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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

INTERAGENCY REPORT: NTS-2

RAPID ESTIMATION OF INDUCED AND REMANENT
MAGNETIZATION OF ROCK SAMPLES, NEVADA TEST SITE

By

C. E. Jahren and G. D. Bath

August 25, 1967

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Abstract

A commercially available fluxgate-type clip-on milliammeter, modified to function as a magnetometer, is used to make rapid measurements of the induced and remanent magnetization of rock samples. Directions are found within 10° and intensities within 6 percent as compared with standard laboratory procedures. Calibration for both remanent and induced intensity is based on an electric current measurement in an auxiliary coil. Samples need be only roughly spherical in shape and may range up to hand specimen size. The directions and intensities calculated are those of an equivalent magnetic dipole located at the center of the sample. Rock sampling procedures are tested by first measuring hand specimens, and then drilling several small cylindrical samples out of each. Intensities measured on the hand specimens fall within a 95 percent confidence interval about the corresponding small-sample averages.

INTRODUCTION

A complete interpretation of the vast amount of aeromagnetic data that has accumulated since the development of the airborne magnetometer awaits a more extensive rock sampling program to provide information on the magnetic properties of anomaly-producing rocks. An analyst of magnetic anomalies today seldom uses data on magnetic susceptibility, or direction and intensity of remanent magnetization. This restricts most interpretations to the use of anomaly gradient to compute depths down to the top of the magnetized unit, anomaly continuity to extend a known magnetic unit into an area where the unit is buried and the geology unknown, and anomaly

extent to estimate the near-surface dimensions of the unit. Reliable prediction of the rock type that is responsible for a particular anomaly, or investigations of the thickness of this unit, cannot be undertaken without relating geologic features to magnetic properties within the area of the magnetic survey.

During the past two decades the results of extensive paleomagnetic research in rock magnetism have not carried over into the interpretation of magnetic surveys. The parameter of chief concern in paleomagnetism, direction of remanent magnetization, shows a striking consistency when compared with the intensity of remanent magnetization for measurements over a certain rock unit. Magnetic interpretation requires both direction and intensity of magnetization, and it is the variable nature of intensity that has discouraged most exploration geophysicists from using magnetic properties in their interpretations.

Paleomagnetic studies show that the thermo-remanent magnetization acquired as igneous rocks cool in the earth's magnetic field is of prime importance in interpretations of magnetic surveys, because it affects the entire cooling unit and it often produces strong intensities. If the intensity is sufficiently great and the cooling unit is sufficiently thick, a significant magnetic anomaly will result, either positive or negative depending on the direction of the earth's magnetic field during the time of cooling. Paleomagnetic results suggest that the earth's magnetic field has undergone periodic reversals throughout Oligocene to Recent time, and that rocks magnetized during this interval have remanent directions either along or opposite to the present magnetic field of the earth.

The large magnetic fields associated with lightning bolts cause an irregular distribution of remanent directions and intensities that is not representative of the igneous feature under study. Lightning effects thus introduce formidable problems in the collection of representative or typical rock samples from surface exposures. The recommended procedure is to collect such samples away from local topographic highs. Most samples taken in underground workings, as well as samples of drill core, are satisfactory. Cox (1961) estimates that these contaminating effects are confined to the upper 10-50 feet of a rock mass.

In this paper, we describe the simplified methods used to obtain the magnetic property data required to interpret an aeromagnetic survey of 5,000 square miles in the general area of the Nevada Test Site. The majority of prominent anomalies are found over Tertiary volcanic rocks where identification of the causative body is necessary before interpretations can proceed. Determining the depth to the top of the body, and superimposing the aeromagnetic data on the excellent geologic maps now available for much of the area may narrow the number of interpretive possibilities. But if there are enough rock exposures, drill holes, or underground workings beneath the anomaly, field measurement of magnetic properties will establish the identity of the anomaly producing rocks without question. The source rocks must have the direction and intensity of magnetization necessary to explain the aeromagnetic anomaly.

