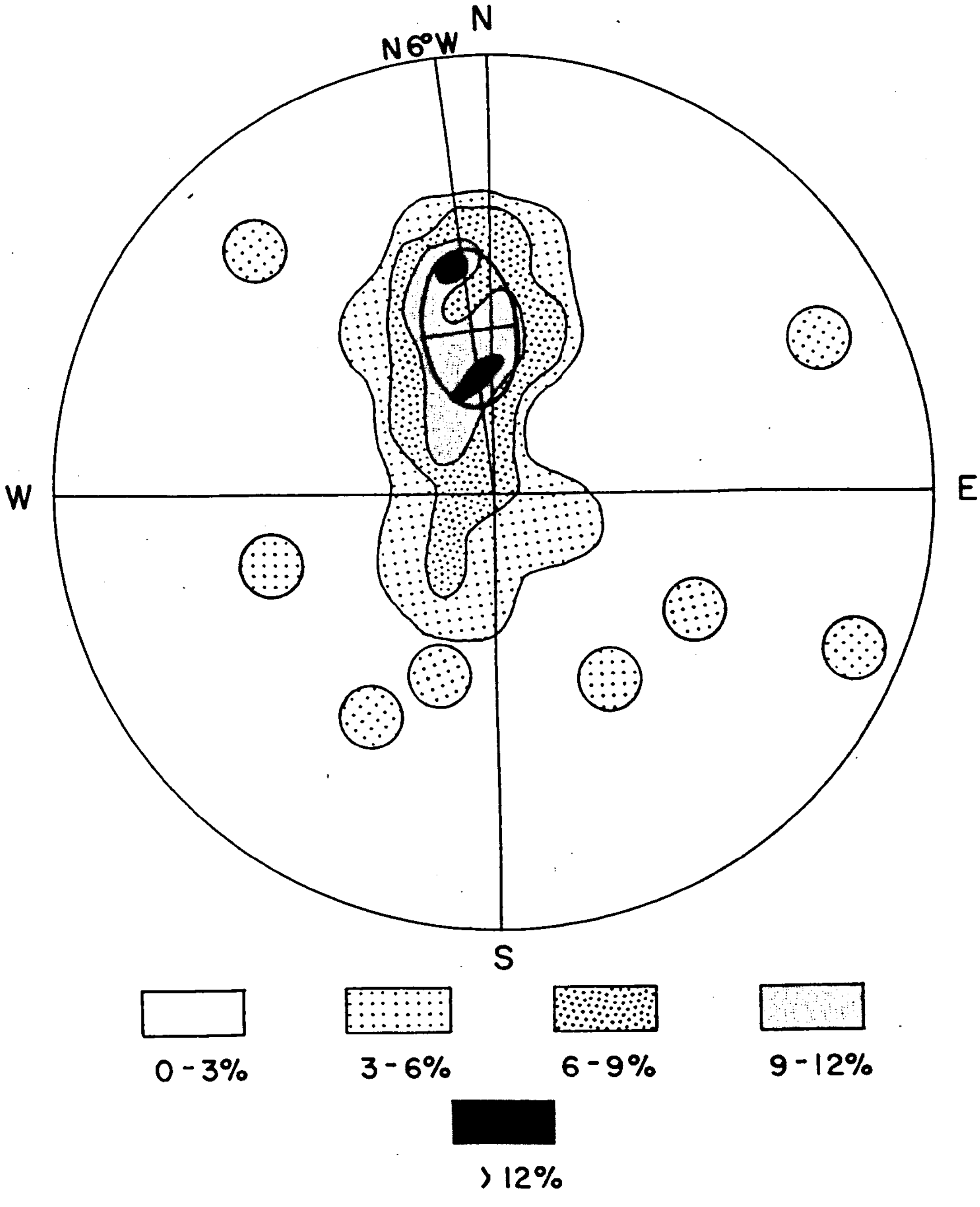


PLATE 12.

