PALEOMAGNETISM OF THE TABLE MOUNTAIN FLOWS NEAR GOLDEN, COLORADO

by

W. D. Evans

ProQuest LLC.
789 East Eisenhower Parkway
P.O. Box 1346
Ann Arbor, MI 48106 – 1346

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Signed: W. D. Evans
W. D. Evans

Golden, Colorado
Date: Feb 19 1962

Approved: P. A. Rodgers
Thesis Advisor

Head of Department

Golden, Colorado
Date: Feb 14 1962

ABSTRACT

Measurements of the remanent magnetism were made on the Paleocene flows which are exposed on North and South Table Mountains near Golden, Colorado. These measurements were performed with an astatic magnetometer on a total of 49 specimens from 15 samples of the three flows. The results indicate that the residual magnetism of the uppermost flow has been affected by some random disturbance and is no longer representative of the earth's ancient field; however, the remanent magnetism of the first two flows is stable and is considered representative of the earth's magnetic field in early Tertiary. This field, in the vicinity of the Table Mountain flows, had a declination of N106($\pm$3)°E and an inclination of 13($\pm$2) degrees downward at the time the first flow solidified. When the second flow acquired its magnetism, the direction of magnetization had changed to N71($\pm$5)°E with an inclination of 18($\pm$2) degrees downward. This change is attributed to the secular variation of the field.

If it is assumed that the earth's field in early Tertiary time

can be approximated by a geocentric dipole, the geomagnetic poles calculated from these results fall between lat. 10°S and lat. 30°N near long. 25°W.

Although the early Tertiary pole is believed to have been near the present pole, the results of this study, as well as the results of previous investigations, do not support this prediction. There are, however, three possible reasons for this discrepancy. First, there has been large-scale continental drift since the early Tertiary. Second, there has been rapid large-scale magnetic polar wandering in past geologic times. Third, the earth's field in the early Tertiary had large non-dipole components and was vastly different from the present field.

All these possibilities may play some part in the final explanation of the results; however, the presently available data fit the last two possibilities as well as, or better than, the first. Therefore, it is concluded that paleomagnetic results should not be used as evidence for, or against, continental drift or geographical polar wandering until the configuration of the field and the magnetic polar wandering curve of past geologic times has been determined.

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INTRODUCTION

This investigation was undertaken to determine the direction and intensity of the remanent magnetism of the basalt flows which are exposed on North and South Table Mountains near Golden, Colorado. Since this report is concerned with the remanent magnetism of rocks, a brief review of the mechanisms which produce this remanent magnetism has been included. Also contained in the following sections are a description of the Table Mountain flows, a discussion of the field and laboratory procedures used to determine the direction and intensity of the remanent magnetism, a report of the results of the work, and an interpretation of these results in the light of previous investigations.

A detailed description of the astatic magnetometer which was constructed to make these measurements has been included in Appendix I.

REVIEW OF PALEOMAGNETISM

During the past 20 years much interest in rock magnetism has been stimulated by the interpretation of paleomagnetic results relevant to polar wandering and continental drift and by the development of magnetometers capable of detecting extremely small fields.

Early studies indicated that many rocks contain ferromagnetic minerals which possess a permanent magnetism perpetuating the earth's field at the time of their extrusion.

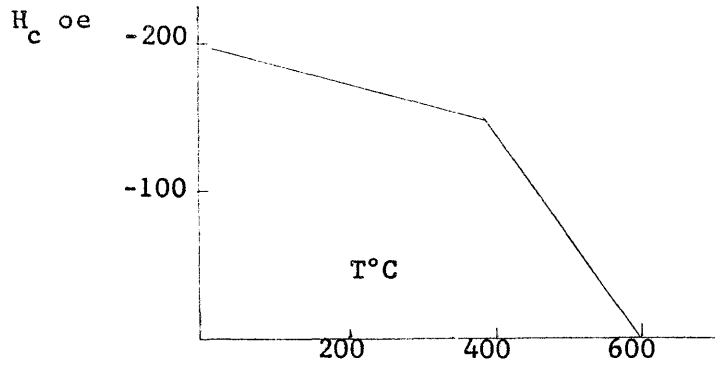
This was demonstrated by Chevallier (1925), who measured the natural remanent magnetism of the several flows on Mount Etna and found that it was parallel to the earth's field measured at near-by observatories at the time of their extrusion. From these measurements he was able to trace the declination and inclination of the earth's field from the thirteenth century to the present.

Similar studies on flows in Japan (Minakomi, 1941) have also shown that they are magnetized in the direction of the earth's field at the time of their extrusion.

This natural remanent magnetism in igneous rocks is, in general, composed of two major components -- thermo-remanent magnetism (T.R.M.) and isothermal-remanent magnetism (I.R.M.) -- and a minor component -- viscous magnetism.

Thermo-remanent magnetism is imparted to an igneous rock, either intrusive or extrusive, when it cools below the Curie temperature of the magnetic minerals. When the rock is further cooled, this T.R.M. is no longer appreciably affected by any field. An example explaining this mechanism is given by Patterson (1958, p. 140):

> The coercivity[1/] of magnetite (figure 1), for example, is but a fraction of an oersted just below its Curie temperature of 575 degrees Centigrade. Consequently, it is magnetized by the earth's field, even though the strength of the latter is only 0.5 oersted. On further cooling its coercivity increases to around 50 or more oersteds and, therefore, its original magnetism is retained and not affected by subsequent changes in the earth's field.



Coercivity of Magnetite
Figure 1

1. The coercivity may be regarded as the magnetic field, which, directed in opposition to the remanent magnetism of the ferromagnetic body, is just sufficient to reduce it to zero. Thus the large coercivity generally means high stability in the face of adverse fields.

Although the major portion of the natural remanent magnetism is T.R.M., an important component may be I.R.M. This is acquired at ordinary temperatures when some of the magnetic particles become magnetized in the direction of the disturbing field (Cox and Doell, 1960, p. 650). The earth's field is seldom strong enough to cause I.R.M.; however, lightning strikes are believed to be a common cause (Cox, 1961).

Even though the earth's field is usually too weak to produce I.R.M. a new component of magnetization is often observed if the rock remains in this field for a sufficiently long period of time. This component is known as viscous magnetization.

Another phenomenon which may have some effect on the remanent magnetism of rocks is magnetostriction which is the effect of stress on the direction and intensity of magnetization. Several investigators have attempted to determine the importance of this mechanism; however, the results have not been conclusive. Stott and Stacey (1959, p. 384) subjected specimens to a compressional stress of 500 kgm per sq. cm while cooling from 625°C and concluded that the effect was negligible. Kern (1961, p. 3802) also concluded that magnetostriction effects on the direction and intensity of T.R.M. were insignificant. However, Hall and Neale (1960) report changes as high as 4 degrees in the direction of T.R.M., and Graham and others (1959, p. 1318) suggest that magnetostrictive processes may be time dependent. Although the effect of time cannot be studied in the laboratory, field tests may

be of interest in evaluating the magnetostrictive processes under natural circumstances. These field tests may be carried out on rocks which are known to have been subjected to stresses. The magnitude of these stresses will not be known; however, the direction is often known, and this may be sufficient to resolve the problem.

THE TABLE MOUNTAIN FLOWS

Location of the Flows

The Table Mountain flows are found just east of Golden, Colorado, on North and South Table Mountains and southeast on Green Mountain. The exposures of these extrusions are confined to T. 3S., Rs. 69 and 70W., and T. 4S., R. 70W. These are bound by latitude 39° 42' 30" and 39° 47' 30" and longitude 105° 7' 30" and 105° 15' 00". The locations of the exposures on North and South Table Mountains are shown on the Index Map, figure 2.

Geology of the Flows

The following discussion of the geology of the flows is based primarily on work by Waldschmidt (1939), LeRoy (1946), and Reichert (1956).

The Table Mountain flows are divided into three separate units indicating three periods of extrusion. These units have been designated by Waldschmidt as Basalt Flow I, Basalt Flow II and Basalt Flow III.

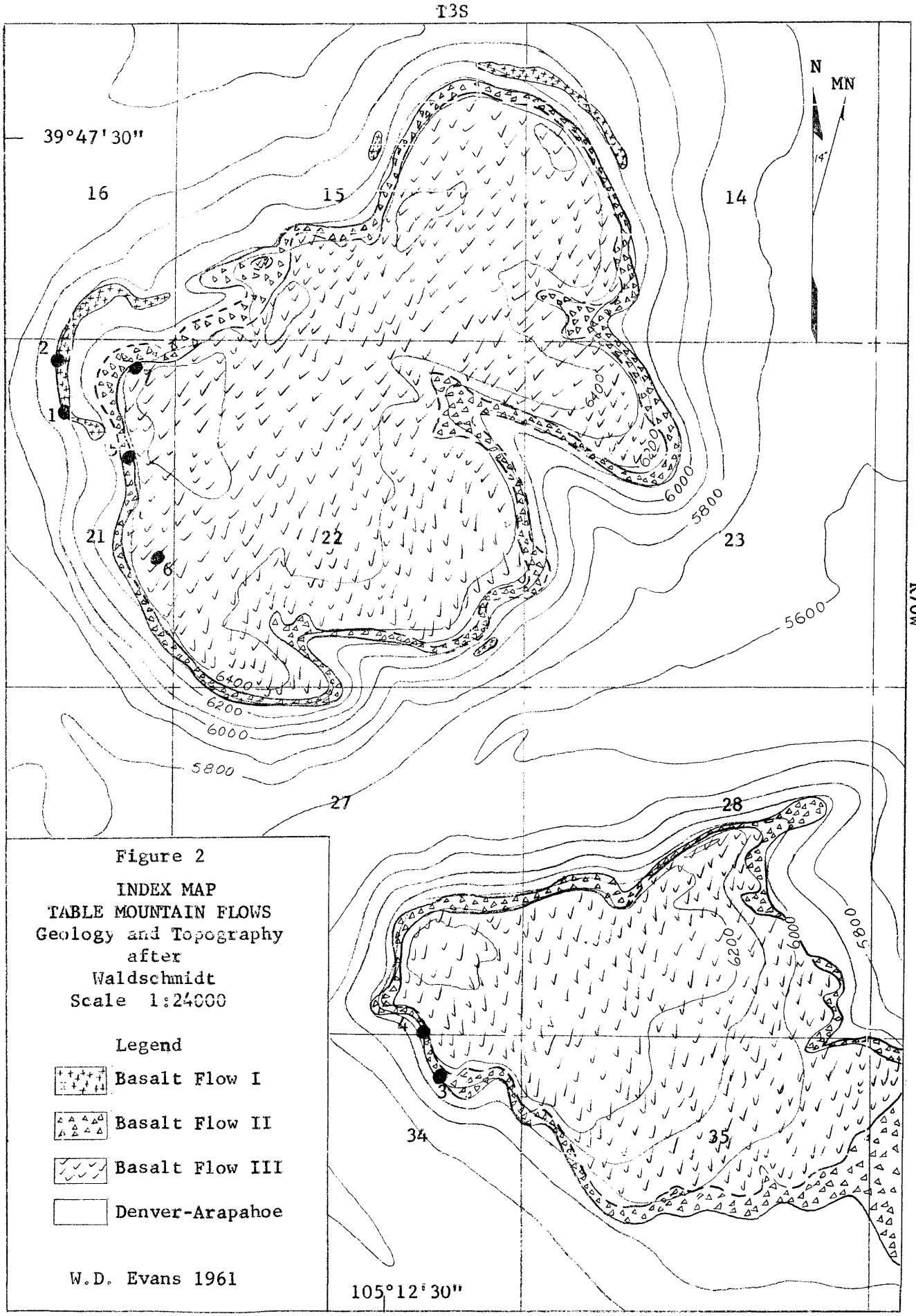


Figure 2

INDEX MAP
TABLE MOUNTAIN FLOWS
Geology and Topography
after
Waldschmidt
Scale 1:24000

Legend

- Basalt Flow I
- Basalt Flow II
- Basalt Flow III
- Denver-Arapahoe

W.D. Evans 1961

Basalt Flow I: This is the earliest flow in the area and is exposed on the flanks of North Table Mountain only. It fills old stream channels in the Denver-Arapahoe sediments and is therefore very variable in thickness, reaching a maximum of 50 feet. The upper part of Flow I is vesicular, whereas the lower part is massive, exhibiting columnar and block jointing.