We have developed simplified methods in order to cut down the time required for each of these measurements. Then we have tried to cope with the problem of variability by using a large number of samples. The

extreme variability of the surface samples presents a special problem. We have found that the required number of such samples can be kept within bounds by field checking when they are collected. As collecting continues the degree of inhomogeneity can be assessed, and obviously atypical samples rejected.

PRINCIPLES OF MEASUREMENT

Both large rock masses and small rock samples must be spherical or ellipsoidal in shape and homogeneous in composition to have strictly uniform magnetization. Nevertheless, uniform magnetization is generally assumed in discussing rock magnetism, regardless of the shapes involved.

In uniformly magnetized material, the magnetization, $\underline{J}$, denotes the dipole moment, $\underline{M}$, per unit volume. A sample of volume, $\underline{V}_s$, has a dipole moment, $\underline{M} = \underline{J} \underline{V}_s$. The magnetic field associated with a rock sample of roughly spherical shape approximates that of a dipole.

Figure 1 shows a rock sample, $\underline{S}$, its equivalent dipole of moment $\underline{M}$, and the lines of force of the associated magnetic field $\underline{H}$ in the vicinity of the sample. For simplicity the dipole is drawn lying in the plane of the paper, its axis making an angle α with the $\underline{y}$ direction. In space the pattern of lines of force makes a figure of revolution about the dipole axis. A detector, $\underline{D}$, in the plane of the paper is a distance $\underline{R}$ from the center of the sample. It measures only the component $\underline{H}_y$ of the magnetic field $\underline{H}$ due to the dipole.

The magnetic potential at $\underline{D}$ is given by

$$\underline{V} = \underline{M} \cos \alpha / \underline{R}^2 \quad (1)$$

Figure 1.--Diagram showing method of measuring remanent magnetization.

in cgs emu (see Maxwell, 1891, p. 9). The radial component of the magnetic field is derived from the potential

$$\underline{H}_R = \underline{H}_y = - (\partial V / \partial R) = 2 \underline{M} \cos \alpha / R^3 , \quad (2)$$

since $\underline{R}$ the vector distance from the sample to the detector is in the y direction.

The dipole moment, $\underline{M}$, can be resolved into components $\underline{M}_y = \underline{M} \cos \alpha$ and $\underline{M}_x = -\underline{M} \sin \alpha$. Equation (2) shows that the field $\underline{H}_y$ measured at $\underline{D}$ determines only the component $\underline{M}_y$ of the dipole moment in the y direction. A similar argument shows that if the dipole had a component in the z direction (downward into the plane of the diagram, figure 1) it would not affect the $\underline{H}_y$ field at $\underline{D}$.

Our measurements of remanent moment, $\underline{M}_r$, are carried out in the earth's magnetic field. The xyz-axes of figure 1 form an orthogonal set with $\underline{x}$ directed toward magnetic north and $\underline{z}$ vertically downward. The earth's magnetic field vector, $\underline{T}_0$, pointing northward and downward, will induce only $\underline{x}$ and $\underline{z}$ components of magnetization in a spherical isotropic sample, and these will not affect the measurements. Various components of remanent moment can be found by rotating the sample as described in the next section.

In a magnetically anisotropic sample, $\underline{T}_0$ might induce a y component of magnetization which would be confused with remanent magnetization. This can be avoided by bucking out $\underline{T}_0$ with approximately placed Helmholtz coils surrounding the entire apparatus. In practice it is convenient to buck out $\underline{T}_{ox}$ with a Helmholtz system aligned parallel to the $\underline{x}$ axis and $\underline{T}_{oz}$ with a second system aligned parallel to the $\underline{z}$ axis. These coils can be mounted on the same frame with a third system designed to apply a known magnetic field in the y direction.