POLAR WANDERING AND AGE DETERMINATION

Studies of polar wandering

Four methods by which rocks acquire their magnetization have already been mentioned. In addition, in the case of sedimentary rocks only, a magnetic moment may be acquired at the time of deposition. This is because magnetic grains in the sediment tend to be oriented by the earth's field during deposition. Johnson, Murphy and Torreson (1948) and others have shown that when varved clays are deposited in still water they acquire a magnetic vector. This vector has the same azimuth as the earth's field but has a smaller inclination. The error in inclination is due to the fact that elongated or flattened magnetic particles tend to be deposited parallel to the bottom.

The magnetic orientations of many stable sedimentary and volcanic rocks from all over the world have been determined during the past twenty years. The diverse orientations of these rocks have caused some workers, led by S.K. Runcorn, to postulate that the position of the earth's magnetic pole has shifted throughout geologic history. By reconstructing the position of the earth's magnetic pole during different geologic periods, Runcorn (1956) has plotted "polar wandering curves". The curves show the pole positions relative to Great Britain, North America and Australia, from Precambrian time to the present. The "curves" show that the pole positions of successive geologic periods lie on a reasonably smooth curve and that they lie successively nearer the present pole as their age diminishes. The subject of rock magnetism in its relation to polar wandering has been discussed recently by Runcorn (1959).

The phenomenon of polar wandering is not universally accepted at the present time. In fact, some of the basic assumptions relating to remnant magnetism and polar wandering have been questioned (Graham, 1956).

Age of the Granite Mountain intrusion.

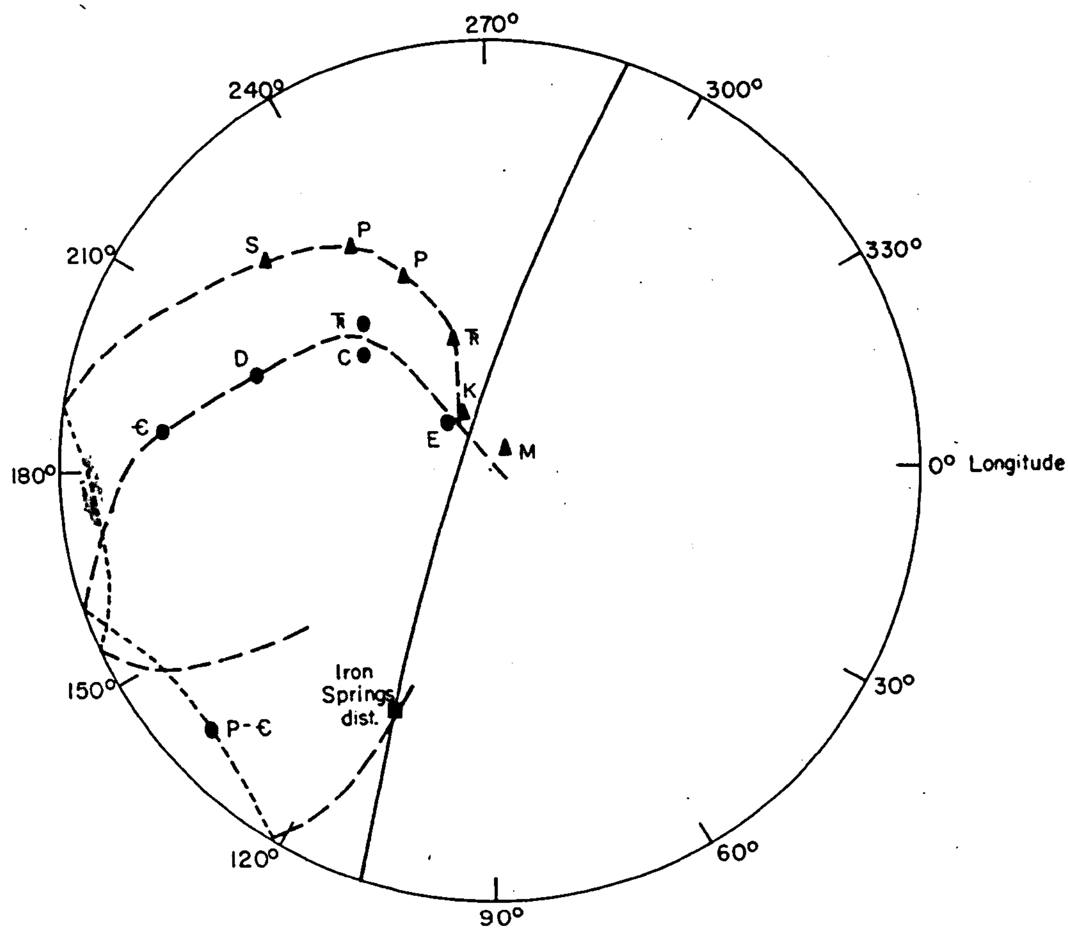
An inspection of Plate 9 shows that there is a preponderance of magnetic vectors with an azimuth between NW and N. This preponderance in orientation is most easily explained as being caused by an overall ambient field — almost certainly the earth's field. Since the earth's field would, in this case, produce vectors with normal plunge, a better picture of the ambient field is obtained from Plate 10. This figure shows a strong maximum at an azimuth of about N 6°W. This azimuth is presumably the azimuth of the earth's field at the time that the rock acquired its magnetism. The point of intersection of this azimuth with Runcorn's "polar wandering curves" should date the intrusion. This is shown in Plate 13. From the diagram it appears that the intersection lies between Eocene and Miocene time. This age for the intrusion is exactly the same as that deduced from geological and other evidence (Mackin, 1954).