Basalt Flow II: Basalt Flow II, separated from Flow I by 150 feet of shale and sandstone, forms the lower part of the caprock on North and South Table Mountains, and is also exposed on the flanks of Green Mountain. Flow II is fairly uniform in thickness on North Table Mountain, averaging about 75 feet; however, on South Table Mountain it ranges from 40 to 70 feet. There are two distinct zones in Basalt Flow II: the lower zone, which rests on Denver sediments, is massive and well jointed; the upper zone is vesicular.

Basalt Flow III: This is the uppermost flow on North and South Table Mountains and rests directly on Flow II. In most exposures it is massive with columnar jointing and ranges in thickness from 30 to 70 feet.

Mineralogy of the Flows

According to Waldschmidt (1939, p. 29) the Table Mountain flows are basalt or basalt porphyry; however, Van Horn (1957) has classified them as mafic latites. Since both classifications are very nearly the same, the writer has chosen to use the more common classification

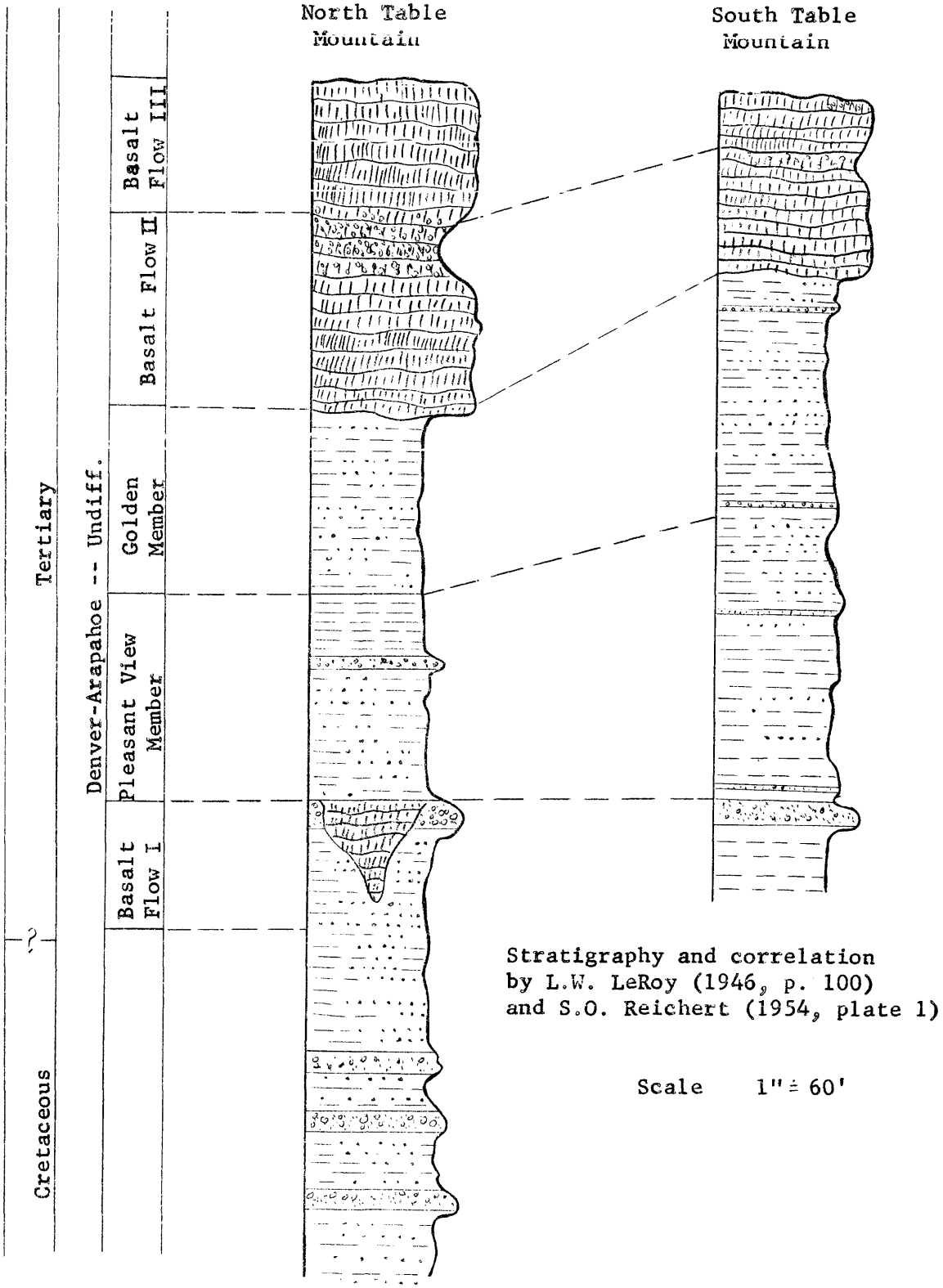
-- basalt. The essential minerals are labradorite or andesine labradorite, potassium feldspar, augite, and olivine; and the accessory minerals are apatite, magnetite, and biotite. In this investigation the magnetite is the most important mineral and fortunately is the most abundant of the accessory minerals. It occurs in small irregular and square-shaped grains distributed throughout the mass of the rock, which is generally fine-grained with some phenocrysts.

Age of the Flows

The age of the flows is based on their position in the stratigraphic section shown in figure 3. Basalt Flow I occupies old erosion channels in the basal part of the Denver formation and the upper part of the Arapahoe formation. Basalt Flows II and III occupy the middle of the Denver formation which is of Paleocene age. Therefore, the flows are also of Paleocene age.

Paleomagnetic Applicability of the Flows

The main condition which must be satisfied by a geologic formation, to be used for a paleomagnetic investigation, is that it be geologically well dated. On the basis of this criterion these flows are well suited for a paleomagnetic study. Another favourable characteristic of the flows is their horizontality and the general absence of any other evidence of post-extrusion displacement. This allows the samples to be oriented in the field under the assumption



Generalized Stratigraphic Columns
North and South Table Mountains
Figure 3

that they have remained fixed since the time of solidification. Also, these flows are in general fine-grained. This, according to Deutsch, (1959, p. 44) favours a large coercivity; hence, the magnetization should be stable over long periods and the flows should be reliable indicators of the direction of the field at the time of their origin.

SAMPLING

The field work for this investigation was begun in August and completed in November, 1961. During this time 15 samples[2/] were taken from seven sites from the three flows on North and South Table Mountains. The locations of the sampling sites are shown on the Index Map, figure 2.

Site 1: Located in the NW$\frac{1}{4}$NE$\frac{1}{4}$sec.21, T.3S., R.70W. on the north side of North Table Mountain above the road leading to the Western Aggregates quarry. Samples A and A' were taken from Flow I at this site.

Site 2: Located in the NW$\frac{1}{4}$NE$\frac{1}{4}$sec.21, T.3S., R.70W. approximately 300 yards east of Site 1. Sample B was taken from Flow I, site 2.

Site 3: Located in the NW$\frac{1}{4}$NW$\frac{1}{4}$sec.34, T.3S., R.70W. on the west side of South Table Mountain approximately $\frac{1}{4}$ mile south of Castle Rock. Samples C and G were taken from the cliff face of

2. The term "sample" will be used to describe the piece of rock removed from the formation; "specimen" will be used to describe pieces of rock cut from the sample and used in the magnetometer.

Flow II and III respectively.

Site 4: Located in the $SE\frac{1}{4}SE\frac{1}{4}$ sec. 27, T. 3S., R. 70W. approximately 200 yards north of Site 3. Samples D and H were taken from the cliff face of Flow II and III respectively.

Site 5: Located in the $SE\frac{1}{4}NE\frac{1}{4}$ sec. 21, T. 3S., R. 70W. above the road leading to the quarry on North Table Mountain. Samples E and F were taken from Flow II. Sample E was taken from approximately 30 feet above the base and sample F was only 10 feet above the base.

Site 6: Located in the $NE\frac{1}{4}SE\frac{1}{4}$ sec. 21, T. 3S., R. 70W. in the quarry on North Table Mountain. Samples I, J, and K, were taken from the quarry walls in Flow III.

Site 7: Located in the $NE\frac{1}{4}NE\frac{1}{4}$ sec. 21, T. 3S., R. 70W. on the north side of North Table Mountain. Samples L and M were taken from near the top of exposures of Flow III.

To tie the results of the laboratory measurements to geographic or magnetic north all samples were oriented while in place. To fix the orientation of the samples, horizontal lines were drawn on at least two faces and a bearing line was drawn on the top using a brunton compass. This bearing line was usually magnetic north; however, when it was not convenient to use a magnetic north bearing line, the magnetic bearing of the line was determined. Since large errors had been reported in compass readings at some places on the flows

(Waldschmidt, 1939, p. 20), several readings were checked by taking bearings on known land marks. In all cases, the effect of the flows was negligible.

LABORATORY PROCEDURES AND DATA REDUCTION

Orientation and Coring

In the laboratory the samples were reoriented for coring. This was done by setting the level lines as they were in the field and mounting the samples in a quick-hardening plaster. With the samples in this position, vertical cores, 1.98 cm in diameter, were cut, using a small portable coring drill. These cores were then cut into specimens approximately 2 cm long for use in the magnetometer. Altogether, 49 specimens were cut from 15 samples.

Throughout the reorientation and coring procedure the bearing line was preserved, and transferred to the top of each specimen. The declination, inclination, and intensity of the remanent magnetism of each specimen were then determined, using the astatic magnetometer described in Appendix I.

Determination of Declination of Remanent Magnetism

To determine the declination of the remanent magnetism it is

necessary to have a reference line of known bearing on the specimen. If the angle between this line and the axis of the magnetometer magnets is known, it is possible to determine the angle between the azimuth of the remanent magnetism and the reference line in the following manner.

1) The specimen is placed in the specimen holder with the reference line at right angles to the axis of the magnets, and the deflection of the magnet system is recorded.

2) The specimen is then rotated clockwise about a vertical axis through 90 degrees where the deflection is again recorded.

3) This is repeated until the specimen is in its first position. This final reading should be the same as the initial reading. Any difference, however, is attributed to drift of the instrument and is distributed over the last three readings.

4) To correct for induced effects, the specimen is inverted and the measurements are repeated and averaged with the first set of readings.

If the corrected readings are a_1, a_2, a_3, and a_4 and θ is the angle between the reference line and the azimuth of magnetization, then

$$\tan \theta = \frac{a_2 - a_4}{a_3 - a_1}$$ as shown in Appendix II.

Since the bearing of the reference line is known, the true declination of the magnetization can be determined.

Determination of Inclination of Remanent Magnetism

To determine the inclination of the remanent magnetism, a procedure similar to the above is followed. The azimuth line of the remanent magnetism, already determined, is set at right angles to the magnets. The deflection is recorded for each of the positions of the specimen at 90 degree intervals around the horizontal axis. If the deflections, corrected for drift and induced effects, are b_1, b_2, b_3, and b_4 and I is the angle of dip, then

$$\tan I = \frac{b_2 - b_4}{b_3 - b_1}$$ as shown in Appendix III.

This will be either positive or negative depending on whether the inclination is up or down.

Determination of Magnetic Moment Per Unit Volume of the Specimen

The magnetic moment per unit volume of the specimen is determined by a comparison method. That is, the deflection of the magnetometer magnets produced by the field of the specimen is compared to the deflection produced by a known field of a small coil.