The detector can be calibrated in terms of magnetic moment by means of a small, current-carrying coil which replaces the sample at S. The magnetic field of a circular coil approximates that of a centered, axially directed dipole. The dipole moment $\underline{M}_C$ of the coil is given by

$$\underline{M}_C = \underline{N} \underline{i} \underline{A} / 10 \text{ emu}, \quad (3)$$

where N is the number of turns, i is the current in amperes, and A is the cross sectional area in cm². (See Maxwell, 1891, p. 141). Our coils are made cylindrical in shape and have approximately the same dimensions as the rock samples.

Induced moment, $\underline{M}_i$, is measured by aligning D along the earth's magnetic field as shown in figure 2. The diagram is in the zx-plane and $\underline{M}_i$ is in the direction of $\underline{T}_0$ for an isotropic sample. Current in the coil C supplied by battery B and controlled by rheostat $\underline{R}_h$ establishes a magnetic field which cancels $\underline{T}_0$ at the detector while altering its magnitude by less than one percent at S provided the distance R is 2 cm or more. The detector can be calibrated by replacing the sample with a current-carrying coil as before.

If the three sets of Helmholtz coils mentioned above are available, the inducing field may be supplied by the y axis coils and the configuration of figure 1 retained. The inducing field must be neutralized at the probe by a coil similar to C of figure 2, a fraction of the main coil current being used for this purpose.

The direction and magnitude of $\underline{M}_r$ can be calculated from the components, and $\underline{J}_r$ is then found, since

$$\underline{J}_r = \underline{M}_r / \underline{V}_s. \quad (4)$$

An exactly analogous equation yields the induced magnetization, $\underline{J}_1$, from $\underline{M}_1$.

If $\underline{T}_0$ is the magnitude of the inducing field,

$$\underline{J}_1 = \underline{k}' \underline{T}_0 \quad (5)$$

where $\underline{k}'$ is the apparent magnetic susceptibility of the sample, related to the susceptibility, $\underline{k}$, by the expression

$$\underline{k} = \underline{k}' / (1 - \underline{N}_d \underline{k}'). \quad (6)$$

$\underline{N}_d$ is the average demagnetization factor and depends on the shape and relative dimensions of the sample. Magnetic susceptibility $\underline{k}$ rather than $\underline{J}_1$ is usually reported for rocks. The distinction between $\underline{k}$ and $\underline{k}'$ is not important for cylindrical samples with length equal to diameter if $\underline{k} < 0.01$ cgs. A simplified discussion of demagnetization effects in rock samples is given by Jahren (1963).

METHODS OF MEASUREMENT

Intensities and directions from components

For the detector at $\underline{D}$ we use a commercially manufactured fluxgate-type magnetometer probe, which feeds into a meter. The meter is marketed as a clip-on direct-current milliammeter, measuring current by detecting the magnetic field surrounding the current-carrying wire. The directionally sensitive probe is available as an accessory. On the most sensitive range, magnetic fields of 100 gammas give full-scale deflection, and one gamma can

just be detected. On other ranges fields up to 10^6 gammas (10 gauss) can be measured. We zero the meter by aligning the detector horizontally and perpendicular to the earth's magnetic field.

We use a plastic holder for probe and sample. Any rigid device made of nonmagnetic material would be satisfactory. It is convenient to have a platform which rotates through measured angles from 0° to 360° with centered recesses for holding cylindrical samples which may be set on their base or side. Standardizing coils should fit in the same recess, so that the distance $\underline{R}$ (see fig. 1) is the same in both standardization and measurement. This is quite critical, since meter readings depend inversely on the cube of $\underline{R}$ as shown in equation (2).

For work in the field other arrangements are possible. The rotating table may be replaced by a simple target, in which case samples positioned on curved surfaces must be propped up with plastic clay. If the samples are lumps rather than cylinders or cubes, distance to the center is somewhat indefinite. Satisfactory results are obtained by careful visual centering. Volume is best found by weighing the sample in and out of water. Hand specimens of irregular shape are propped on an old magnetometer tripod using plastic clay. The tripod head has provision for 360° rotation. Wire coils wound on beakers simulate larger samples for calibration purposes.