The orientation of the earth's field, at the time of formation of the Granite Mountain intrusion, cannot however, be represented correctly by a single azimuth. Plate 12 shows that most of the normally plunging vectors are close to the mode. Sixty percent of these lie within an oval whose short axis corresponds to a spread in azimuth from N 5°E to N 25°W. The area of the oval is proportional to the deviation of the true orientation of the earth's field from the mode (N 6°W). Superimposing these limits on Runcorn's "polar wandering curves" we obtain a range of age from Triassic to Recent. While this is certainly a large segment of time, the result must be considered in the light of the very limited nature of the present study.

The author believes that more detailed research may show that the magnetic orientation within an igneous intrusion may be of some value in determining its age.

PLATE 13

Age of Granite Mountain determined by means of polar wandering curves. The diagram is a projection of the northern hemisphere of the earth showing the paths of migration of the north pole deduced from European (—•—) and North American (—▲—) rocks. The great circle of azimuth N 6°W through the Iron Springs district, Utah, cuts the path of the pole between its Eocene and Miocene positions.



POLAR PATH IN NORTHERN HEMISPHERE

POLAR PATH IN SOUTHERN HEMISPHERE

PATH INFERRED FROM BRITISH ROCKS

PATH INFERRED FROM AMERICAN ROCKS

(AFTER RUNCORN, 1959)

PLATE 13.

Igneous intrusions are sometimes very difficult to date except by radioactive decay methods, which cannot always be used. It is in these cases that a clue to the age of the intrusion may be provided by studying its magnetism.

Incidentally, the fact that the modal azimuth of the remnant magnetism differs significently from the present direction of the earth's field (N 16°E), is contributory evidence that the remnant magnetism of Granite Mountain is stable.

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PLATE 14

Figure 1. Panoramic view of Granite Mountain.

Figure 2. Typical topography and vegetation of Granite Mountain.

PLATE 14

Figure 1.

Figure 2.

PLATE 15

Figure 1. Contact of intrusive with Homestake limestone. The pale, ash colored rock on the left is the lower part of the Homestake limestone. The brown rock to the left is the intrusive. The contact is located at the north western edge of the Three Peaks laccolith.

Figure 2. Out crop of replacement body of iron ore, Little Mormon ore body.

PLATE 15

Figure 1.

Figure 2.