It was found (see Appendix I) that the sensitivity S of the magnetometer was $(1/2.16) \times 10^{+6}$ mm/oersted or the inverse sensitivity was 2.16×10^{-6} oersteds/mm at a scale distance of 1 meter. Thus, the field at a given distance from the specimen can be determined directly, and the magnetic moment per unit volume can be calculated as shown

by the following development.

If M_h is the total horizontal component of the magnetic moment of the specimen, the dipole component of the field at the lower magnet is given by

$$h_1 = M_h/Z_1^3,$$

where Z_1 is the distance from the lower magnet to the centre of the specimen.[3/]

Since

$$M_h = M \text{ Cos } I,$$

$$h_1 = M \text{ Cos } 1/Z_1^3$$

where I is the angle of inclination of the field.

Similarly, the field at the upper magnet is

$$h_u = M \text{ Cos } I/Z_u^3$$

where Z_u is the distance from the upper magnet to the centre of the specimen.

Therefore, the net field acting on the magnet system is

$$h_1 - h_u = M \text{ Cos } I \left(1/Z_1^3 - 1/Z_u^3 \right)$$

or

$$\Delta h = m \text{ V Cos } I \left(1/Z_1^3 - 1/Z_u^3 \right)$$

where m is the magnetic moment per unit volume and V is the volume of the specimen.

Since $S = D/\Delta h$, or $1/S = \Delta h/D$

the magnetic moment per unit volume

$$m = D/S \text{ V Cos } I \left(1/Z_1^3 - 1/Z_u^3\right) \text{ gauss},$$

3. It has been shown (Blackett, 1952, p. 342) that provided a specimen of radius 1 cm and height 2 cm is kept at a distance of at least 4.5 cm the dipole component of the field is 95 percent of the total field.

where D is the deflection produced by the horizontal component of the field of the specimen, S is found by calibration, V is calculated, and Z_l and Z_u are measured.

Determination of Geomagnetic Pole Positions

In paleomagnetic investigations it is often convenient for comparison with other results to represent the data in terms of the geomagnetic pole positions. If it is assumed that the earth's field can be represented by the field produced by a geocentric dipole, the declination and the inclination of the field at any point on the surface of the earth defines the orientation of this dipole.

If P is the angle along a great circle between the point of observation and the geomagnetic pole then

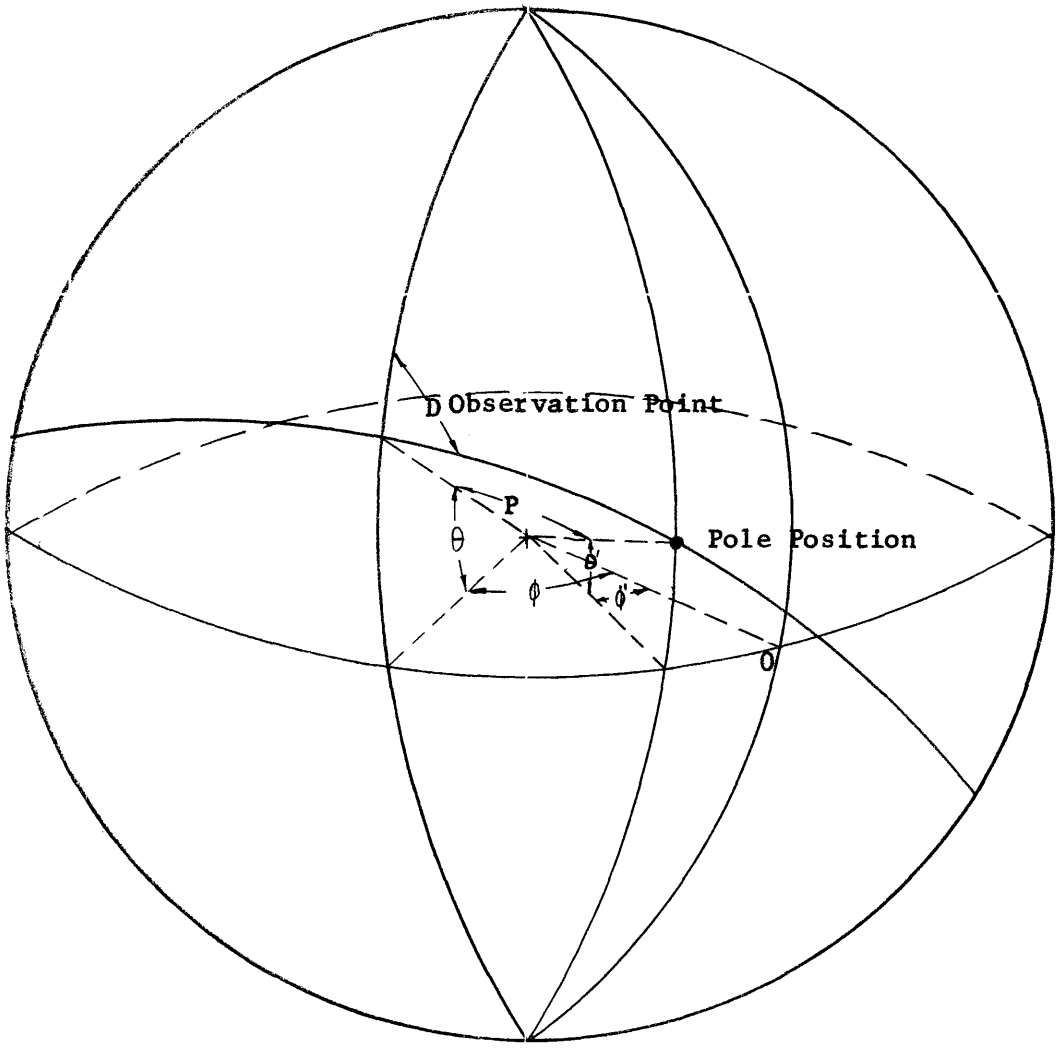
$$\text{Cot } P = \frac{1}{2} \tan I$$

where I is the inclination of the field at the point of observation (Hood, 1958, p. 6). Thus, since P can be determined and D is known it is possible by spherical trigonometry to determine the latitude θ' and the longitude ϕ' of the geomagnetic pole by the following relationships:

$$\text{Sin } \theta' = \text{Sin } \theta \text{ Cos } P - \text{Cos } \theta \text{ SinP CosD}$$

$$\text{Sin } (\phi - \phi') = (\text{Sin P Sin D})/ \text{Cos } \theta',$$

where θ is the latitude of the observation point, D is the declination of the magnetic field, and ϕ is the longitude of the observation point as shown in figure 4.



Spherical Representation of Relationships

Figure 4

RESULTS

Results from Table Mountain Flows

The results of measurements of 49 specimens from 15 samples from the three flows are tabulated in tables I, II and III and are summarized in table IV. To compare these results with the results of previous studies, the direction of the remanent magnetism is also presented in terms of geomagnetic pole positions in figure 5. This type of presentation is based on the assumption that the earth's field has been a dipole field.

Results from Previous Studies

The results of all paleomagnetic studies have been compiled by Cox and Doell (1960, p. 750) and Runcorn and Collinson (1960, p. 928). Although there have been no previous paleomagnetic investigations of Paleocene rocks, there are several results of studies on rocks dated as Eocene, possible Eocene or early Tertiary. Since these results will be considered in the interpretation of the magnetization of the Table Mountain Flows, they are presented in terms of geomagnetic pole positions in figure 6.

TABLE I

Magnetization of Specimens from Flow 1

Specimen No.	Location Lat.	Long.	Remanent Magnetism Decl'n.	Incl'n	Pole Position Lat.	Long.	Intensity (gauss)
A1	39°47'N	105°12'W	N105°E	11°D[4/]	8°S	26°W	9.6×10^{-3}
A2	"	"	N106°E	13°D	7°S	31°W	9.0 "
A3	"	"	N106°E	16°D	7°S	31°W	9.4 "
A4	"	"	N97°E	12°D	1°S	22°W	9.9 "
A5	"	"	N107°E	13°D	8°S	31°W	8.2 "
A'1	"	"	N114°E	12°D	14°S	35°W	9.6 "
A'2	"	"	N106°E	13°D	8°S	30°W	8.9 "
A'3	"	"	N105°E	13°D	7°S	30°W	9.1 "
A'4	"	"	N105°E	13°D	7°S	30°W	8.1 "
B1	"	"	N112°E	13°D	12°S	35°W	32.0 "
B2	"	"	N103°E	12°D	6°S	28°W	-
B3	"	"	N108°E	17°D	8°S	34°W	30.0 "
B4	"	"	N108°E	14°D	9°S	32°W	32.0 "
B5	"	"	N108°E	12°D	9°S	32°W	29.8 "
B6	"	"	N109°E	5°D	8°S	29°W	32.6 "

4. The letter D indicates an inclination downward from the horizontal; the letter U indicates an inclination upward from the horinzontal.

TABLE II

Magnetization of Specimens from Flow II

Specimen No.	Location Lat.	Long.	Remanent Magnetism Decl'n	Incl'n	Pole Position Lat.	Long.	Intensity (gauss)
C1	39°47'N	105°12'W	N76°E	19°D	17°N	20°W	6.4×10^{-3}
C2	"	"	N75°E	19°D	18°N	20°W	6.8 "
C3	"	"	N75°E	20°D	18°N	25°W	6.2 "
C4	"	"	N74°E	16°D	19°N	20°W	8.9 "
D1	"	"	N62°E	22°D	28°N	26°W	6.2 "
D2	"	"	N73°E	19°D	19°N	22°W	5.9 "
D3	"	"	N64°E	12°D	24°N	28°W	8.6 "
E1	"	"	N76°E	52°D	30°N	35°W	.13 "
E2	"	"	N77°E	61°D	34°N	45°W	.12 "
F1	"	"	N72°E	55°D	34°N	37°W	.11 "
F2	"	"	N77°E	44°D	25°N	36°W	.08 "

TABLE III

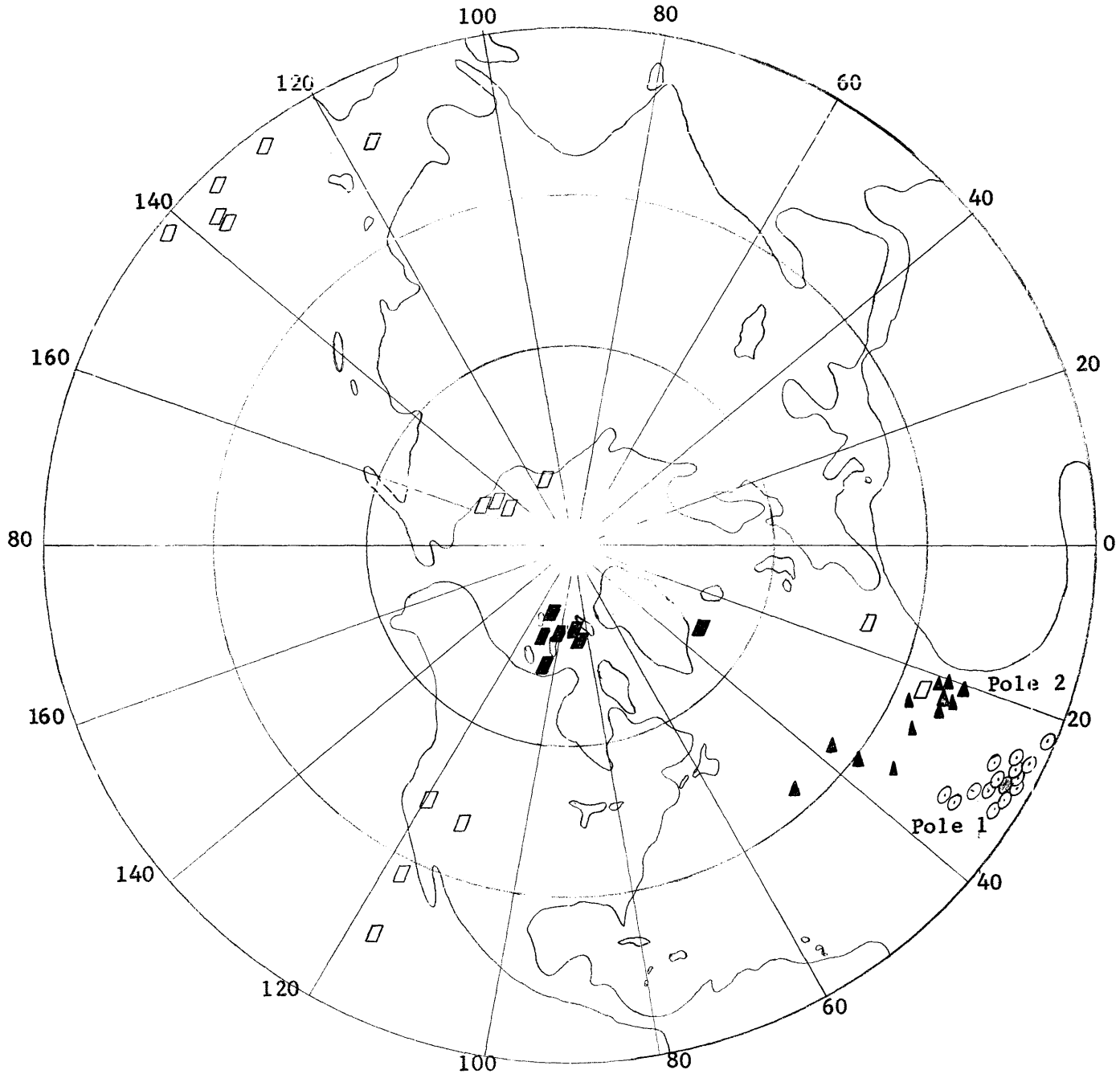
Magnetization of Specimens from Flow III