The steps in the measurement of remanent moment are best described with reference to figure 1. First orthogonal axes $\underline{x}$ ' $\underline{y}$ ' $\underline{z}$ ' are established with reference to the orientation of the sample before it is drilled from the rock mass. All subsequent directions are referred to these axes.

When convenient, they are geographic north, east, and vertically downward respectively. If the $\underline{x}'$ component of $\underline{M}_r$ is to be measured, the sample is placed so that $\underline{x}'$ lies along the $\underline{y}$ axis in figure 1. The meter reading $\underline{m}_+$ is noted. The sample is then rotated 180° about $\underline{z}'$ (which is parallel to $\underline{z}$) so $\underline{x}'$ lies along the negative $\underline{y}$ axis and a new reading $\underline{m}_-$ is noted. The meter throw $\underline{m} = \underline{m}_+ - \underline{m}_-$ is a measure of the moment in the $\underline{x}'$ direction, positive when the moment is directed along the positive sense of $\underline{x}'$.

To evaluate $\underline{m}$ in terms of moment, a current $\underline{i}$ is directed through the calibrating coil with the rotation sense of a right-handed screw advancing along the $\underline{y}$ axis. Then the deflection of the meter establishes the positive direction on its scale. Reversing the current in the coil reverses the direction of the calibrating moment and is equivalent to rotating the sample 180° . If the calibrating deflections are $\underline{m}_{c+}$ and $\underline{m}_{c-}$, a calibration constant $\underline{C}_m$ can be defined

$$\underline{C}_m = \underline{M}_c / (\underline{m}_{c+} - \underline{m}_{c-}), \quad (7)$$

where $\underline{M}_c$ is given by equation (3). Using $\underline{C}_m$ the remanent moment in the $\underline{x}'$ direction is given by

$$\underline{M}_{rx'} = \underline{C}_m \underline{m}. \quad (8)$$

$\underline{M}_{ry'}$ and $\underline{M}_{rz'}$, can be found in the same manner by aligning the appropriate direction of the sample along the $\underline{y}$ axis of figure 1. Then

$$\underline{M}_r = (\underline{M}_{rx'}^2 + \underline{M}_{ry'}^2 + \underline{M}_{rz'}^2)^{1/2}. \quad (9)$$

The azimuth of $\underline{M}_r$ is given by

$$\alpha' = \tan^{-1} (\underline{M}_{ry'} / \underline{M}_{rx'}), \quad (10)$$

and the inclination by

$$\underline{i}' = \sin^{-1} (\underline{M}_{rz}' / \underline{M}_r). \quad (11)$$

In practice it is convenient to express all moments directly in units of meter throw $\underline{m}$, and so use them in equations (9), (10), and (11). $\underline{M}_r$ can be converted to emu by use of $\frac{C}{\underline{m}}$.

Direct reading of instruments

Taking advantage of the rotating table, angles and moments can be read directly. If $\underline{S}$ is rotated counter clockwise through an angle $\mathcal{A}$, a maximum reading $\underline{m}_+$ is obtained, since point $\underline{A}$ in the field pattern of the dipole is at the detector. A 180° rotation about $\underline{z}$ brings point $\underline{A}'$ to the detector and yields a minimum reading $\underline{m}_-$. Then $\underline{m} = \underline{m}_+ - \underline{m}_-$ measures the moment $\underline{M}_{rx'y'}$ in the $\underline{x'y'}$ plane. From the angle readings

$$\bar{\alpha} = (\alpha_{\underline{A}} + \alpha_{\underline{A}'} - 180^\circ)/2 = (\alpha_{\underline{A}} + \alpha_{\underline{A}'})/2 - 90^\circ, \quad (12)$$