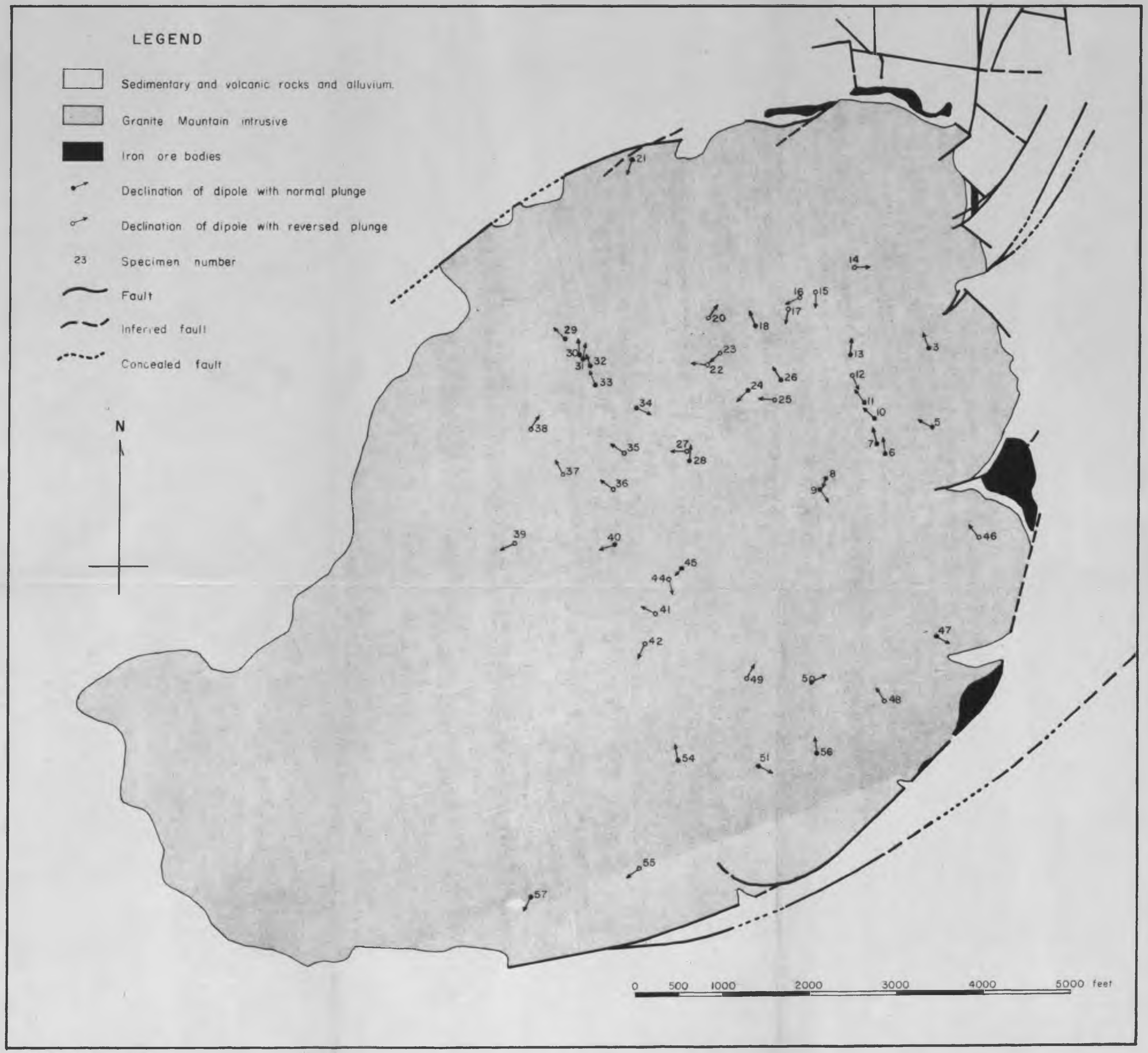

PLATE 7. LOCATION AND DECLINATION OF REMNANT MAGNETIC DIPOLES OF GRANITE MOUNTAIN.

(GEOLOGY AFTER MACKIN, 1954)