Specimen No.	Location Lat.	Long.	Remanent Magnetism Decl'n	Incl'n	Pole Position Lat.	Long.	Intensity (gauss)
C1	39°47'N	105°12'W	N23°E	50°D	69°N	36°W	75×10^{-3}
C2	"	"	N18°W	30°D	77°N	112°W	77 "
C3	"	"	N9°E	44°D	70°N	108°W	79 "
H1	"	"	N15°E	41°D	69°N	102°W	14 "
H2	"	"	N13°E	42°D	69°N	101°W	12.5 "
H3	"	"	N11°E	42°D	69°N	103°W	14 "
H4	"	"	N10°E	45°D	68°N	103°W	12 "
H5	"	"	N11°E	44°D	69°N	103°W	9.9 "
I1	"	"	N164°E	52°U	76°S	150°E	2.3 "
I2	"	"	N154°E	51°U	67°S	150°E	2.7 "
I3	"	"	N169°E	51°U	76°S	115°E	2.1 "
I4	"	"	N157°E	56°U	70°S	155°E	2.5 "
J1	"	"	N185°E	15°D	42°S	111°W	1.3 "
J2	"	"	N189°E	8°D	46°S	120°W	.9 "
K1	"	"	N166°E	34°D	37°S	17°W	1.0 "
K2	"	"	N193°E	45°D	29°S	119°W	.8 "
K3	"	"	N159°E	45°D	27°S	22°W	1.0 "
L1	"	"	N88°W	44°U	18°S	117°E	20.0 "
L2	"	"	N74°W	41°U	3°S	137°E	16.5 "
L3	"	"	N74°W	35°U	1°S	141°E	18.2 "
M1	"	"	N76°W	40°U	4°S	138°E	19.8 "
M2	"	"	N70°W	39°U	1°S	135°E	19.8 "
M3	"	"	N76°W	41°U	4°S	137°E	20.0 "

TABLE IV

Summary of Results

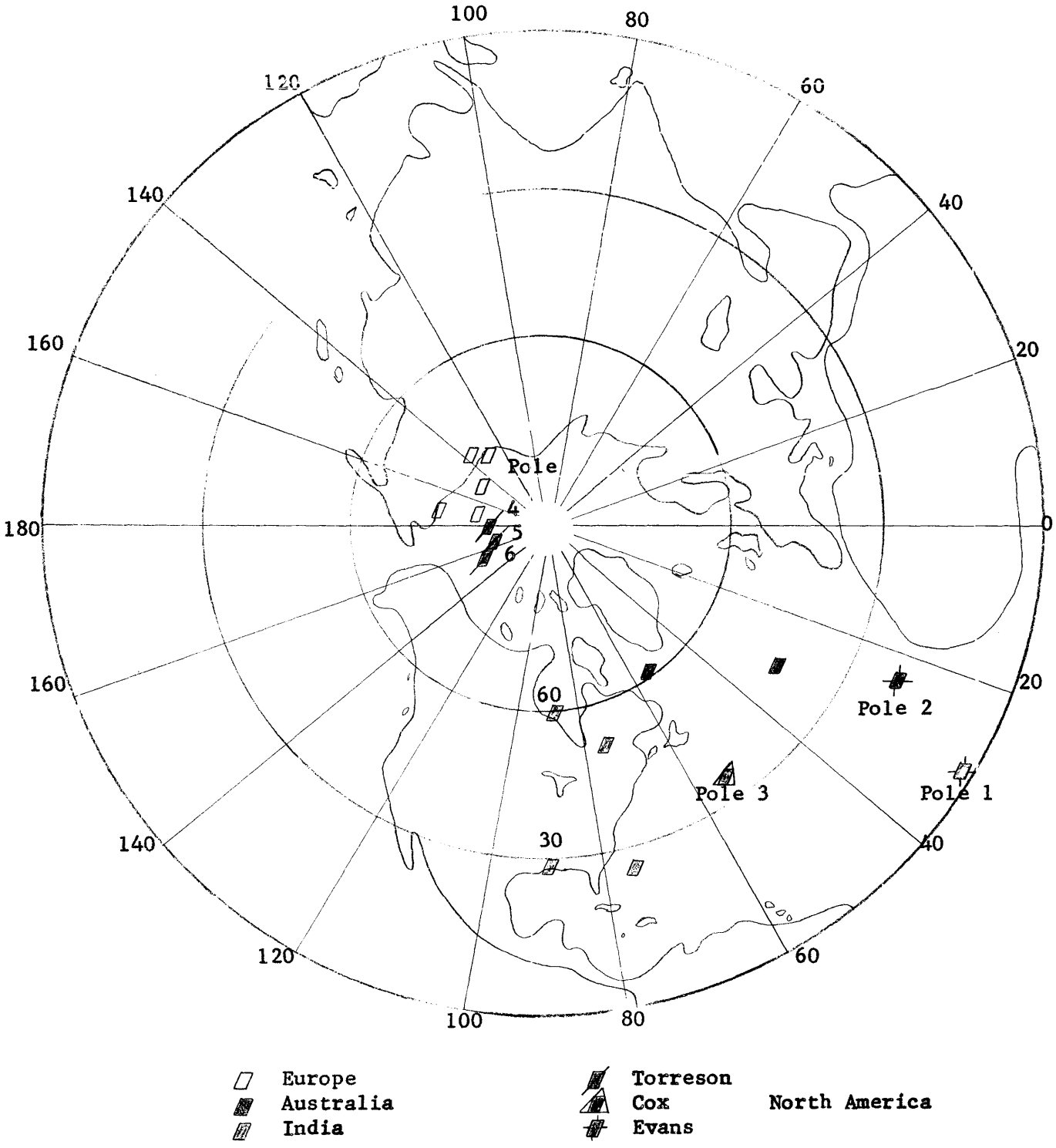
	Mean Decl'n	Mean Incl'n	Pole Position Lat.	Pole Position Long.	Intensity (gauss)	
Flow I	N106($\pm$3)°E	13($\pm$2)°D	8°S	30°W	9	x 10^{-3}
Flow II STM	N71($\pm$5)°E	18($\pm$2)°D	20°N	21°W	6.4	"
NTM	N74($\pm$2)°E	53($\pm$5)°D	30°N	38°W	.1	"
Flow III	Unstable	Unstable	Unstable		Unstable	



	Northern Hemisphere	Southern Hemisphere
Flow I----	⬮	○
Flow II---	▲	△
Flow III--	▰	▱

Geomagnetic Pole Positions
Calculated from Table Mountain Flow Data

Figure 5



Previous Early Tertiary Geomagnetic Pole Positions
- after Cox and Doell

Figure 6

DISCUSSION OF RESULTS

Direction of Remanent Magnetism

The results of measurements on 15 specimens from Flow I show that the remanent magnetism is aligned along an azimuth of N106($\pm$3)°E with a downward inclination of 13($\pm$2) degrees. Measurements on 11 specimens from Flow II on South Table Mountain yielded a mean azimuth of remanent magnetization of N71($\pm$5)°E and a downward dip of 18($\pm$2) degrees; however, measurements on 4 specimens from Flow II on North Table Mountain give an azimuth of N74($\pm$2)°E and a steeper dip of 53($\pm$5) degrees downward. The change in the declination observed between Flow I and Flow II probably represents the secular variation of the field between the time Flow I solidified and the time Flow II solidified. The steep inclination observed in Flow II on North Table Mountain can most likely be attributed to post solidification slump of the block from which samples E and F were taken.

Although the results from Flow I and Flow II are only in broad

agreement, they are quite consistent; whereas, the results of measurements on 26 specimens from Flow III are widely scattered. This brings up the question of the stability of the magnetization and the validity of the results.

Generally stability is assumed to exist if the direction of magnetization of different samples is consistent and different from the present field (Graham, 1949). On the basis of this criterion the remanent magnetization of Flows I and II can be considered stable and representative of the earth's field at the time of solidification. However, the inconsistency in the results of different samples from Flow III indicates that the magnetization is not stable and, therefore, not representing the ancient earth's field. Furthermore, if the magnetism were produced by some natural process, such as viscous magnetization, the results, even though they may be scattered, should fall symmetrically about some mean direction (Runcorn, 1960, p. 917). Since this is not the case, it must be assumed that the magnetism has been affected by some random disturbance; however, the consistency in the results of specimens from the same sample indicates that the effect of this disturbance was uniform throughout a volume of at least sample size. This disturbance may have been stress during cooling, which was more severe in Flow III than in Flows I and II. Flow III may also have been more sensitive to these stresses. This anomalous magnetization may also have been produced by the sampling and coring operations.

In any case, since the magnetization of Flow III cannot be attributed to any specific phenomenon, and it provides no information about the ancient field, the discussion in the following sections will be limited to Flows I and II.

Calculated Pole Positions

In calculating the geomagnetic pole positions shown in figures 5 and 6 the assumption was made that the earth's field in early Tertiary, could be closely approximated by a dipole field. This, however, is not intended as an interpretation of the results, but rather as a method of presentation.

The calculated pole position for Flow I (Pole I) falls near lat. 8°S and long. 30°W. Those from Flow II (Pole 2) fall somewhat north of this near lat. 30°N and long. 38°W for North Table Mountain and near lat. 20°N and long. 21°W for South Table Mountain. This apparent northward movement of the pole may be a result of secular variation of the field between the time of extrusion of Flow I and Flow II.

In comparing these results with the results of previous investigations we find that they are in close agreement with those of Cox (1957) (Pole 3), for early Tertiary flows in Oregon, but they do not agree with the results of Torreson, Murphy and Collinson (1949) (Poles 4, 5 and 6), whose calculated pole positions are very near the present pole. However, the validity of the latter results has been questioned.

(Cox and Doell, 1960, p. 755; Irving, 1959, p. 65) on the basis of insufficient evidence for stability.

Intensity of Magnetization

The intensity of magnetization of each specimen has been calculated and found to vary from 8×10^{-3} to 32×10^{-3} gauss in Flow I and from 0.1×10^{-3} to 9×10^{-3} gauss in Flow II (see Tables I and II). These intensities, especially from Flow I, are somewhat higher than is usually reported for extrusive rocks of early Tertiary age (see Table V). It can probably be assumed, however, that the intensity of 32×10^{-3} gauss is anomalous, and if more measurements were made, the mean intensity of Flow I would be considerably lower; most likely near that found in Flow II, which is in reasonable agreement with previous results.