where $\bar{\alpha}$ is an average value. ($\alpha_{\underline{A}}$ is the value read off the degree circle when the point $\underline{A}$ of the field pattern is at the detector.) A more accurate value of $\bar{\alpha}$ is obtained by rotating the sample an additional 90° to bring point $\underline{B}$ to the detector, since the dipole field is changing more rapidly with angle at this point (see equation 2). We know $\underline{B}$ is at the detector when the meter reads $\underline{m}_0$ as it would read with the sample completely removed. $\underline{m}_0$ can also be obtained from $\underline{m}_0 = (\underline{m}_+ + \underline{m}_-)/2$, since the zero reading is the same as the average

of the positive and the negative deflections. A further check is to rotate an additional 180° to bring point $\underline{B}'$ to the detector. If $\alpha_{\underline{B}}$ and $\alpha_{\underline{B}'}$ give readings of $\underline{m}_0$, $\bar{\alpha} = (\alpha_{\underline{B}} + \alpha_{\underline{B}'} - 180^\circ)/2 - 90^\circ$, or $\bar{\alpha} = (\alpha_{\underline{B}} + \alpha_{\underline{B}'})/2 - 180^\circ$. While averaging procedures such as these increase precision slightly, they also increase the time required to make a measurement.

Next the sample is positioned so that the $\underline{z}'$ axis is aligned with the y axis and $\underline{M}_{\underline{rz}'}$ is determined as before.

For routine work we have found it best to measure $\underline{M}_{\underline{rx}'\underline{y}'}$, and $\underline{M}_{\underline{rz}'}$ and compute

$$\underline{M}_{\underline{r}} = (\underline{M}_{\underline{rx}'\underline{y}'}^2 + \underline{M}_{\underline{rz}'}^2)^{1/2} \quad (13)$$

and

$$\underline{i}' = \tan^{-1} (\underline{M}_{\underline{rz}'}/\underline{M}_{\underline{rx}'\underline{y}'}). \quad (14)$$

Susceptibility measurements

If the induced magnetization is to be measured in the earth's field $\underline{T}_0$, the sample and detector are aligned as shown in figure 2. First, rheostat $\underline{R}_h$ is adjusted so current in coil $\underline{C}$ nullifies the earth's field at $\underline{D}$. Then the sample is placed at $\underline{S}$ and meter reading $\underline{m}$ noted. The sample is then replaced by a standard coil and the current through it adjusted to give the same reading $\underline{m}$. From this current, $\underline{i}$, the induced moment is then calculated by equation (3). There must be no component of $\underline{M}_{\underline{r}}$ in line with $\underline{T}_0$.

Figure 2.--Diagram showing method of measuring induced magnetization.

If the setup of figure 1 is to be used, a Helmholtz coil system provides a field $\underline{I}$ in the $\underline{y}$ direction which may be made equal in magnitude to $\underline{I}_0$ or may be given some convenient value such as one-half gauss. In any case $\underline{I}$ should be kept at the same order of magnitude as the earth's field. A small fraction of the Helmholtz-coil current is shunted through the coil wound about the probe. With no sample at $\underline{S}$ the fraction of shunt current is adjusted to make the meter read zero and continue reading zero when $\underline{I}$ is reversed in sense. With the sample present the reversing induced moment of magnitude $\underline{M}_1$ causes a meter throw $\underline{m} = \underline{m}_+ - \underline{m}_-$. Susceptibility is then found from equations (4), (5), and, if necessary (6).

This second method has the advantage of giving twice the meter throw for a given susceptibility since a reversal is involved. Moreover, a component of $\underline{M}_1$ in the direction of measurement will not cause an error.

EXPERIMENTAL RESULTS

Remanent magnetization

The direction and intensity of remanent magnetization of nine cylindrical rock samples with dimensions of the order of 1 inch are listed in table 1. Measurements obtained with a rock-generator magnetometer of the type described by Doell and Cox (1965) are compared with results of the probe method described in this paper. The rock-generator values can be assumed correct. The probe method appears sufficiently accurate for our routine work, since the maximum disagreement is 9° in angle and 6 percent in intensity.

The results of measurements on 10 hand-specimen size samples are listed in table 2. After the measurements were completed, several small cylindrical samples were drilled from each large one and measured. Results are indicated in table 3, where standard deviations and standard errors are listed for the intensity measurements. A 95-percent confidence interval about the small-sample mean can be defined in a way that there is a 95-percent chance that the true (population) mean will be included. Here the true mean for a particular hand specimen can be taken as the intensity listed in table 2. The 95-percent confidence interval about the small-sample mean is shown in figure 3 for each hand specimen. The true mean is indicated by an arrow. The interval covers, or very nearly covers, the true mean in all cases.

The variability noted in comparing small-sample with large-sample measurements is common to all magnetic measurements on rocks. In tables 4 and 5 are shown results of measuring, using a Schmidt-type

Figure 3.--Confidence intervals about small-sample means listed in table 3.

Table 1.--Direction and intensity of remanent magnetization as measured by probe method compared with same quantities as measured by rock-generator method

[Samples are cylinders of 1X1-inch, approximately.]

Sample number	Volume of sample (cm ³)	Magnetization from rock-generator magnetometer			Magnetization from probe magnetometer		
		Azimuth (degrees)	Inclination (degrees)	Intensity (X10 ⁴ emu/cm ³)	Azimuth (degrees)	Inclination (degrees)	Intensity (X10 ⁴ emu/cm ³)
A-3	10.2						
B-7	9.2	1	50	4.0	4	48	3.8
C-4	9.4	6	67	6.6	12	66	6.2
D-3	9.1	330	44	6.9	331	46	6.5
E-2	9.3	179	-79	9.8	182	-70	9.4
F-4	10.8	337	20	35	343	22	33
G-7	10.5	91	46	51	96	45	51
H-2	10.9	30	-28	97	28	-28	98
I-3	10.9	338	37	84	338	38	83
J-1	10.7	2	33	119	2	32	113

Table 2.--Remanent magnetization of 10 large rock samples of irregular shape

Sample number	Volume of sample (cm ³)	Magnetization		
		Azimuth (direction)	Inclination (degrees)	Intensity (X10 ⁴ emu/cm ³)
A	870	S	30	1.2
B	2,670	N	53	5
C	6,050	N	60	5
D	8,650	N. 30° W.	42	6
E	3,340	S	-58	9
F	1,015	N	14	33
G	5,750	E	39	52
H	1,320	N. 30° E.	-28	115
I	1,920	N	37	112
J	1,020	N	21	134

Table 3.--Remanent magnetization of 92 small cylindrical samples drilled from the 10 large rock samples listed in table 1

Sample no. of large rock	Number of small samples drilled	Average volume (cm ³)	Magnetization				
			Direction		Intensity		
			Average azimuth (degrees)	Average inclination (degrees)	Average magnitude (X10 ⁴ emu/cm ³)	Standard deviation (X10 ⁴ emu/cm ³)	Standard error (X10 ⁴ emu/cm ³)
A	3	9.4	178	40	9.0	1.0	0.6
B	7	9.1	359	54	5.6	0.5	0.2
C	12	9.7	357	66	5.9	1.0	0.3
D	12	9.5	343	45	7.1	0.7	0.2
E	10	9.2	169	-73	9.4	2.1	0.7
F	10	10.8	342	19	31	0.9	0.3
G	11	10.7	105	40	56	4.7	1.4
H	5	10.8	38	-26	108	6.2	2.8
I	13	10.8	338	34	114	32	8.7
J	9	10.7	19	29	135	25	8.2

Table 4.--The magnetization of a continuous length of trachybasalt, Core A

[Core A, 87 cm long and of 15.2-cm diameter, as obtained by breaking the core into six pieces, and measuring the remanent inclination and intensity of each piece.]