TABLE V

Intensity of Magnetization of Lava Flows

Location	Age	Intensity $\times 10^{-3}$ gauss	Reference
Japan	Pleistocene	.48-4.2	Nagata (1956, p. 139)
Iceland	Tertiary	1.7	Hospers (1954, p. 42)
India	"	.29-3.5	Deutsch and Others (1959, p. 42)
Australia	"	1 - 12	Irving (1957, p. 354)

Although a detailed petrographic and chemical analysis of the specimens would be necessary to determine the reason for the variation of the intensity of magnetization, it can probably be attributed to two factors:

1. Variation in the amount of magnetic minerals in the basalt.
2. Variation in the degree of alteration of magnetite to hematite.

Possible Errors

In the sampling and measuring procedures there were several sources of error. However, all the known possible errors were random. These errors can be considered under two categories:

1. The errors in the determination of declination.
2. The errors in the determination of inclination.

The declination determined from each specimen may be in error as much as 6 degrees. This is made up of 3 degrees in the uncertainty in the position of the azimuth line on the sample in place, 1.5 degrees in the uncertainty in transferring this azimuth line to the top of each specimen, and 1.5 degrees in the uncertainty in positioning the specimen beneath the magnetometer.

The possible error in each determination of inclination is 6.5 degrees, made up of 2 degrees in the position of the horizontal lines on the sample in place, 2 degrees in the uncertainty in reorienting the sample for coring, 1 degree introduced while cutting the specimens, and 1.5 degrees in the uncertainty in the position of the specimen

beneath the magnetometer.

Since all the errors were random, the errors that were introduced in cutting the specimens and positioning the specimens beneath the magnetometer have been minimized by taking several specimens from each sample. Similarly those errors introduced in the original orientation of the sample in place and in the reorientation in the laboratory have been minimized by using several samples from each flow.

INTERPRETATION OF RESULTS

In general, the results of any paleomagnetic investigation can be explained by one or more of the following hypotheses:

a) The direction of the remanent magnetism of a rock represents the direction of the earth's field at the time of solidification or deposition.

b) The direction of the remanent magnetism of a rock does not represent the direction of the ancient field.

c) The geomagnetic field in the past has been that of a dipole parallel to the axis of rotation, but the earth's crust has shifted.

d) The earth's field has been a dipole field but the magnetic pole has wandered in past geologic time.

e) The continents have shifted relative to one another.

f) The earth's field has been a dipole but it has reversed its polarity several times in the past.

g) Continents or parts of continents have shifted about a vertical axis.

h) The earth's field has had strong non-dipole components in past geological times, which changed the regional configuration of the field.

Many of the early investigators of remanent magnetism found that most of the results could be explained by polar wandering and continental drift. These interpretations were based on assumption a, c, d and e. Many of these interpretations have now become widely accepted; however, in many recent investigations it has become increasingly difficult to explain all the results on the basis of these assumptions alone.

The first phenomenon that could not be explained was that of reversed magnetism. This problem has tentatively been solved, not by modifying the previous assumptions but by adding another. That is, the earth's field has in the past reversed itself several times. This is not believed to be a gradual change but rather a rapid "flopping" of the field through 180 degrees (Elsasser, 1956, p. 94).

Another problem has been brought to light by the widespread scattering of early Tertiary results. Because this problem is of particular interest in this investigation, the remainder of this section will be devoted to a discussion of the possible solutions.

Let us begin this discussion by establishing the probable position of the geographic and geomagnetic poles in the early Tertiary. To determine the position of the geographic pole in the past, paleoclimatic evidence is the most conclusive. The map of climatic zones

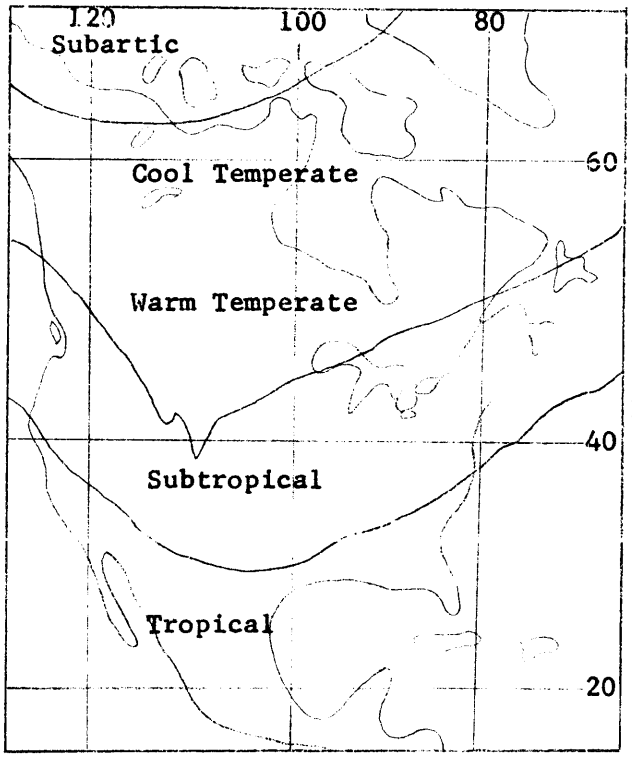


Figure 7

Early Tertiary Climatic Zones
(Dorf, 1960, p. 346)

in the early Tertiary (figure 7) indicates that the pole in the early Tertiary was very near its present position, probably slightly closer to eastern Siberia. To establish the position of the geomagnetic pole, we must rely on paleomagnetic evidence. Although the results from Mesozoic and early Tertiary rocks are not conclusive, we can set broad limits on the pole position during these times by considering Permian and post-Eocene data, which are very consistent.

If we accept this consistency as sufficient evidence for the dipole nature of the earth's field, we can position the Permian pole near lat. 45°N and long. 160°E and the post-Eocene pole near the present pole as shown in figure 8. By interpolating between these sets

of data, we can predict that the magnetic pole in early Tertiary time was near the post-Eocene pole, probably near north-eastern Siberia. On the basis of this argument and the available European data Runcorn (1955, p. 284) placed the early Tertiary pole at lat. 76°N long. 133°E. Unfortunately the available data from India, Australia, and North America do not support this prediction.

There are at least three possible explanations for this discrepancy.

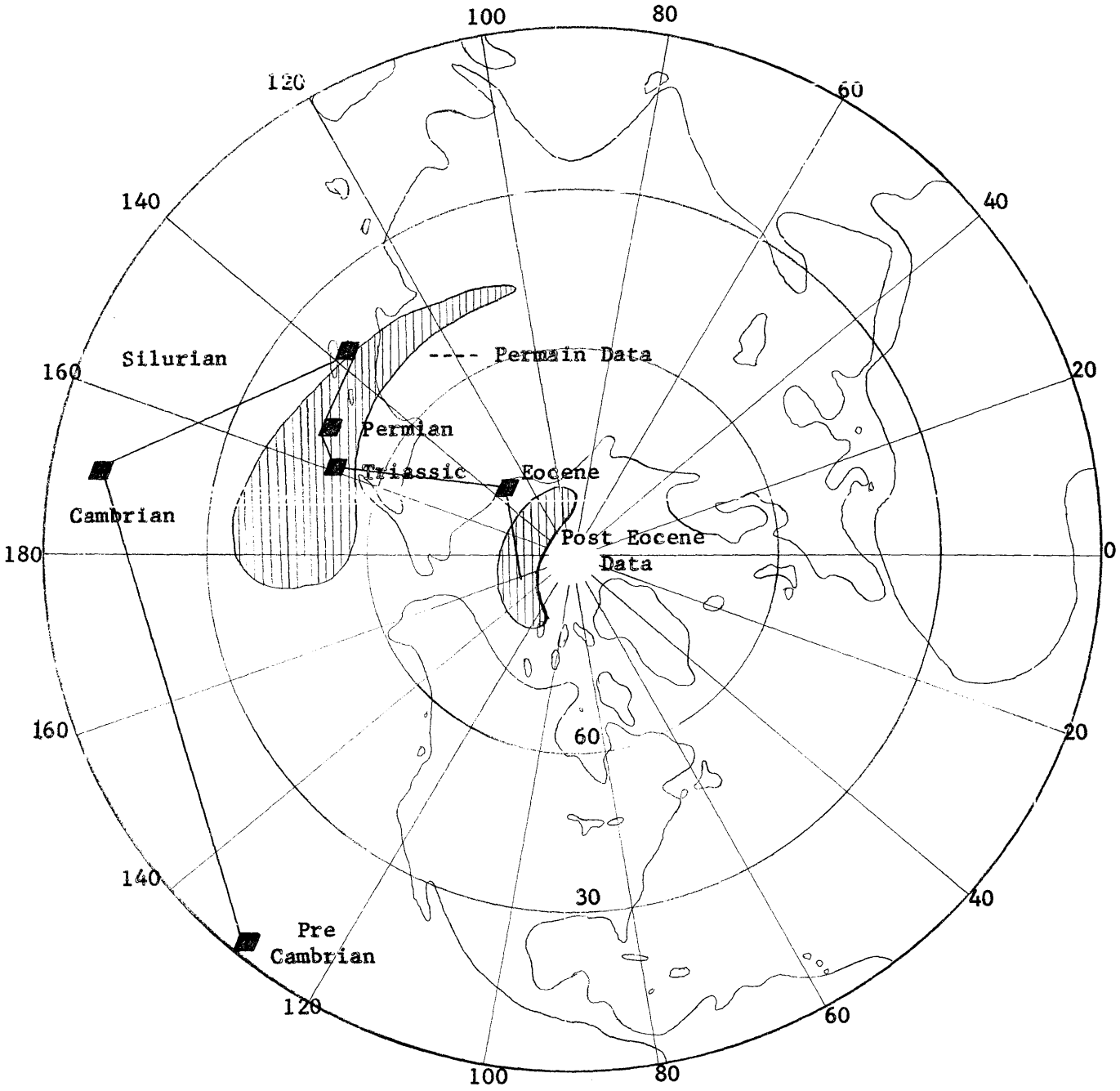
1) There has been considerable continental drift as well as rotations of continents and parts of continents about vertical axes since the early Tertiary.

2) There has been wide and rapid magnetic polar wandering.

3) The earth's field in early Tertiary had strong non-dipole components which changed the configuration of the field.

The results of investigations in India (Deutsch and others, 1959) and Australia (Irving and Green, 1957) have been explained by continental drift; however, the data are so scanty that any interpretation is little more than pure speculation. Although the results in North America are also very scanty, when interpreting these results we must consider the latter two possibilities.

Let us now consider the North American data shown in figure 5. To explain these observations, several investigators have suggested the first alternative listed above. Irving (1959, p. 65), in discussing the results obtained by Cox (1957, p. 685) on the Siletz River volcanic rocks of Eocene age in Oregon, suggested that a region including Oregon



Polar Wandering Curve
- after Runcorn

Figure 8

may have rotated since early Tertiary time. This rotation would have to be on the order of 70 degrees clockwise. Since the direction of magnetization of the Table Mountain flows compares with that of the Oregon flows there must have been no relative motion between the two areas. Therefore, if this interpretation is correct, a large portion of the Western United States must have rotated clockwise through 70 degrees to 90 degrees since the early Tertiary.

Although this interpretation satisfies the conditions dictated by other evidence, both paleomagnetic and paleoclimatic, it is rather hard to envisage, especially if the results of Torreson and others (1949) are valid (see figure 6, poles 4, 5, and 6). This would require a region including Wyoming to remain stationary while the region including Colorado and Oregon rotated through a large angle. However, if Torreson's results are not valid, the whole of North America may have rotated since early Tertiary. This interpretation is a rather broad extrapolation; furthermore, it would not be compatible with paleoclimatic evidence. Therefore it seems necessary to present an alternative explanation.

Let us now direct our attention to the last two possibilities. Although magnetic polar wandering cannot be differentiated from geographical polar wandering on the basis of paleomagnetic observations, rapid geographical polar wandering such as would be necessary to explain the results can almost certainly be ruled out. However, a combination of the two may explain the results. Runcorn (1955, p. 289) has

approximately represented the observed directions of magnetization of rocks by a polar wandering curve in the Pacific as shown in figure 8. There are, however, wide discrepancies from the curve. This may be explained, at least in part, by assuming that the geographical pole moved along this path and at the same time the magnetic pole deviated from the axis of rotation. This deviation may have been a regular rotation of the magnetic pole about the geographic pole or it may have been an irregular movement of the magnetic pole. The former type of movement, however, is the more probable. Johnson, Murphy and Torreson (1948, p. 356) and Griffiths (1955, p. 113) have found from measurements on varved sediments in North America and Sweden respectively, that in recent times there has been an apparent cyclic precession of the magnetic pole, which confirms, to some extent, the above prediction. However, such a precession of the magnetic pole could not account for all observarions unless it has been considerably greater in past geologic history. This possibility of course cannot be excluded; in fact, it may even be most probable.

If this magnetic polar wandering hypothesis is the correct explanation of the results, one would expect the positions of the geomagnetic poles calculated for all land masses to agree at the same geological epoch; however, if the pole has wandered as rapidly as the data from Mesozoic and early Tertiary rocks indicate, all formations studied must be precisely dated. Since this information is not available the rapid geomagnetic polar wandering hypothesis cannot be

tested. Therefore, any conclusion regarding its validity can only be made when a great many more observations on well dated rocks can be taken into account.

The third alternative explanation is that the earth's field in the past has had strong non-dipole components which have changed the configuration of the main dipole field. At present the non-dipole component of the earth's field, which is the part of the field that remains after the dipole field is subtracted, is not uniform, but appears to be concentrated at random positions over the earth. This component of the field is much more time dependent than the main field. For this reason, a map of the secular variation of the total field is believed to be a good representation of the non-dipole field (Elsasser, 1950, p. 21). At present the movement of the field is rapid enough that over a period of 50 to 100 years the average field is very near the dipole field. Therefore, to increase the effect of the non-dipole field it is necessary not only to increase its strength but also to reduce the rate of fluctuation.

If this explanation of the results is correct one would expect the rate of change of the field with distance on the earth's surface to be more rapid than at present. This can be tested by comparing the direction of the remanent magnetism of rocks of the same age taken from widely separated sites over a large land mass that has remained rigid in the past, or over a land mass that can be reconstructed. If it is assumed that North America satisfies this requirement and that

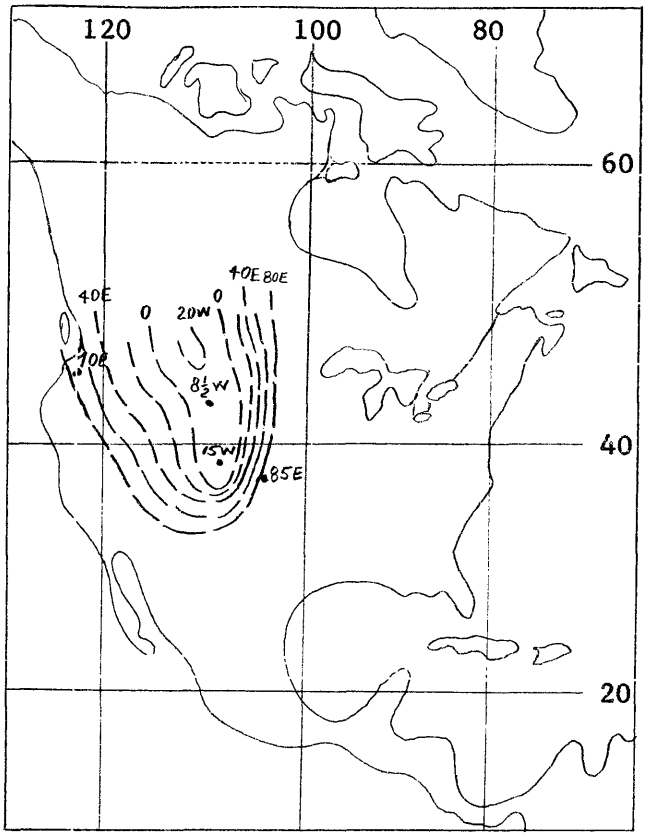
the available data are valid, the configuration of the field in Western United States can be drawn. Figure 9 shows the lines of equal declination in the early Tertiary, Jurassic and Triassic based on data compiled by Cox and Doell (1960, p. 712) and tabulated in table VI. These maps indicate not only that the earth's field in the early Tertiary was much more variable than the present field, but also that the anomalous configuration of the field persisted over a long period of time. Therefore, the writer concludes that the scatter in the results from rocks of early Tertiary and Mesozoic age is not due to rapid large-scale movements of the earth's crust as many authors have suggested, but rather, due to the configuration of the earth's field at the time the rocks acquired their magnetization or, to rapid geomagnetic polar wandering. This latter possibility is not excluded, because of the lack of evidence as emphasized earlier.

Although these two explanations present many problems, there seems to be no direct conflict between the assumptions made and the generally accepted theories of the earth's field or the principle of uniformitarianism. They also fit the available data as well as the drift hypotheses, without requiring rapid shifts and rotations of parts of the earth's crust. Therefore, before interpreting paleomagnetic results as evidence for, or against polar wandering or continental drift, these last two possibilities must first be considered.

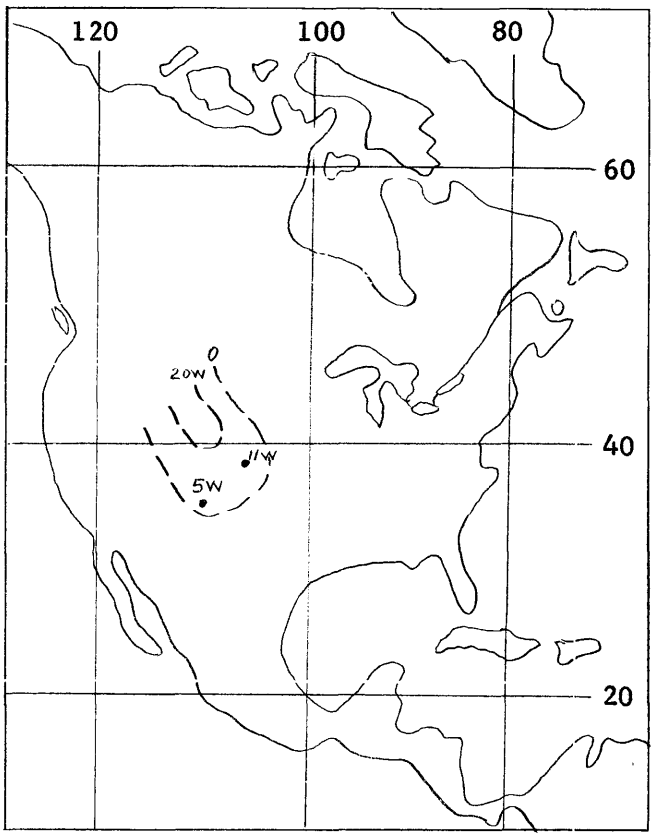
TABLE VI

Paleomagnetic Data

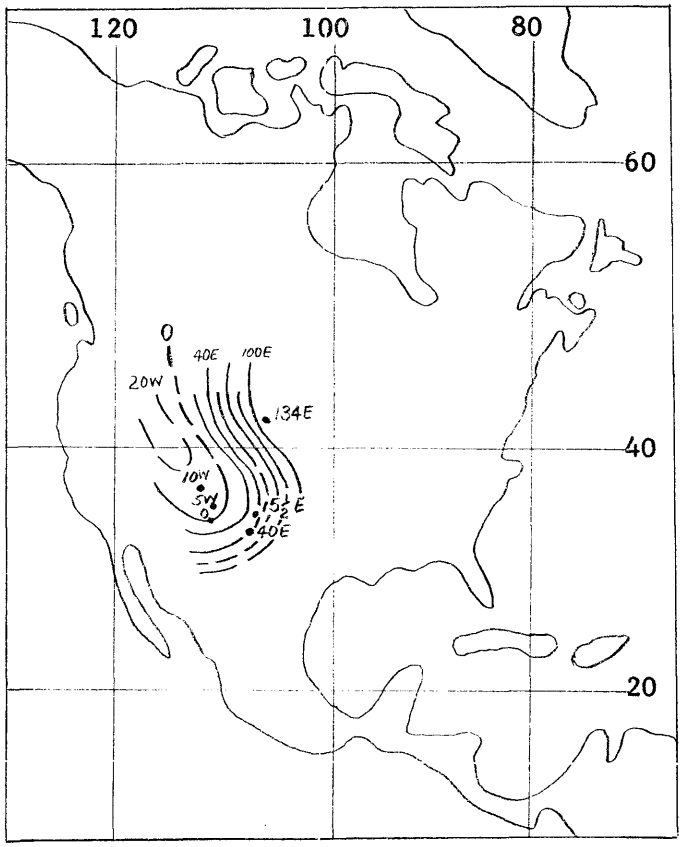
Age	Formation	Location	Declination
Triassic	Springdale	37½N, 113W	16W
"	Redonda	35N, 104W	16½E
"	Chinle	35½N, 105W	15½E
"	Chinle	35N; 105W	40E
"	Chinle	36N, 111½W	5W
"	Chugwater	42N, 106½W	134E
"	Moenkopi	36N, 111½W	0
Jurassic	Kayenta (ave)	36N, 111W	5W
"	Carmel	38½N, 109½W	11W
Early Tertiary	Siletz	45N, 123½W	70E
"	Green R.	39½N, 168W	15W
"	Wasatch	44½N, 109W	8½W
"	Table Mt. Flows	39½N, 105W	85E



Declination in Early Tertiary
(a)



Declination in Jurassic
(b)



Declination in Triassic
(c)

Figure 9

Obviously there is as yet no single, outstandingly successful explanation of all paleomagnetic results; however, as the data accumulates, all explanations presented may contribute significantly to the formulation of a theory explaining all paleomagnetic phenomena.

SUGGESTIONS FOR FURTHER RESEARCH

If further paleomagnetic investigations are carried out on the Table Mountain flows, the writer suggests the following projects be considered:

1) A detailed study of the petrography and magnetization of Basalt Flow III in order to determine whether there is any relation between the petrography and the instability observed in this study.

2) A detailed study of the effects of magnetostriction on the remanent magnetism. Such a study may be done on the many polygonal blocks which are exposed on the cliff faces of Flows II and III. Since the direction of the stress in each polygon is approximately known, it may be possible to determine, at least qualitatively, the relation between the remanent magnetism and the stresses.

3) An extension of the study to include the exposures in the vicinity of Ralston Reservoir to determine the relationship between the Table Mountain flows and the so-called Ralston Dyke.

Since the available data in North America are extremely limited,

any investigation of rock magnetism, especially on Tertiary rocks, may contribute greatly in defining the configuration of the earth's field. This requires accurate dating of the formations studied; therefore the writer suggests that age determinations be made if at all possible.

APPENDIX I

DESCRIPTION OF ASTATIC MAGNETOMETER

Introduction

The measurement of the direction of the natural remanent magnetization of strongly magnetized rocks can often be determined, at least qualitatively, with a compass needle (den Boer, 1954, p. 107). In detailed investigations, however, it is necessary to use more sensitive methods. The two most widely used methods are 1) the spinner magnetometer or "rock generator" method and 2) the astatic magnetometer method.

In this investigation the astatic magnetometer method was chosen because the rocks were highly magnetized, thus requiring only a simple magnetometer which could be constructed quickly and cheaply.