Core A, piece no.	Volume (cm ³)	Remanent magnetization	
		Inclination (degrees)	Intensity ($\times 10^4$ emu/cm ³)
1	1575	39	13.5
2	1710	37	12.5
3	1980	33	11.5
4	4320	44	16.1
5	3600	39	16.2
6	2520	45	23.2
Average		39.5	15.5
Standard deviation		4.5	4.2
Standard error		1.8	1.7

Table 5.--The magnetization of a continuous length of trachybasalt Core B

/Core B, 113 cm long and of 15.2-cm diameter, as obtained by breaking the core into nine pieces, and measuring the remanent inclination and intensity of each piece./

Core B, piece no.	Volume (cm ³)	Remanent magnetization	
		Inclination (degrees)	Intensity ($\times 10^4$ emu/cm ³)
1	2700	87	24
2	1980	73	24
3	1260	82	23
4	3600	88	31
5	1440	88	27
6	3240	88	22
7	1890	85	16.3
8	1980	85	19.5
9	2550	82	18.0
<hr/>			
Average		84.2	22.8
Standard deviation		4.9	4.5
Standard error		1.6	1.5

magnetometer, successive chunks broken from 15.2-cm diameter drill cores, and in table 6 are the results of similar work on another 15.2-cm diameter core. Standard deviation, which measures the variability from sample to sample, is about the same in all cases. Standard error, which estimates the variability from sample mean to sample mean, is reduced by increasing the number of samples.

Induced magnetization

The magnetic susceptibility, k , is listed for 13 cylindrical rock samples in table 7. Values obtained by our probe method are in good agreement with values obtained using a laboratory-type alternating-current susceptibility bridge described by Anderson (1961).

The samples were measured using the set-up of figure 1. A magnetic field of 0.50 gauss was applied along the y -axis perpendicular to the cylindrical axis of the sample. Reversing the field, and hence the induced magnetization of the sample, gave a meter throw m , from which induced magnetization $\underline{M}_i$ and apparent susceptibility k' was calculated. Before this measurement was taken, the sample was rotated about its cylindrical axis (coincident with the z -axis) until the horizontal component of its remanent magnetization pointed along the x -axis. The vertical component of the remanent magnetization pointed along the ($\pm$) z -direction, so only the induced magnetization of the sample affected these meter readings.

Table 6.--The magnetization of 29 samples of drill core from the trachybasalt of Buckboard Mesa.

Trachybasalt Core Piece no.	Volume (cm ³)	Remanent magnetization	
		Inclination (degrees)	Intensity ($\times 10^4$ emu/cm ³)
1	12.8	74	24
2	14.1	73	24
3	12.5	75	24
4	14.0	75	31
5	14.0	75	34
6	12.6	71	22
7	12.8	73	28
8	12.8	70	19.0
9	14.6	73	17.6
10	13.2	71	22
11	13.4	68	17.9
12	13.5	70	22
13	12.8	72	24
14	13.2	73	23
15	12.2	65	23
16	12.3	66	17.2
17	13.4	65	15.7
18	13.4	70	19.4
19	17.2	48	13.7
20	17.8	59	14.5
21	17.8	60	15.2
22	16.9	49	11.8
23	21.7	75	16.2
24	16.0	75	17.6
25	25.1	73	13.4
26	18.5	73	23
27	14.2	70	19.4
28	19.3	74	24
29	17.7	71	19.2

Average	69.0	20.5
Standard deviation	3.0	5.2
Standard error	0.5	1.0

Table 7.--Magnetic susceptibility of small rock samples as determined by two different methods of measurement.