Review of the Astatic Magnetometer Method

The astatic magnetometer has been used for almost a century; however, it was not until the last two decades that it has been used

for the determination of the direction and intensity of the remanent magnetism in rocks. Rowland (1885), using an astatic magnetometer, first demonstrated that a moving charge produces a magnetic field. In 1903 Eichenwald repeated this experiment, using an astatic magnetometer with which he was able to detect fields of somewhat less than 10^{-7} gauss. In 1952 Blackett developed an astatic magnetometer to test the Schuster-Wilson hypothesis that a rotating body produces a magnetic field large enough to explain the stellar and terrestrial magnetism. This development by Blackett provided the incentive to extend the use of the astatic magnetometer to the determination of the direction and intensity of magnetization of weakly magnetized sediments. To this time it had been used only on the more strongly magnetized igneous rocks.

An astatic magnetometer is essentially a magnetic gradiometer. The magnet system consists of two parallel, horizontal and oppositely polarized magnets fixed to a vertical rod which is suspended by a torsion fibre. The moment M of each magnet is made nearly equal. The more nearly equal the magnets, the less the system is affected by a uniform field. A perfect astatic system--that is, one in which the resultant magnetic moment of the two magnets is exactly zero, will be undisturbed by a uniformly changing magnetic field, for example, the earth's field or the field of a magnetized body at a great distance. In a non-uniform field, however, the deflection is proportional to the difference in the horizontal field between the upper and lower

magnets, that is, the deflection is proportional to Δh.

Blackett's magnetometer was of the conventional astatic type; however, a new and different method of astatizing the system was employed. This new method involved the use of small trimming magnets which enable a very high degree of astatizm to be attained (Blackett, 1952).

Collinson (1957, p. 73) developed a similar magnetometer for use in the problem of determining the intensity and direction of magnetization of weakly polarized specimens such as those from sedimentary rocks. Also in 1955 Kumagai and Kawai (Nagata, 1956, p. 65) developed an astatic magnetometer beneath which the specimen was rotated with a period of rotation equal to the oscillation of the magnet system. This increased the sensitivity of the instrument considerably.

Details of the Magnetometer

The Magnet System: As mentioned in the previous section, the basic requirement of an astatic magnetometer is that it remain undisturbed by a uniform magnetic field. To satisfy this ideally the resultant moment of the two magnets must be exactly zero. However, it has been found (Deutsch, 1958, Personal communcation) that a magnetometer with an astatism, $A = (M_1 + M_2)/2(M_1 - M_2)$, of 200 is sufficiently sensitive to measure the remanent magnetization of most Tertiary flows. On the basis of this, the magnets used were magnetized so

that their moments were equal to within 1/2 percent. These magnets were of Alnico VI, 2.45 mm x 2.0 mm x 5.0 mm long, manufactured, magnetized, and stabilized by the Arnold Engineering Co. of Marengo, Illinois.

The magnets were then mounted, 4 cm apart, on a lucite rod as shown in figure 10. Slightly above the midpoint of the rod was attached a plane mirror. The distance between the magnets was chosen on the basis of the suggestion by Blackett (1952, p. 321) that the field produced by the specimen at the upper magnet should be on the order of 1/4 of the field at the lower magnet. That is, if

$$\Delta h = h_l - h_u$$

is the resultant field acting on the system, where h_l and h_u are the fields of the lower and upper magnets, the last term should be approximately 1/4 of the first. Therefore,
$h_l/h_u = 4/1 = Z_l^3/Z_u^3$ or $Z_u = 1.6\ Z_l$ where Z_l and Z_u are the distances from the centre of the specimen to the lower and upper magnet respectively. Assuming that the limits of Z_l will be 3 cm and 10 cm, the limits of L, where L is the distance between the magnets, will be 2 cm and 6 cm. An average distance between the magnets of 4 cm was chosen to give the best results. Although increasing the distance between the magnets would increase the sensitivity, too large a value of L would increase the effect of external disturbances. Therefore, if the magnetometer is to be used in a magnetically disturbed area

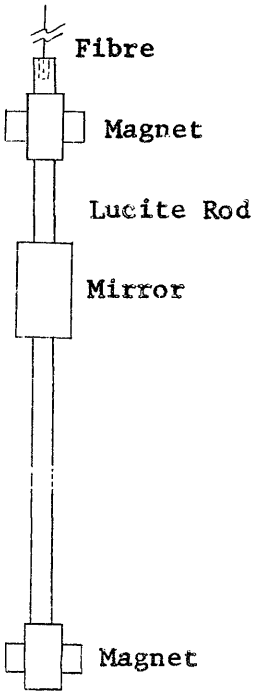


Figure 10

The Magnet System

Twice Actual Size

the distance between the magnets must be kept at a minimum, provided the necessary sensitivity can be obtained.

The main factors which were considered in the actual construction of the magnet holder were to have a low moment of inertia and a high mechanical stability and balance to minimize the pendulous motion of the system and reduce the effect of external disturbances as much as possible.

The Magnetometer Housing: The magnetometer housing shown in figure 11 was made of brass. The upper part houses the suspension fibre and the lower part houses the magnet system. The housing is mounted on levelling screws so that the suspension will hang vertically. The

torsion head fits into the upper part of the housing and is designed to enable the suspension to be rotated, raised, and lowered. This allows the system to be set at some zero deflection point and also provides a means of removing the tension from the suspension fibre when the instrument is not in use.

The Optical System: To take the necessary readings of the deflection of the magnet system, a telescope and scale unit was used. This was placed at a distance of 1 meter from the mirror. When the magnet system was undisturbed, the deflection was zero, which was the 50-cm point on the scale. When the specimen was introduced beneath the system, the magnets deflected. This deflection could be read directly through the telescope.

The Specimen Holder: To determine the direction and intensity of the residual magnetism, it is necessary that a number of measurements be taken with the specimen in several positions relative to the magnetometer system. Since rotation or translation of the magnetometer would upset its balance, it is necessary that the specimen be moved. The specimen must be moved up and down, as well as rotated about its horizontal and vertical axes. The vertical movement allows the distance of the specimen below the magnet system to be varied, depending on the strength of the residual magnetism. The horizontal rotation provides a means of measuring the azimuth of the remanent

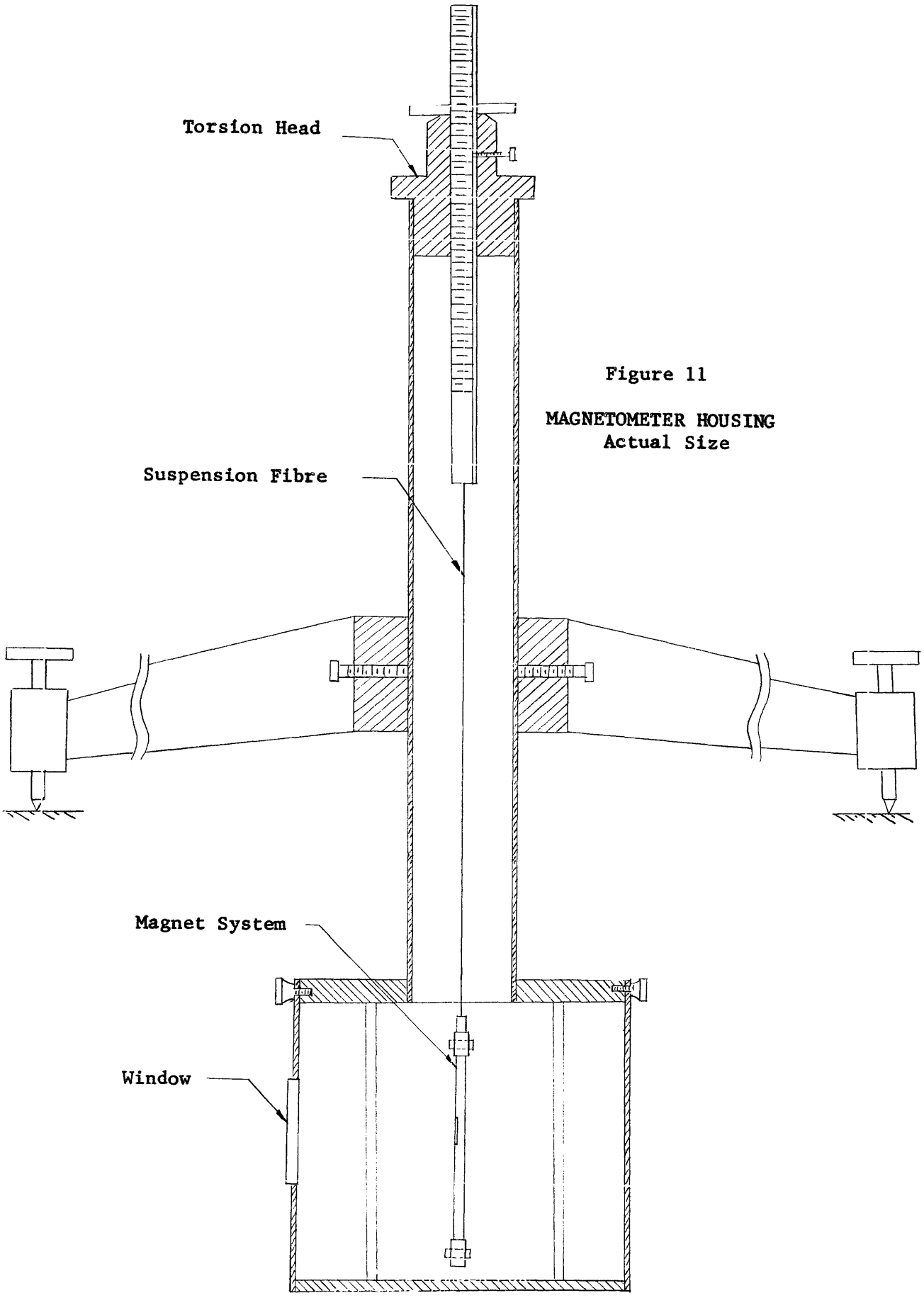


Figure 11

MAGNETOMETER HOUSING
Actual Size

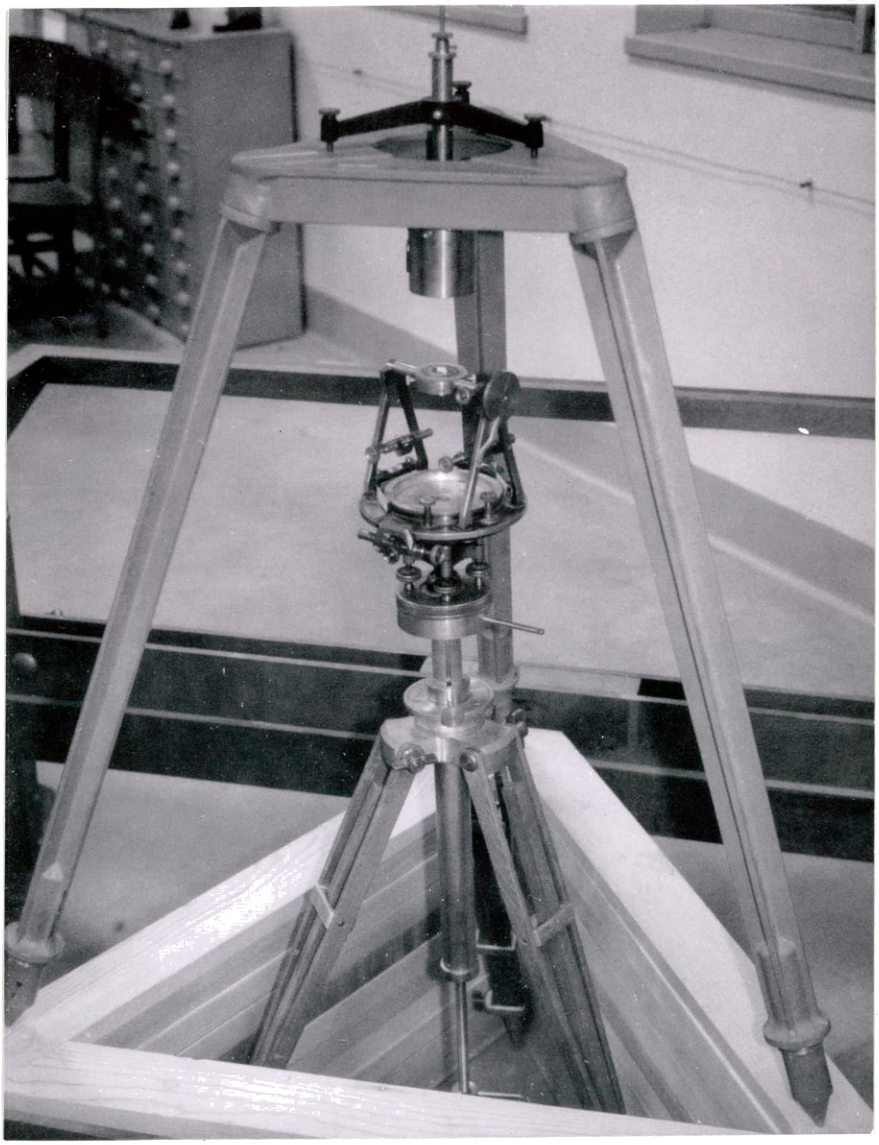


Figure 12

General View of Astatic

Magnetometer

magnetism, and the rotation about the horizontal axis provides a method of measuring the inclination or dip of the remanent magnetism. To perform these functions, a transit was modified as shown in figure 12.

Calibration of Instrument: To determine the sensitivity of the instrument, which is defined as $S = D/\Delta h$ where D is the deflection and Δh is the net horizontal field acting on the magnetometer system, a small coil was constructed. This coil had a cross-sectional area A of 2.4 cm^2, 90 turns of 30 gauge copper wire and length 2 cm.

The field produced by this coil at a distance Z, measured perpendicular to the axis of the coil, is given by

$$h = \frac{niA}{10Z^3} .$$

Therefore, the net field Δh acting on the system is

$$\Delta h = \frac{niA}{10} (1/Z_l^3 - 1/Z_u^3) \text{ oersteds,}$$

where Z_l and Z_u are the distances from the coil to the lower and upper magnets, respectively.

Hence, $1/S = \frac{niA}{10D} (1/Z_l^3 - 1/Z_u^3)$ oersteds/mm which was determined for various values of i, Z_l and Z_u and found to be very near the average value of 2.16×10^{-6} oersteds/mm at a scale to mirror distance of 1 meter. This calibration data is given in table VII.

TABLE VII

Calibration Data

Z_1 cm	i milli Amp.	D mm	1/S oer/mm x 10^{-6}
15	30	44.5	2.19
"	25	37.3	2.18
"	20	30.0	2.16
"	10	15.0	2.16
14	20	39.0	2.14
"	15	29.2	2.14
"	10	19.5	2.14
13	20	51.1	2.14
"	15	38.0	2.17
"	14.7	37.1	2.16
"	12	30.6	2.14
"	10	25.5	2.14
12	15	50.0	2.16
"	12	40.1	2.17
"	10	34.0	2.14
11	7.5	34.3	2.15

TABLE VIII

Summary of the Details of the Magnetometer

L (distance between magnets)	4 cm
l (length of magnets)	5.0 mm
b (width of magnets)	2.45 mm
c (breadth of magnets)	2.0 mm
period (of system)	6 sec.
1/S oersteds/mm	2.16×10^{-6}
diameter of fibre	10 u
length of fibre	15 cm
mirror dimensions	0.25 x 0.15 x 0.01 in.

APPENDIX II

AZIMUTH OF REMANENT MAGNETISM

The angle θ between the reference line on the specimen and the azimuth of remanent magnetization is given by

$$\tan \theta = (a_2 - a_4)/(a_3 - a_1),$$

where a_1, a_2, a_3 and a_4 are the deflections of the magnet system determined by the procedure outlined on page 16. This relationship is developed in the following manner.

Consider the specimen with an assumed azimuth of remanent magnetization h, and a reference line R set at 90 degrees to the axis of the magnets in their rest position as shown in figure 13a.

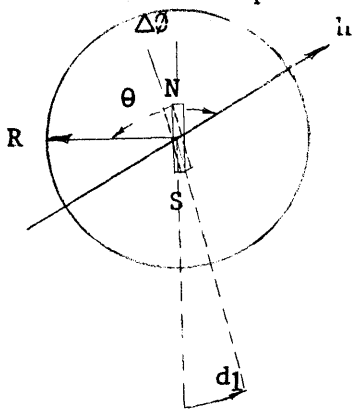


Figure 13a

Plan view of specimen

and lower magnet

When the specimen is placed below the magnetometer, the magnet system will rotate anticlockwise to an equilibrium position according to

$$kd_1 = K\left\{\mathrm{Sin}(\theta - 90 + \Delta\phi_1)\right\}$$

or,

$$kd_1 = K\left\{\mathrm{Sin}\left[(\theta + \Delta\phi_1) - 90\right]\right\},$$

where $\Delta\phi$ is the angular rotation of the magnet system, k is the torsion constant of the fibre divided by twice the scale to mirror distance, provided $\Delta\phi < 5°$, and K is the net field acting on the magnet system, times the moment of the magnets. If the specimen is rotated 90 degrees about a vertical axis, as in figure 13b, the equation of equilibrium becomes

$$kd_2 = K\left\{\mathrm{Sin}\left[180 - (\theta + \Delta\phi_2)\right]\right\}.$$

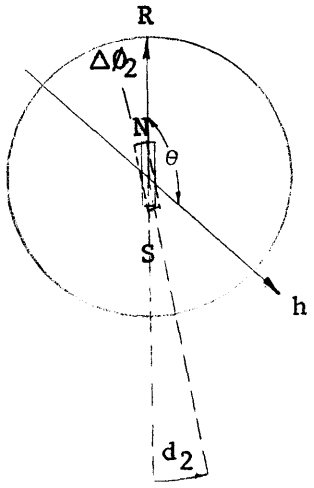


Figure 13b

Plan view of Specimen

and Lower Magnet

similarly, if the specimen is again rotated 90 degrees

$$-kd_3 = K\left\{\text{Sin}\left[(\theta - \Delta\phi_3) - 90\right]\right\},$$

where the $-kd_3$ indicates a clockwise rotation of the magnet system, and

$$-kd_4 = K\left\{\text{Sin}\left[180 - (\theta - \Delta\phi_4)\right]\right\}.$$

When the specimen is inverted to remove the induced effects the same equation apply. Therefore, if the deflections for the inverted specimen are d_1', d_2', d_3' and d_4'; and $\frac{d_1 + d_1'}{2} = a_1$, $\frac{d_2 + d_2'}{2} = a_2$, etc., expanding the sine terms results in

$$\frac{a_2 - a_4}{a_3 - a_1} = \frac{\text{Sin}\ (\theta + \Delta\phi_2) + \text{Sin}\ (\theta - \Delta\phi_4)}{\text{Cos}\ (\theta - \Delta\phi_3) + \text{Cos}\ (\theta + \Delta\phi_1)}$$

Further expansion of the sine and cosine terms and collecting on Sin θ and Cos θ gives

$$\frac{a_2 - a_4}{a_3 - a_1} = \frac{\text{Sin}\ \theta(\text{Cos}\ \Delta\phi_2 + \text{Cos}\ \Delta\phi_4) + \text{Cos}\ \theta(\text{Sin}\ \Delta\phi_2 - \text{Sin}\ \Delta\phi_4)}{\text{Cos}\ \theta(\text{Cos}\ \Delta\phi_3 + \text{Cos}\ \Delta\phi_1) - \text{Sin}\ (\text{Sin}\ \Delta\phi_3 - \text{Sin}\ \Delta\phi_1)}.$$

Since Cos $\Delta\phi \doteq 1$, and Sin $\Delta\phi \doteq 0$

$$\frac{a_2 - a_4}{a_3 - a_1} = \frac{2\ \text{Sin}\ \theta}{2\ \text{Cos}\ \theta} = \tan\theta.$$

APPENDIX III

INCLINATION OF REMANENT MAGNETISM

The angle of inclination, I, of the remanent magnetism is given by

$$\tan I = (b_2 - b_4)/(b_3 - b_1),$$

where b_1, b_2, b_3 and b_4 are the deflections as defined on page 17. This relationship is developed by a procedure similar to that used in Appendix II.

In this development consider the specimen beneath the magnetometer with the previously determined azimuth of magnetization, h, set

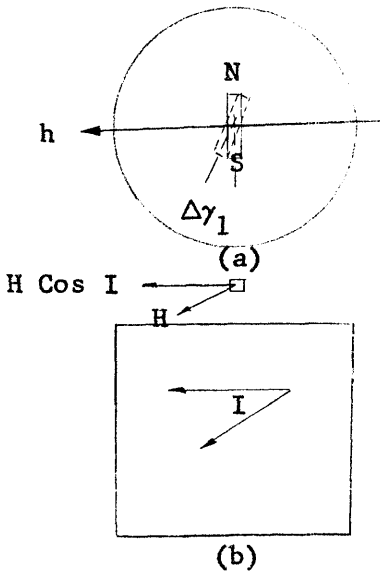


Figure 14
Plan and Side Views of
Specimen and Lower Magnet

at 90 degrees to the axis of the magnets in their rest position, as shown in figure 14a. This will produce a clockwise deflection of the magnet system according to

$$- kc_1 = mH \text{ Cos } I \text{ Sin } (90 - \Delta\gamma_1),$$

where H Cos I is the horizontal component of H acting on the magnets as shown in figure 14b. As in Appendix II, $\Delta\gamma$ is the angular rotation of the magnet system, k is the torsion constant of the fibre divided by twice the scale to mirror distance provided $\Delta\gamma < 5°$, and m is the magnetic moment of the magnets.

If the specimen is now rotated clockwise 90 degrees about a horizontal axis as shown in figures 15a and 15b, the equilibrium equation becomes

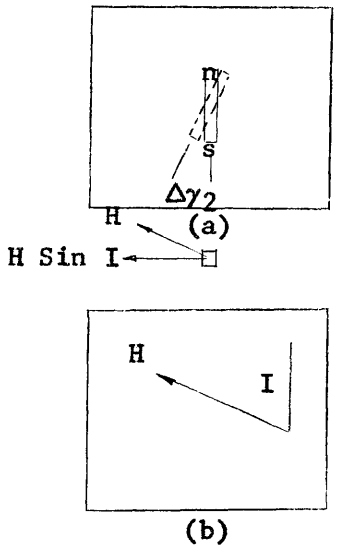


Figure 15

Plan and Side Views of

Specimen and Lower Magnet

$$- kc_2 = mH \text{ Cos } (90 - I) \text{ Sin } (90 - \Delta\gamma_2)$$

$$= mH \text{ Sin } I \text{ Sin } (90 - \Delta\gamma_2).$$

Repeating the procedure gives two more equations

$$kc_3 = mH \text{ Cos } I \text{ Sin } (90 - \Delta\gamma_3)$$

and

$$kc_4 = mH \text{ Sin } I \text{ Sin } (90 - \Delta\gamma_4).$$

When the specimen is inverted the deflections are very nearly the same as the first set of readings, and the same equations apply. If these deflections are c_1', c_2', c_3' and c_4' and if $(c_1 - c_1')/2 = b_1$ and $(c_2 - c_2')/2 = b_2$ etc., then

$$(b_2 - b_4)/(b_3 - b_1) = \frac{-mH \text{ Sin } I \text{ (Cos } \Delta\gamma_2) - mH \text{ Sin } I \text{ (Cos } \Delta\gamma_4)}{mH \text{ Cos } I \text{ (Cos } \Delta\gamma_3) - mH \text{ Cos } I \text{ (Cos } \Delta\gamma_1)}$$

Since $\Delta\gamma < 5°$ and Cos $\Delta\gamma = 1$ and

$$(b_2 - b_4)/(b_3 - b_1) = - \frac{\text{Sin } I}{\text{Cos } I} = \tan I,$$ where the negative sign indicates a downward inclination.

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