Sample number	Volume (cm ³)	Susceptibility by probe method		Susceptibility by laboratory alternating current bridge
		Apparent susceptibility ($\times 10^4 \frac{k'}{\text{emu/cm}^3}$)	Susceptibility ($\times 10^4 \frac{k}{\text{emu/cm}^3}$)	Susceptibility ($\times 10^4 \frac{k}{\text{emu/cm}^3}$)
15	12.0	640	880	680
17	12.0	2	2	2
18	12.1	40	41	38
20	12.1	61	63	50
24	12.0	1	1	1
25	12.1	1	1	1
26	12.0	2	2	2
27	12.0	19	19	17
29	12.0	5	5	5
30	12.0	9	9	7
31	12.0	47	48	46
33	12.0	1	1	1
34	12.0	84	87	120

These measurements were made in the presence of the earth's magnetic field, which had components in the $\underline{x}$ - and $\underline{z}$ -directions only. A few samples were measured again after nullifying the earth's field by means of the Helmholtz coil systems. No difference was found in the apparent susceptibility values.

Susceptibility, $\underline{k}$, was calculated from $\underline{k}'$ using equation (6). The demagnetization factor, $\underline{N}_d$, was taken as $4\pi/3$. This value is correct for a sphere and approximately valid for a cylinder with length equal to diameter. The difference between $\underline{k}$ and $\underline{k}'$ is less than 2 percent for $\underline{k}' < 0.005 \text{ emu/cm}^3$.

The samples with higher susceptibility show a greater difference between probe measurements and alternating-current measurements. The latter were made in the direction of the cylindrical axis of the sample. Highly magnetic samples often show a variation of susceptibility with direction (see Jahren, 1963), so this probably accounts for the discrepancy. A different assignment of demagnetization factor will not improve the agreement in all cases.

The probe magnetometer was used to estimate the susceptibility of four samples of hand-specimen size, again using the setup of figure 1. The applied field in the $\underline{y}$ direction had a strength of 0.49 gauss, and was reversed to obtain the meter throw $\underline{m}$. The remanent magnetization of the sample was made to point in the $\underline{x}$ direction so as not to affect the readings. Four readings were taken and averaged, the sample being rotated

90° about the x axis after each determination. This was done to minimize centering errors due to irregular sample shape. The results are summarized in table 8. Susceptibility is small enough so that the difference between k' and k may be ignored.

From each hand specimen several 1 X 1-inch cylindrical samples were drilled and the susceptibility determined on a mutual inductance alternating-current bridge similar to one described by Mooney (1952). Average values, standard deviation, standard error, and 95-percent confidence intervals are listed in table 9. The large-sample mean falls within the 95-percent confidence interval about the small-sample mean for all except specimen K, for which only order-of-magnitude agreement is obtained. In any case the value obtained from the full specimen is probably more reliable. The comparison was made here to be sure that the irregular shape of the hand specimens would not radically alter the susceptibility values obtained.

Table 8.--Magnetic susceptibility of four hand specimens measured with the probe magnetometer.

Specimen no.	Rock type	Volume (cm ³)	Magnetic susceptibility ($\times 10^4 \frac{\text{k}}{\text{emu/cm}^3}$)
K	Quartz monozonite	1680	16
L	Quartz monozonite	1900	17
M	Welded tuff	1560	6
N	Welded tuff	912	3

Table 9.--Magnetic susceptibility of small samples drilled from hand specimens listed in table 8.

Specimen number	Number of small samples	Magnetic susceptibility ($\times 10^4$ emu/cm ³)		Statistics ($\times 10^4$ emu/cm ³)	
		Average	Standard deviation	Standard error	95-percent confidence interval <u>1/</u>
K	12	23	4.7	1.4	$20 < \mu < 26$
L	15	20	5.8	1.5	$17 < \mu < 23$
M	12	6.1	0.13	0.038	$6.0 < \mu < 6.2$
N	7	2.3	0.71	0.27	$1.6 < \mu < 3.0$

1/ "True" population mean can be taken as specimen mean from table 8.

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